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ABSTRACT

Background: Developmental coordination disorder (DCD) is one of the most prevalent developmental disorders in school-aged children. The mechanisms and etiology underlying DCD remain somewhat unclear. Altered visuomotor adaptation and internal model deficits are discussed in the literature.

Aims: The study aimed to investigate visuomotor adaptation and internal modelling to determine whether and to what extent visuomotor learning might be impaired in children with DCD compared to typically developing children (TD). Further, possible compensatory movements during visuomotor learning were explored.

Methods and procedures: Participants were 12 children with DCD (age 12.4 ± 1.8, four female) and 18 age-matched TD (12.3 ± 1.8, five female). Visuomotor learning was measured with the Motor task manager. Compensatory movements were parameterized by spatial and temporal variables.

Outcomes and results: Despite no differences in visuomotor adaptation or internal modelling, significant main effects for group were found in parameters representing movement accuracy, motor speed, and movement variability between DCD and TD.

Conclusions and implications: Children with DCD showed comparable performances in visuomotor adaptation and internal modelling to TD. However, movement variability was increased, whereas movement accuracy and motor speed were reduced, suggesting decreased motor acuity in children with DCD.

What this paper adds?

The underlying mechanisms and etiology of DCD remain somewhat unclear. Over the last decade, a great variety of hypotheses

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Abbreviations: BMI, body mass index; DCD, developmental coordination disorder; DCDQ, Developmental Coordination Disorder Questionnaire; DEPV, directional error at peak velocity; DOM, duration of outward movement; EACD, European Academy for Childhood Disability; HPL, half path length; MTM, Motor task manager; OT, onset time; rANOVA, separate mixed repeated measures; SD, standard deviation; TD, typically developing children; WISC-IV, Wechsler Intelligence Scale for Children; ZGT, Zurich Graphomotor Test; ZNA-2, Zurich Neuromotor Assessment, second version.

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have been advanced and investigated, all concluding that several processes of motor learning, especially visuomotor learning, seem to be impaired in DCD. Most research investigating visuomotor learning in DCD so far has focused on visuomotor adaptation. However, the successful recall of a previous visuomotor adaptation performance and its transfer to a recurring perturbation error through a successfully updated internal model has hardly been studied in DCD. Therefore, the present study adds to the limited research on internal modelling and on possible simultaneous compensatory movements, which may also underlie the movement deficits seen in DCD. Compensatory movements can reduce the efficiency of a movement. The novelty of this study was that investigating visuomotor adaptation, internal modelling, and compensatory strategies simultaneously in one multilevel study approach allowed us to observe possible interactions between these factors during the same visuomotor adaptation task. The results indicated that children with DCD exhibited comparable performances in visuomotor adaptation and internal modelling to age-matched TD controls. However, increased movement variability and decreased motor acuity suggest the presence of compensatory movements in DCD. Both movement accuracy and motor speed were reduced. This study raises awareness of ‘‘hidden’’ compensatory movements that may also underlie the movement deficits seen in DCD, as they reduce movement efficiency.

Data availability

Data will be made available on request.

1. Introduction

Developmental coordination disorder (DCD) is one of the most prevalent developmental disorders in school-aged children, with an estimated prevalence between 5% and 6% (Blank et al., 2019). According to the most recently published interdisciplinary clinical practice recommendations (Blank et al., 2019), approved by the European Academy for Childhood Disability (EACD), DCD is defined as motor performance below expected levels given the child’s chronological age and the presence of four criteria: The child must have had sufficient opportunities to acquire motor skills (criterion 1 of the EACD). The disorder must interfere significantly with activities of daily living, academic achievement, leisure, and/or play (criterion 2 of the EACD). The impairment should be explainable neither by a medical, neurodevelopmental, or psychological disorder, nor by social circumstances or cultural background (criterion 3 of the EACD). Finally, the onset of DCD symptoms must lie in childhood (criterion 4 of the EACD).

Studies have shown that impaired motor functions in children increase the risk to mental health (Harrowell et al., 2017; Lingam et al., 2012), psychological well-being (Piek et al., 2007), social integration (Missiuna et al., 2008; Sylvestre et al., 2013), and academic achievement (Harrowell et al., 2018; Zwicker et al., 2012). Notably, DCD tends to persist into adolescence and adulthood (Kirby et al., 2011; Losse et al., 1991). Early diagnosis and treatment of DCD is therefore important to reduce its negative consequences in the long term. However, diagnosing DCD is challenging, because the disorder is heterogeneous in its nature and its presentation of symptoms (Wilson, Smits-Engelsman, Caeyenberghs, Steenbergen, 2017a), involves many clinical aspects (Farmer et al., 2017), and is often accompanied by comorbidities such as attention-deficit/ hyperactivity disorder and autism spectrum disorder (Lingam et al., 2010; Schoemaker et al., 2013).

The mechanisms and etiology underlying DCD remain somewhat unclear (Blank et al., 2019). However, the last decade has seen an increase in research about the neural and motor factors which might underlie the disorder. A number of hypotheses have been advanced and investigated, as described in reviews by Subara-Zukic et al. (2022), Emanuele, Polletta, Marini, & Fadiga (2022), and Wilson et al. (2017b). The majority of researchers reached the same conclusion: that motor development, motor control, and motor learning are impaired in children with DCD. Motor learning is of particular interest for our research project.

Motor learning defines experience-dependent improvement in motor performance, which includes explicit, consciously controlled processes and implicit, consciously unaware ones. Motor learning aims to produce more effective movements (Krakauer et al., 2019) that are marked by, for instance, decreased variability, higher precision, or faster execution. In everyday life, humans primarily perform movements in a dynamic environment that is characterized by sudden unexpected changes. Such changes lead to movement errors, which are detected by the sensorimotor system through feedback strategies. Such error feedback provides a teaching signal by which the brain learns from the error (Albert & Shadmehr, 2016; Imamizu et al., 2000). The central nervous system generates a template or map (Albert & Shadmehr, 2016), also known as an internal model, that serves as the neural representation of how the body will respond to a motor command under consideration of the current circumstances of body position and velocity. Once a repetitive movement pattern has been recognized, the internal model enables the central nervous system to predict the consequences of motor commands and to update such motor commands from recall of the error feedback. Thus, the brain uses internal models to control movements more accurately, such as by inducing movement adjustments to correct an error (Kawato & Wolpert, 1998; Shadmehr et al., 2010). The ability to generate internal models is an important factor for motor learning and motor control, because they predict movement outcome much faster, before sensorimotor feedback becomes available to the brain (Wolpert, 1997). Therefore, internal models provide stability to the motor system, reduce movement variability, and increase movement effectiveness (Izawa et al., 2008).

The internal model is adjusted and updated by a type of motor learning called motor adaptation (Krakauer & Mazzoni, 2011; Shadmehr et al., 2010; Smith et al., 2006), which reduces the systematic error induced by a perturbation (Hadjiosif et al., 2021; Shadmehr et al., 2010). Because motor adaptation relies on sensory-guided feedback, it is also referred to as sensorimotor adaptation and as sensorimotor learning (Krakauer & Mazzoni, 2011). Studies suggest that some aspects of sensorimotor learning are impaired in DCD; these include sensorimotor processing (Allen & Casey, 2017), which is the ability to couple sensory information with related motor responses in the central nervous system. In particular, the ability to coordinate visual information in relation to movement, known as visuomotor skills, seems to be affected in children with DCD (Pinero-Pinto et al., 2022). Consequently, several studies have suggested that motor adaptation from a visual input, termed visuomotor adaptation, is disturbed in DCD too (Bo & Lee, 2013; Brookes et al., 2007; Gómez-Moya et al., 2020; Kagerer et al., 2004, 2006; Zwicker et al., 2011). In contrast, other studies have found no general difference in visuomotor adaptation between subjects with DCD and those without (Cantin et al., 2007; Gheysen et al., 2011; King et al., 2011). Some researchers conclude from this inconsistency that visuomotor adaptation might be strongly impacted by task type and task difficulty (Blank et al., 2019; Wilson, Smits-Engelsman, Caeyenberghs, Steenbergen, 2017a). Visuomotor adaptation difficulties are seen in more complex tasks that require a higher degree of motor precision and higher movement speed (Wilson, Smits-Engelsman, Caeyenberghs, Steenbergen, 2017a). Visuomotor adaptation is understood to occur largely in the cerebellum (Rabe et al., 2009; Shadmehr et al., 2010; Sokolov et al., 2017). Cerebellar dysfunction has also been linked to several developmental disorders (Stoodley, 2016), including DCD (Debrabant et al., 2013; Zwicker et al., 2010), which supports the theory of altered motor adaptation in DCD.

Most research in visuomotor learning in DCD so far has focused on motor adaptation (Kagerer et al., 2004; Kagerer et al., 2006) and has not investigated the successful recall of previous visuomotor adaptation and transfer to recurring perturbation error. Such an approach thus neglects another theory in the current state of research in DCD. Children with DCD face a fundamental deficit in their ability to generate and utilize internal models for motor learning and control (Adams et al., 2014; Subara-Zukic et al., 2022; Wilson et al., 2013; Wilson, Smits-Engelsman, Caeyenberghs, Steenbergen, 2017a), sometimes termed an internal modelling deficit (Wilson et al., 2013; Wilson, Smits-Engelsman, Caeyenberghs, Steenbergen, 2017a). Such a deficit prevents children with DCD from updating their motor commands from error information, thereby reducing their motor learning capabilities (Adams et al., 2014) and predictive control (Ruddock et al., 2015; Wilmut & Wann, 2008). This means that even if children with DCD adapt to sudden error such as a visual perturbation, they may be reduced in their capability to recall their previous adaptation learning in an updated internal model during a recurring error event. Such recall of internal models was investigated by Gómez-Moya et al. (2020) in children with DCD; this study revealed that a significant larger proportion of participants with DCD exhibited a reduced ability to adapt to a recurring visual perturbation after a visuomotor adaptation task, which suggests an impaired acquisition of an internal model.

A third frequently disregarded aspect is motor-behavior-related processing effort. Motor learning involves higher cognitive processes in processing movement-related information such as sensory feedback and information about the movement outcome (Thon, 2015). Children with DCD require higher processing efforts, for instance under dual task conditions (Parr et al., 2022) or seen through altered cortical activation using functional magnetic resonance imaging when performing visually guided motor reactions during a predictive encoding task (Debrabant et al., 2013), which may account for the motor coordination deficits. Subara-Zukic et al. (2022) describe how motor planning and control rely on a more energy-intensive approach, thus leading to reduced capacities in the cognitive networks, especially during more complex tasks, explaining a motor-cognitive trade-off (Schott, 2019). Such higher processing effort can make children with DCD less efficient and effective during movement and more prone to functional compensatory strategies such as higher movement variability and slower responses to reduce function degradations (Blank et al., 2019; Subara-Zukic et al., 2022). For example, this has been observed during gait on uneven surfaces or stair ascent, where children with DCD demonstrated smaller step length, reduced gait velocity, increased sway, and greater variability in their foot-clearances than typically developing peers (Gentle et al., 2016; Parr, Foster, Wood, Thomas, & Hollands, 2020). Such compensatory movements require more resources from the motor system, such as muscle force and physical endurance, which further reduces motor quality and precision (Cook et al., 2014; McGibbon et al., 2003). Consequently, only investigating possible alterations in motor adaptation and/or internal modelling in DCD is not sufficient, because neither can detect the simultaneous use of compensatory strategies, which may also underlie the movement deficits seen in DCD.

This study follows several approaches: The first aim is to investigate visuomotor learning in children with and without DCD. A visuomotor adaptation task is used that creates a visual feedback perturbation leading to altered motor commands without changing the proprioceptive feedback from the muscle. Visuomotor learning can be evaluated by how well the subject adapts to the perturbation. We hypothesize that children with DCD performing a visuomotor adaptation task will display a slower rate of performance improvements than age-matched typically developing children (TD).

The second aim of this study is to investigate differences between children with and without DCD in the ability to successfully acquire an internal model during a visuomotor adaptation task by measuring its recall during a recurring perturbation. This takes our investigations of visuomotor learning in DCD a step further than previous research into DCD. We hypothesize that participants with DCD show poorer internal modelling than age-matched TD.

As a third aim, we analyze spatial and temporal parameters during the visuomotor task, which enables us to detect possible compensatory movements during visuomotor learning in children with and without DCD. We hypothesize that children with DCD show greater movement variability, and decreased movement speed and/or accuracy to achieve similar results to age-matched TD.

The novelty of this study is that investigating visuomotor learning during adaptation, internal modelling, and compensatory strategies simultaneously in one multilevel study approach allows us to consider possible interactions between these factors during the same motor task. Moreover, the recall of an internal model after visuomotor learning has scarcely been studied in DCD so far.

2. Material and methods

2.1. Participants

A total of 30 right-handed children and adolescents aged 8–16 years participated in the study between 2016 and 2018. Our sample size was primarily based on the sample size of similar/ comparable studies (Furrer et al., 2020; Kagerer et al., 2004, 2006; Wilhelm et al., 2014). Participants with suspected or diagnosed DCD were enrolled through the University Children's Hospital Zurich, occupational therapy centers, and pediatric practices in the greater Zurich area. TD were recruited via flyers and advertisements placed at schools, universities, and medical practices. Preliminary interviews with a parent or guardian and standardized questionnaires ensured that the participants were right-handed, had no history of suspected neurological or psychiatric disorder, cognitive impairments, or sleep disorders. Those children who suffered from attention-deficit/ hyperactivity disorder (n = 3), a typical comorbidity of DCD (Montes-Montes et al., 2021), did not take any medication at the time of the study.

Due to the heterogeneous clinical picture of DCD, several instruments were used to detect children with DCD. DCD criterion 1 of the EACD guidelines (Blank et al., 2019), motor performance below expected levels, was operationalized with the Zurich Neuromotor Assessment-2 (ZNA-2), a standardized procedure to measure motor performance in children and adolescents aged 3–18 years (Kakebeeke et al., 2019), and the Zurich Graphomotor Test (ZGT) to assess graphomotor skills (Knaier et al., 2022). Criterion 2, interference with activities of daily living, academic achievement, leisure, and/or play, was operationalized with the Developmental Coordination Disorder Questionnaire (DCDQ), a parent-based questionnaire designed to screen for coordination disorders or motor difficulties during daily activities (Wilson et al., 2000). Criterion 3, exclusion of neurodevelopmental or psychological disorder, social circumstances, or cultural background as cause, was operationalized with the fluid intelligence index of the Wechsler Intelligence Scale for Children (WISC-IV), an intelligence test for children between 6 and 16 years of age (Petermann & Petermann, 2007) and data from a previous interview with a parent. Criterion 4, symptom onset during childhood, is given for all participants due to age restriction of this study to 8–16 years.

Written informed consent was obtained from a primary parent or guardian and from all participants 14 years and older. Additionally, participants younger than 14 years gave verbal consent. The studies were performed according to the Declaration of Helsinki and approved by the local ethics committee (KEK-ZH-No. StV-40/07).

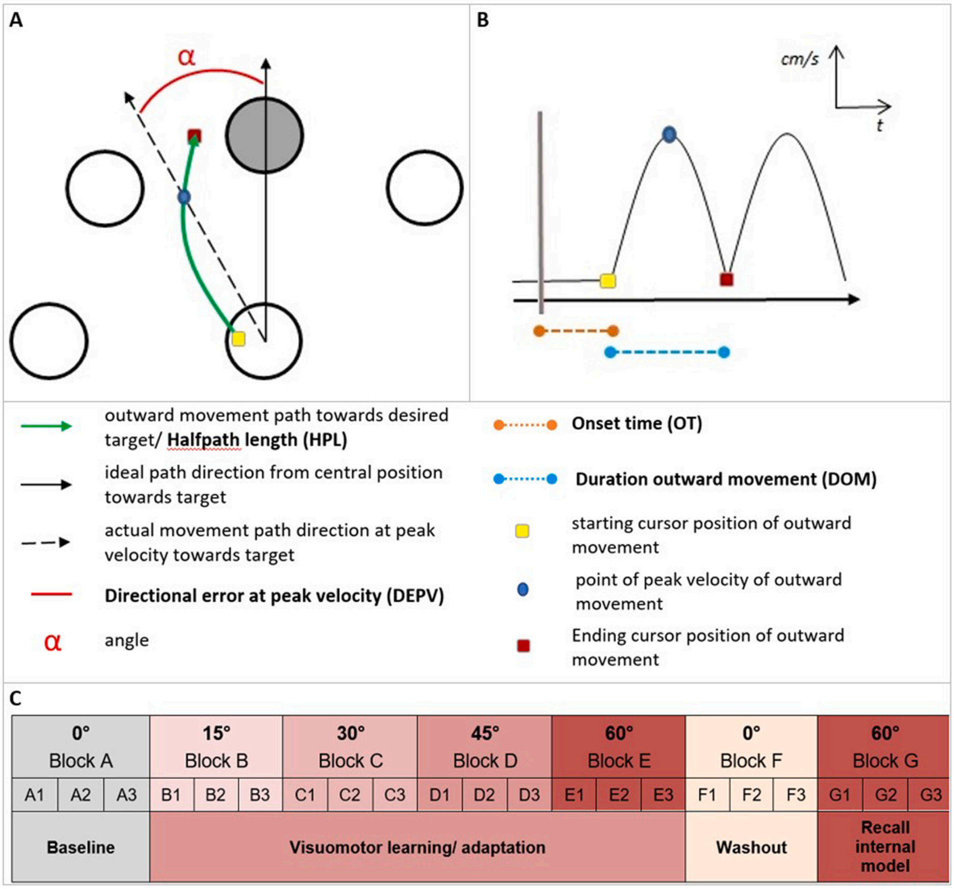

Fig. 1. : Visuomotor adaptation task (measured with MTM) and its parameters. **A**: Computer screen displays four target points and a center position from which the outward movement starts towards the target, appearing in gray; during the visuomotor adaptation blocks, the cursor position is rotated counterclockwise relative to the hand position by a fixed angle. **B**: Marked parameters investigated during the course of movement speed over time of an outward movement in the visuomotor task; gray bar represents the time at which a target point lights up. **C**: Sequence of the blocks without rotation (Block A, Block F) and with rotation by a fixed angle (Block B – E, Block G) and its rationale for visuomotor learning investigation.

2.2. Instruments

2.2.1. Motor task manager (MTM)

Visuomotor learning through adaptation was measured with the Motor task manager (MTM, version 7.1). This task involves an implicit motor learning paradigm, which is suitable for prolonged sessions and enables accurate parameterization of motor performance and its improvement (Huber et al., 2004). The MTM consists of a digitizing tablet connected to a computer and a computer screen that displays five points together with the cursor position; this is instead of eight points as used with adults in Huber et al. (2004). The MTM with five points (see Fig. 1A) was used in previous studies at our center (Furrer et al., 2020; Wilhelm et al., 2014) and is especially useful when investigating children and adolescents because it reduces the difficulty and the length of the task (Wilhelm et al., 2014). The study participants performed out- and backward movements with the dominant right hand from a central starting position to one of four targets. Targets appear in combination with an auditory signal randomly at 1-second intervals in a pseudorandomized order. The task comprises seven blocks (A-G), each of which includes three trials with 44 movements in the same learning condition and a 1-minute rest between the trials. The task starts with a baseline block (Block A, no rotation), followed by visuomotor learning blocks in which the cursor position is rotated counterclockwise relative to the hand position by a fixed angle unknown to the participant. Block B involves angles of 15°, Block C 30°, Block D 45°, and Block E 60°. The adaptation task is followed by a washout phase in which subjects are returned to a no-rotation condition (Block F: 0°) before performing a block of abrupt maximum rotation again (Block G: 60°), which provides information about the subject's implementation of an internal model (see Fig. 1C for an overview). The entire task lasts about 30 min.

During the task, the participant's vision of the hand is occluded by an experimental apparatus so the participant cannot see their own movement path. All participants were instructed to move as fast and as accurately as possible to the target. Both actions were intended to improve implicit learning.

2.3. Procedure

Participants were tested individually in a quiet environment. First, the WISC-IV test was applied followed by the ZNA-2 and ZGT. After a break of 45 min and a snack, the participants performed the MTM. A study experimenter guided the participants throughout the task and ensured that their performance did not deteriorate due to decreasing motivation, a lack of understanding of the task, or changes in posture.

2.4. Theory and calculation

Visuomotor adaptation can be measured by several parameters. In this study, we used Krakauer et al.'s (2005) approach and defined directional error at peak velocity (DEPV) as the primary outcome (aim 1). DEPV is the angular difference between the direction linking the center and the point of the peak velocity of target direction, which describes the degree of deviation of the movement curve from the ideal path at the instant of highest speed. Visuomotor adaptation can be parametrized by a decrease of DEPV across the three trials of the same rotation in each block and across all blocks by the mean values of each trial across the course of the task (Krakauer et al., 2005). In this study, only Blocks A, B, and E were analyzed to investigate visuomotor adaptation. For data analysis, DEPV was normalized by the angle of the imposed rotation in Blocks B, E, and G.

The first trial of Block G (G1) was used to assess the level of implementation of an internal model as second outcome (aim 2) by comparing the mean DEPV of G1 (immediate readaptation to 60° rotation) normalized between the groups. Significant differences in DEPV between the groups would suggest that internal modelling differed between the groups, and higher DEPV values would indicate a less defined internal model.

Finally, compensatory movement outcomes (aim 3) were analyzed for the investigation of possible hints for compensatory strategies, decreased efficiency and/or instability of motor behavior in participants with DCD (see Fig. 1B for an overview). These were parametrized by onset time (OT), the time period between the appearance of the target and the start of subject's movement (i.e., reaction time); standard deviation onset time (OT-SD), the variability of reaction times indicating movement flow and rhythm; halfpath length (HPL), the length of the actual outward movement; and duration outward movement (DOM), the time period between the start of subject's movement and the completion of the outward movement. Additionally, standard deviation values of all parameters except DOM provided markers of movement variability, a parameter reflecting the stability of motor behavior and neuromuscular control (Stergiou & Decker, 2011).

Movements in which the child was not paying attention to the target or attempted to guess the next appearing target point were excluded from further analysis. This generally affected less than 10% of all trials and did not differ substantially between the groups ($p = .074$).

Separate mixed repeated measures ANOVAs (rANOVAs) were performed on the visuomotor parameters with factor group (DCD, TD) as between-subject factors and block (A–E) as within-subject factors (representing the factor time). For each visuomotor measure except for DEPV in Block G1, we ran a separate model. In case of a significant main effect or interaction in rANOVAs, post hoc comparisons were calculated to further elucidate the effect (e.g., at which time point the groups differed). We tested for homogeneity of covariances, assessed by Box's test, and homogeneity of the error variances, assessed by Levene's test. The Greenhouse–Geisser adjustment was used when we needed to correct for violations of sphericity. Group differences for aim 2 were analyzed using independent *t*-test analysis. The level of significance was set to $p \leq 0.05$. All statistical analyses were performed with IBM SPSS statistics (version 28).

3. Results

Of the 30 participants recruited, 12 were children meeting the criteria for DCD (which was confirmed by one of the last authors (OGJ, board licensed developmental pediatrician) and 18 were TD for their ages and thus allocated to the control group. Group characteristics are shown in Table 1.

The mean ZNA-2 SDS of − 1.19 in the DCD group reflects the general motor performance that is far below expected level for chronological age. When looking at the individual motor components of the ZNA-2, motor deficits (defined as ≤ -1.0 SDS) in the DCD group did not always affect all motor areas. 50% of the DCD group showed an impairment in the fine motor domain, while 42% presented severely impaired gross motor function. Only 17% of DCD children showed severe problems in both motor domains.

3.1. *Visuomotor adaptation (Aim 1)*

The rANOVA revealed a significant time effect, with $F(2.3, 64.4) = 8.4$, $p < .001$, but was not significant for factor group $F(2.3, 64.4) = .7$, $p = .346$ and the interaction between group and time, with a Greenhouse–Geisser $F(2.3, 64.4) = .7$, $p = .516$, partial $\eta^2 = .025$. Postanalysis revealed a similarly significant decrease for both groups (see Fig. 2).

3.2. *Internal modelling (Aim 2)*

An independent t-test showed that there was no significant difference between DCD and TD in DEPV in Block G1 ($p = .761$), indicating that both groups implemented their internal model equally well immediately after returning to 60° rotation.

3.3. *Compensatory movements (Aim 3)*

The rANOVAs indicated no statistically significant interaction between time and group for OT, OT-SD, HPL, HPL-SD, DOM, and DEPV-SD; see details in Table 2. A significant main effect for group was found in DOM ($F = 6.6$, $p = .016$, partial $\eta^2 = .19$), HPL ($F = 5.0$, $p = .033$, partial $\eta^2 = .15$), and DEPV-SD ($F = 4.2$, $p = .049$, partial $\eta^2 = .13$). All other parameters revealed no main group effect. Bonferroni adjusted post-hoc analysis of DOM revealed significant group differences in the Blocks A3 ($p = .005$), B1 ($p = .005$), B2 (($p = .008$), B3 ($p = <.001$), E3 ($p = .035$), with the DCD group on average 43.3 ms (95% CI [−77.95, −8.65]) slower than the TD group. For the parameter HPL, Bonferroni-adjusted post hoc analysis revealed significant group differences in Blocks A3 ($p = .008$), B1 ($p = .024$), and E2 ($p = .045$), with the DCD group moving the cursor on average 0.47 cm further (95% CI [0.04, 0.91]) toward the target point. These observations indicate that the DCD participants were less accurate and less efficient than the TD participants when aiming and reaching the target. Bonferroni-adjusted post hoc analysis of DEPV-SD revealed significant group differences in Blocks A1 ($p = .005$) and E1 ($p = .003$), with the DCD group being on average 1.05 SD more variable than the TD group in their movement performance curve from the ideal path at the time of the highest speed.

4. Discussion

4.1. *Visuomotor adaptation (Aim 1)*

The primary aim was to determine whether and to what extent visuomotor adaptation might be impaired in DCD. Results indicate that both DCD and TD groups performed equally well in the visuomotor task throughout the whole course of the task. Therefore, our initial hypothesis that children with DCD would show a higher directional error at peak velocity, the marker for visuomotor adaptation, than TD children during a visuomotor adaption task was not confirmed. These findings are in contrast to Kargerer et al.'s (2006) results, which showed that gradual visuomotor distortion does not facilitate adaptation in children with DCD, in contrast to abrupt distortion. However, Kargerer et al.'s study differs from ours in its methodological approach. In our study, perturbation in the MTM task was gradually increased by 15°, whereas Kargerer et al. used 10° increments. Kargerer and colleagues (2006) themselves demonstrated in a study that children with DCD respond more effectively to an abrupt visuomotor change than to a gradual one. Although only a 5-degree higher perturbation was used in our study than in Kargerer et al.'s, our approach is more like an abrupt

Table 1
Participant characteristics of both groups investigated.

	DCD (N = 12)	TD (N = 18)
Female (%)	4 (33)	5 (28)
Age (years)	12.4 ± 1.8	12.3 ± 1.8
BMI (kg/m^2)	18.9 ± 2.8	18.4 ± 2.4
ZNA-2 (SDS)	**-1.19 ± 0.7**[**]	**0.01 ± 0.8**[**]
ZGT (SDS)	**-1.58 ± 0.9**[*]	**-0.56 ± 1.1**[*]
DCDQ (total score)	**48.7 ± 7.9**[**]	**67.1 ± 4.4**[**]
WISC-IV (WLD index score)	115 ± 10.1	107 ± 13.2

[*] $p < 0.05$.

[**] $p < 0.005$.

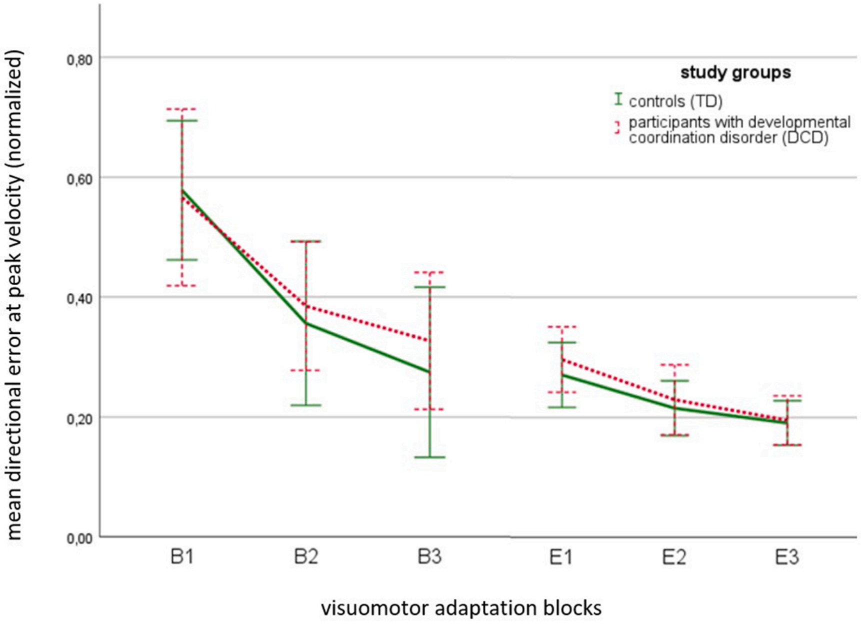

Fig. 2. **:** Learning curves for the visuomotor adaptation task in Block B (15° rotation) and Block E (60° rotation) showing a significant decrease of the mean directional error at peak velocity (normalized) in both groups over the course of the task and across the three trials of the same rotation blocks, but no significant difference in adaptation between the groups. Bars represent standard deviation.

Table 2

Results of repeated measures ANOVAs of interaction effects calculated for parameters investigating compensatory movements (Aim 3).

Group*time	**F**	**df**	**p**	**η^2**
onset time (OT)	.76	3.16	.528	.026
standard deviation values for onsettime (OT-SD)	1.40	3.82	.241	.048
halfpath length (HPL)	1.10	3.50	.357	.038
standard deviation values for halfpath length (HPL-SD)	1.24	4.58	.297	.042
duration outward movement (DOM)	1.55	2.46	.215	.053
standard deviation values for directional error at peak velocity (DEPV-SD)	2.21	5.07	.056	.073

Note: Group (DCD/TD); Time (Block A1-E3)
η^2: Eta squared.
* $p < 0.05$.
* * $p < 0.005$.

perturbational change and thus could possibly explain the different findings between both studies.

However, our findings are in line with Biotteau et al. (2016) and King et al. (2011). Biotteau et al.'s review outlined that children with DCD show certain impairments in motor adaptation but no general learning deficit, as they are able to acquire, retain, and transfer skills (Biotteau et al., 2016). King et al. used additional auditory feedback, as we did during the visuomotor adaptation task, whereas Kargerer et al. (2006) did not include auditory feedback. The question arises whether auditory feedback might support the learning process. Indeed, a recent study (Blais et al., 2021) investigated the effect of auditory and visual stimuli feedback on perceptual motor learning in children with DCD. It found that when the auditory stimuli were omitted, the number of errors increased significantly, and when the auditory stimuli was reintroduced, the errors were once more minimized in the motor task (Blais et al., 2021). This indicates that additional auditory information can help children with DCD during the establishment of perception–action coupling (Blais et al., 2021; Lê et al., 2021), which leads to better performance. This aligns with the assertion that children with DCD are more reliant on additional feedback than children without DCD (Blank et al., 2019), especially during tasks involving a high number of visual cues, because children with DCD may have problems processing visual information appropriately (Smyth et al., 2001).

The results of this study are comparable with another (Furrer et al., 2020) investigating visuomotor adaptation with the same tool (MTM) in children with attention-deficit/ hyperactivity disorder, a common comorbidity of DCD (Lingam et al., 2010). Furrer et al. found no difference in visuomotor adaptation in attention-deficit/ hyperactivity disorder patients compared to TD children. Both studies are comparable in participants' age ranges, and the magnitudes of the DEPV normalized parameter are comparable between both studies throughout the tasks.

4.2. Internal modelling (Aim 2)

The second aim of this study was to investigate differences between the groups in the ability to successfully acquire an internal model during a visuomotor task and transfer it to a recurring perturbation. In fact, the groups showed no significant difference in Block G1 (immediate recall of the internal model), meaning that the internal model was equally well acquired and transferred to the recurring perturbation of 60° in both DCD and TD. This is surprising and stands in contrast to our hypothesis, as we expected that even in the case of comparable learning and adaptation rates of DCD and TD children with DCD would differ in their ability to acquire a precise internal model and use it during a recurring error event.

Our findings differ from those reported by Gómez-Moya et al. (2020), where a significantly larger number of DCD participants exhibited a reduced ability to recall the internal model when presented with a recurring visual perturbation after visuomotor learning. However, a generally smaller adaptation magnitude in DCD participants was also observed during the preceding adaptation task of the same study (Gómez-Moya et al., 2020), which may also interfere with the ability to acquire a good internal model. If motor adaptation is less accurate and more variable, the quality of the internal model will most likely also be compromised. However, this precondition is not given in our study, because visuomotor adaptation skills were comparable between children with and without DCD.

It is difficult to interpret our results in relation to other studies, with the exception of Gómez-Moya et al. (2020). Most researchers (e.g., Adams et al., 2014; Cantin et al., 2007; Kagerer et al., 2004; Kagerer et al., 2006) used a different approach when investigating internal modelling in DCD. Those studies used aftereffects as a measure of adaptation performance and thus of a successfully acquired internal model. Aftereffects are the first movements after a rotation exposure, which are performed without any rotational perturbation similar to the washout block in our study. The authors of those studies argue that the higher the amplitude of the aftereffect, the more successful was the adaptation performance and the acquisition of a stable internal model. However, a successful adaptation can also be parametrized by the gradual reduction of the directional error (e.g., DEPV) over the course of the rotation task (Shadmehr et al., 2010), as we used in this study. Directional error defines the degree of deviation of the movement curve from the ideal path. The lower the directional error, the better was the adaptation performance. Our study also investigated the ability to recall the internal model that was acquired during the visuomotor adaptation task. Such recall of the internal model can be tested with a block involving abrupt maximum rotation directly following a washout block in which participants are returned to a no-rotation condition after learning blocks. This block provides information about the participant's acquired internal model. With children with DCD, this approach allowed us to examine whether they are able to recall and apply what they have learned after being exposed to errors, thereby expanding their motor learning and control for future recurring events. This approach has hardly been studied so far in children with DCD.

It is evident from other studies that the degree of restriction in motor adaptation and internal modelling in DCD is strongly dependent on the nature of the task. However, we do not suspect that our results on visuomotor learning were influenced by the chosen task. We expected that the MTM task fulfills the requirement for spatial and temporal precision, advanced motor planning, and perceptual-motor cues that require adaptation, as mentioned by Blank et al. (2019).

4.3. Compensatory movements (Aim 3)

Our third aim was to investigate differences between the groups in spatial and temporal parameters to identify markers for compensatory strategies during the adaptation task in children with DCD. The results of this study show that the DOM and HPL parameters differed significantly between the groups. The DCD group was less efficient when moving the cursor during the task as it took these children longer to move. Further, the DCD group moved a longer distance than the ideal path. Both parameters are interdependent, as it is most likely that more time is needed to move a longer distance. It remains unknown whether movement speed or movement accuracy are primarily problematic in children with DCD. But since more blocks (five out of nine) differed significantly in DOM than in HPL (three out of nine), slower movement speed likely plays a greater role in children with DCD. However, both results suggest that even though children with DCD are able to fulfil the task with comparable DEPV (primary outcome, see Aims 1 and 2) they require compensatory strategies to keep up with the task and must invest more effort to achieve results similar to those of their TD peers.

The speed–accuracy tradeoff (SAT) is a fundamental principle in human coordination and movement control (Fitts, 1954); it states that to move faster, humans are forced to lower accuracy, and vice versa. However, SAT does not explain the poorer performance in children with DCD, because both accuracy and speed were compromised. Shmuelof et al. (2012) consider another component important in motor skill learning, which they defined as motor acuity. Motor acuity describes the shift in SAT function for a task, meaning motor skill learning can be defined as an improved trade-off between speed and accuracy, primarily driven by a reduction of movement variability (Shmuelof et al., 2012). In our study, children with DCD showed both decreased movement accuracy and motor speed, which could be interpreted as lower motor acuity in DCD than TD. In addition, our results showed higher variability of the DEPV parameter, but only in Blocks A1 and E1. A generally increased variability in children with DCD could not be found in other parameters of the study. Therefore, results are only partly in line with other studies (Golenia et al., 2018; King et al., 2011; Parr, Foster, Wood, & Hollands, 2020). While higher movement variability might suggest a general deficit in neuromuscular control, studies also postulated that higher variability is not necessarily a drawback for children with DCD and may be associated with exploration and learning processes (Golenia et al., 2018). Further, Parr and colleagues presented in a task in which children with DCD ascended and descended a staircase, that increased variability and slower walking speed may reflect a protective adaptation/ compensation to maintain balance control (Parr, Foster, Wood, & Hollands, 2020). Decreased reaction time, as reported in Debrabant et al. (2013), could not be confirmed in this study. Both groups had comparable onset and reaction times.

4.4. Limitations

This study is not free of limitations. First, it is possible that the small sample size and the broad age range in both groups prevented this study from reaching sufficient power to detect significant differences. Second, the heterogeneity and the broad spectrum of motor deficits in our sample, typically for DCD children (Dewey & Wilson, 2001; Visser, 2003; Wilson, Smits-Engelsman, Caeyenberghs, Steenbergen, 2017a), may hamper to detect differences in the adaptation coefficients. Furthermore, this heterogeneity may have had an impact on the visuomotor learning performance, because visuomotor problems may have not be equally occurring in all individuals with DCD. Thirdly, we cannot be sure that the internal model was acquired as we did not analyze the washout block. Even though such a course of events seems highly unlikely, the groups may have not adapted to the washout block and therefore kept the DEPV from the final block of visuomotor learning (Block E) to the recall block for internal modelling (Block G). Nevertheless, because both groups adapted to the gradual increase in perturbation from Block B to Block E, we are confident that readaptation to baseline condition also occurred during the washout block. Further analyses should confirm this. Lastly, we analyzed only Block G1 when investigating the recall of the internal model, because we were interested in immediate readaptation to 60° rotation. However, we cannot exclude that there may have been differences between groups in prolonged readaptation to 60° (Block G2 and G3).

5. Conclusion

Children with DCD overall showed comparable performances in visuomotor adaptation and internal modelling to TD controls. Thus, the theory of altered motor adaptation and an internal model deficit in DCD as described in the literature was not confirmed by this study. However, the study results suggest decreased motor acuity in children with DCD, as both reduced movement accuracy and motor speed were observed during a visuomotor adaptation task. Therefore, in therapeutic settings of children with DCD, increased attention should be paid to performing accuracy and speed tasks. In addition, it is also important to practice combination tasks that involve both, accuracy and speed (e.g., tasks under increasing time pressure) as in educational settings, children are generally under pressure to finish their work successfully and efficient within required time frames. Further, studies suggest that combined action observation and motor imagery facilitates visuomotor adaptation in children with DCD (Marshall et al., 2020; Scott et al., 2021) and therefore should be included in therapeutic training.

6. Perspective

Krakauer and colleagues (2019) state that reacquiring a motor skill generally takes less time than its initial acquisition. Previous studies have demonstrated that healthy participants with previous experience of a task showed faster visuomotor adaptation in subsequent similar tasks (Krakauer et al., 2005; Seidler & Noll, 2008), which may result from well-acquired internal models. Even though visuomotor adaptation and acquired internal models were observed to be comparable between children with and without DCD in this study, it would be interesting to investigate if this effect remains the same between DCD and TD over longer periods of, for instance, 4 h, 1 day, or 1 week. Different abilities to retain internal models could also explain motor learning difficulties in DCD.

CRediT authorship contribution statement

EK: Investigation, Data curation, Writing – original draft, Writing – review & editing. CEM: Investigation, Data curation. JAC: Conceptualization, Supervision. RH: Conceptualization, Methodology, Supervision, Writing – review & editing. THK: Conceptualization, Investigation, Project administration, Writing – review & editing. OGJ: Conceptualization, Funding acquisition, Project administration, Writing – review & editing.

Declarations of interest

none.

Data availability

Data will be made available on request.

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