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RESEARCH ARTICLE

Alteration of body representation in typical and atypical motor development

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Abstract

Developmental coordination disorder (DCD) impacts the quality of life and ability to perform coordinated actions in 5% of school-aged children. The quality of body representations of individuals with DCD has been questioned, but never assessed. We hypothesize that children with DCD have imprecise body representations in the sensory and motor domains. Twenty neurotypical children, seventeen children with DCD (8–12 years old) and twenty neurotypical adults (25–45 years old) performed both sensory and motor body representation tasks: a limb identification and a limb movement task. We observed lower accuracy in the sensory task but not in the motor task. In both tasks, we observe a larger amplitude of errors, or synkinesis, in children with DCD than in neurotypical children. In neurotypical children, accuracy was lower than in neurotypical adults in the motor and sensory task, and the amplitude of sensory errors and synkinesis was higher than in neurotypical adults. Using a linear regression model, we showed that sensory accuracy is a good predictor of synkinesis production, and that synkinesis production is a good predictor of sensory accuracy, as can be expected by the perception-action loop. Results support the hypothesis of an imprecision of body representation in DCD. We suggest that this imprecision arises from noise in the body representation used at the level of internal models of action. Future studies may assess whether slower plasticity of body representations, initial imprecision, or both may account for this observation. At the clinical level, prevention strategies targeting body representation in early childhood are strategically important to limit such impairments.

KEYWORDS

body representation, body schema, developmental coordination disorder (DCD), dyspraxia, internal models, synkinesis

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1 | INTRODUCTION

Developmental Coordination Disorder (DCD) stands as a neurodevelopmental disorder characterized by the struggle to acquire motor skills (5th ed.; DSM-V; American Psychiatric Association, [APA] 2015). Children with DCD face challenges in both gross and fine motor performance (Hoare, 1994; Larkin, 1991), along with difficulties in maintaining static and dynamic balance (Hoare, 1994) when compared to their neurotypical peers. Beyond diagnostic features, individuals with DCD also exhibit inferior cognitive performance in areas such as planning (Dewey & Kaplan, 1994), attention (Dewey et al., 2002), visual-spatial processing (Dewey & Kaplan, 1994; Pisella et al., 2021; Wilson et al., 2013), and visual-memory (Dwyer & McKenzie, 1994). These challenges significantly impact their participation in academic and social activities, thereby making daily life demanding (Magalhães et al., 2011). On a large cohort of children with DCD, Vaivre-Douret (2011) reported that 60% struggle with sports, 88% with writing activities, 56% with gesture imitation, 63% with finger knowledge, 70% with body spatial knowledge and 33% with precise oral movements.

In the context of typical development, cognitive models of voluntary movement postulate the existence of mental representations of movement that allow us to interact with our environment and to move (Wolpert, 1997). These cognitive models are called internal models with two coexisting functions. The *inverse model* creates a motor command adapted to the situation and to our representation of the body; it takes into account, for example, the biomechanical constraints of the body and its current state (Wolpert & Ghahramani, 1995). The *forward (predictive) model*, on the other hand, anticipates the sensory consequence of the movement from an efference copy of the motor command, and therefore must take into account the sensory representation of the body (Wolpert, 1997). The realization of a movement thus depends on an estimate of the body state at the present moment and a prediction of its future state after the performance of the movement.

Remarkably, meta-analyses and systematic reviews have shown strong evidence in favor of an internal modeling deficit in children with DCD, that is, in predictive control (Adams et al., 2014; Gabbard & Bobbio, 2011; Wilson et al., 2013). These children have particularly poor imagery skills and fail to show a strong isochrony in mental imagery tasks between their motor performance and their ability to mentally plan the movement to be performed (Deconinck et al., 2006). We have suggested that one explanation for such impairments in internal modeling could be a lack of accurate body representations (Gomez & Sirigu, 2015). Indeed, internal models require accurate representations of the body for action (Wolpert, 1997; Wolpert et al., 1998), known as the *body schema* (de Vignemont, 2010), in turn the sensory representation of the body is necessary for predictive models of action. The purpose of the present study is to clarify how body representation is altered in children with DCD.

Here, we define body representation as the ability to represent one's body for action (efferent) and perception (afferent pathway). The internal representation of the body as a whole and in its segmentation during action has been theorized and conceptualized under the term

Research Highlights

- Body representation is impaired in children with DCD and has a significant cost in terms of the accuracy of sensory identification of body parts and associated movements.
- Inaccuracies in the body representation measured in perception and in action (error amplitude and synkinesis) are related in both NT children and adults.
- In typical development, we provide evidence of a strong link between body schema and body image.

body schema (de Vignemont, 2010; Head & Holmes, 1911; Martel et al., 2016). The body schema is an implicit system that continuously regulates posture and movement, in other words, it is a system of motor and sensory abilities that can operate below the threshold of vigilance (Assaiante et al., 2014; de Haan et al., 2018; Manser-Smith et al., 2019; Martel et al., 2016; Sirigu et al., 1991). This internal representation of the body is constructed from multimodal integration of sensory and motor information (Assaiante et al., 2014; Manser-Smith et al., 2019; Martel et al., 2016) and from a psychological perspective, examining the position and configuration (Yoshioka et al., 2014) of the body as a volumetric object in space (Assaiante et al., 2014). Body representation for perception is often called *body image* (de Vignemont, 2010; Head & Holmes, 1911; Martel et al., 2016). It mainly corresponds to a multi-sensory system used explicitly and allowing the visualization of metric properties of the body (de Vignemont, 2010; Martel et al., 2016).

The body schema and body image systems are expected to work relatively independently in adulthood. Indeed, arguments for two independent systems come from the observation of neuropsychological dissociations in deafferented patients, that maintain some level of motor coordination despite the loss of bodily sensations and numb-sense patients who experience difficulties in recognizing their own body, even though they can still feel bodily sensations (Paillard, 1999). Several views before us have criticized this distinction on empirical and theoretical grounds (see Pisella et al., 2006 for a review). To the other extreme on this continuum of theoretical position, the enactive approach completely rejects this perception-action dichotomy within body representation (Hurley, 1998; Noë, 2004; O'Regan & Noë, 2001). Without going too far toward that extreme, what is usually debated is whether or not the two pathways work in isolation without interacting. We take the position that this assumption is much too strong in the context of neurodevelopment, and therefore consider body representation for both action and perception. Hence, studying body representation in the context of DCD may also shed new light on the key mechanisms of the typical development of motor coordination abilities and body representation.

In typical development, the emergence of the body schema is not innate; rather it gradually unfolds through the integration of multimodal sensory information (Bremner, 2016; Fontan et al., 2017). Prior research suggests that multisensory integration matures with age,



influencing body schema calibration and consequently, the reliability of internal action models. Nardini et al. (2013) with a cohort of neurotypical children aged 4–12 years and adults showed that adults, as well as the 7–9-year-old group, integrate multimodal sensory information more efficiently than 4–6 and 10–12-year-olds. The development of the internal representation of the body is not linear, particularly because of the important morphological changes that occur during adolescence. These changes can disturb the calibration of visual and proprioceptive information, and consequently the reliability of multimodal integration. Thus, the body schema matures during growth (Assaiante et al., 2014; Schmitz et al., 2002), which likely makes updating of internal action models more difficult in children than in adults (Assaiante et al., 2014). In children with DCD, we know that proprioceptive information is poorly processed (Li et al., 2015).¹ However, studies like that of Li et al. (2015), among others, do not clarify if the slowness or imprecision observed in sensory decision making is related to an imprecision in body representation, and whether this impacts sensorimotor noise and action variability. To do so, it would be interesting to study the relationship between sensory and motor errors and variability in DCD. An alternative approach within the realm of typical developmental literature, a strategy has emerged to tackle the matter of the body schema in children. This involves directing attention towards the capacity to predict postural perturbations during voluntary actions. In this task, neurotypical children have to adjust their posture when a weight is removed from a plate they are holding, with sensory adjustment serving as a measure (Schmitz et al., 2002). However, with this type of task, if children fail or are slower, it remains ambiguous whether the underlying cause is related to executive functions pivotal in this context (which are still developing at the age of 8 and are also affected in DCD), or if it stems from deficits in the body schema itself. In order to assess the body representation directly, we therefore decided to remove this executive component, using a task involving the representation of the body during a simple movement as will be described below.

Recent evidence also suggest that DCD affects the updating of the body schema (Martel et al., 2022). Martel et al. (2022) used a tool-use paradigm to show that when children with DCD were asked to reach for an object with their hand before and after extensive tool-use, children with DCD explicitly judged, as well as their neurotypical peers, that their arm was shorter after tool use. However, tool use affected the movements of participants with DCD only in terms of amplitude, but not latency. The authors were also able to show that for tool use, initial motor control was similar between groups, as well as their improvements in motor control of tool use. These data suggest a dissociation between plasticity of explicit and implicit body representations. This study supports the hypothesis that there is a deficit in body schema plasticity for useful planning and executing movements. Yet, their results do not support the existence of a body image plasticity deficit in DCD. However, it is unclear from this study whether this poor ability to update the body schema is due to a poorer initial body schema per se, solely an inability to update this representation in the short term, or both. As pointed out earlier, this question is of great relevance since the body representation in particular is a key compo-

nent of internal models of action. An inaccurate body schema could therefore constitute an early precursor of DCD, and the impact of this inaccuracy could have cascading effects on other motor coordination mechanisms.

Regarding the body schema, we focus on a simple body part movement task, an experimental paradigm designed to assess a straight-forward movement using a specific body part, such as a finger, in a controlled and structured manner, in order to isolate and examine fundamental aspects of motor function, such as precision, coordination, and accuracy, without the complexity or involvement of multiple body parts or complex motor sequences. We contend that this task holds great value for measuring the accuracy of body representations as it provides an opportunity to observe synkinesis movements. Synkinesis, often observed during typical motor development (Licari et al., 2006), denotes involuntary movements that manifest in body parts not actively engaged in motor tasks. A woman applying mascara, for instance, may unintentionally open her mouth as she intends to lift only her eyelid—a prime example of synkinesis. These associated movements impede biomechanical efficiency, elevate the energy expenditure of movements, and disrupt the aesthetic quality of motor performance (Licari et al., 2006). Severe or persistent synkinesis is often indicative of neurological dysfunction or developmental delay (Barral et al., 2009). Despite their potential to shed light on the organization of body representations within internal models, these linked movements have yet to be studied in the context of body schema precision. As they could reveal underlying relationships such as proximity of effectors on motor maps—hand-mouth, spatial proximity of effectors—index-major, lateral inhibition mechanisms—right hand-left hand. The type of synkinesis error generated could be indicative of how body representations are organized within internal models (proximity of effectors on motor maps, for example). Because of the persistent presence of synkinesis during atypical development, several authors have focused on the use of these persistent typical motor behaviors in children with DCD (Vaivre-Douret et al., 2011). Interestingly, Vaivre-Douret et al. (2011) report that they are one of the most generalizable behavioral markers across sub-types of DCD (63% of the time). Here, we will study the accuracy of localization of the body part moved as well as the synkinesis across body parts as a measure of body representation organization (efferent pathway) in children with DCD and during typical development.

Regarding the body representation for perception, our focus shifts to a tactile localization task, an experimental procedure used to assess an individual's ability to accurately perceive and locate tactile stimuli on their body. In this task, participants are presented with controlled tactile stimuli and asked to indicate the exact location of the stimulus on their body. This task helps investigate the development and integration of sensory information and provides insights into alterations in body representation across different populations and developmental stages. Indeed, performance of neurotypical children on the tactile localization task highlights significant errors in localization at age four (sometimes over multiple fingers), and yet reveals an already structured internal representation of the hand at this early age (Yoshioaka et al., 2014). This experiment also shows that errors decrease



exponentially over development, reaching adult levels for adolescent participants (Yoshioka et al., 2014). In the context of DCD results are scarce. Previous indirect evidence has already pointed to impaired multisensory body representations by showing weaker somatosensory localization in participants with DCD (Elbasan et al., 2012; Johnston et al., 2017). Our goal here is to extend these lines of research to study the accuracy of localization of the touched body part as a measure of body representation organization (afferent pathway) without the confounding influence of visual information.

In summary, we aimed to characterize the body representations in children with DCD, and compare them with those of neurotypical children and adults. We hypothesized that children with DCD would have a noisier internal representation of the body that impacts access to this representation in both afferent (i.e., perception) and efferent (i.e., motor) sensorimotor pathways. Therefore, we decided to study the body representation both during a tactile localization task, and during a simple motor production task. We used a passive tactile localization task to establish the organization and accuracy of the body representation in children with DCD in the afferent (i.e., perception) pathway, and independently of access to internal models of actions. We employed the execution of a simple movement of a body part to establish the functional organization and accuracy of body representation in children with DCD in the efferent (i.e. motor) pathway when the access to internal models of actions is required (but executive demands are relatively low). First, given the “noise hypothesis of DCD” in the sensorimotor pathways, we expected a more imprecise body representation in children with DCD on the passive tactile localization task than in their peers in terms of accuracy, but most importantly also in terms of error amplitude. Second, given the “internal modeling deficit hypothesis of DCD,” we expected body representation to also be less accurate in children with DCD compared to their peers when access to internal models is required. We predicted that this effect would be evident in the motor task in terms of movement accuracy, but most prominently in terms of amplitude of synkinesis. Furthermore, because we expected both tasks to reflect the access to a common body representation level, we expected that the sensory and motor imprecision (error amplitude and synkinesis) of the body representation measured in one task would be related to that measured in the other task.

2 | MATERIALS AND METHODS

2.1 | Participants

Fifty-seven participants were included: 20 neurotypical (NT) adults (mean age: 25.63 years; SD = 4.19; 10 males), 20 NT children (mean age: 9.45 years; SD = 1.73, 13 males) and 17 children with DCD (mean age: 9.68 years; SD = 1.59, 11 males). Children were matched based on age ($t(35) = -0.423, p > 0.05$) and the three groups were matched regarding sex ratio ($\chi^2(2,57) = 1.19, p > 0.05$). Data collection took place in France, where collecting data on race/ethnicity is not legally permissible.

All participants had normal or corrected vision and were right-handed. All children with DCD had received a diagnosis from a medical doctor according to the DSM-5 (APA, 2015). To be included, an updated screening conducted by the main author, a neuropsychologist, ensured that all children with DCD met the four diagnostic criteria of the DSM-5 for DCD. To do so, they had to show a significant motor coordination deficit as indicated by a score below the 15th percentile in the MABC (Criteria A of the DSM-5, Henderson & Sugden, 1992). The MABC checklist and a parental interview were used to assess whether the motor impairment significantly affected daily living. This criterion was further confirmed by testing participants using the full MABC battery. Significant repercussions on daily life were assessed by the fact that participants were referred to the school or to the Departmental Center for People with Disabilities (transl. *MDPH*). As such, all children with DCD were known by the Departmental Center for People with Disabilities (transl. *MDPH*) due to the adverse effects of their poor motor coordination on daily life and/or academic performance, and 11 children received human and/or material assistance for their writing difficulties on official recommendations of the school doctor (Criteria B) during the experiment. All children met criteria D as they had no other medical or neurological conditions and no intellectual difficulties (Criterion D).

Parents of the neurotypical children completed the MABC assessment questionnaire, and their children completed the full M-ABC battery to confirm the absence of motor difficulties. Neurotypical children were included if they scored above the 20th percentile (i.e., a total test score) on the M-ABC. The included children (with and without DCD) were aged between 7 and 12 years, while the adults' ages ranged from 18 to 35 years. Neurotypical adults were included if they self-reported that they did not experience any motor difficulties in the present or during their childhood using an in-house French translation of the ADC questionnaire (Kirby et al., 2010). Exclusion criteria included current or a history of neurological or psychiatric disorders, current organic disease, pharmacologic medication, intellectual disability (assessed by clinical observation combined with scores on the Similarities and Matrix subtests ≤ 8 of the WISC-IV, Wechsler, 2005, or WAIS-IV, Wechsler, 2011, depending on participant age), or left-handed dominance (on the Edinburgh Test, Oldfield, 1971, laterality coefficient must be greater than 0.5).

One adult was not included due to a left-handed classification on the Edinburgh test, one child was not included as they were subsequently diagnosed with a specific learning disorder involving reading impairment, and one child with DCD was not included because they scored above the 15th percentile on the M-ABC.

Furthermore, additional neuropsychological assessments were conducted to characterize participants' working memory (tested using the Number Memory subtest of the WISC-IV, Wechsler, 2005, or WAIS-IV, Wechsler, 2008, depending on the age of the participant) and visuospatial abilities (EVSP, Pisella et al., 2013, 2020). Parents completed the BRIEF questionnaires for children executive function (Gioia et al., 2014).

All participants or their legal representatives provided written informed consent prior to the experiment. The experiment received

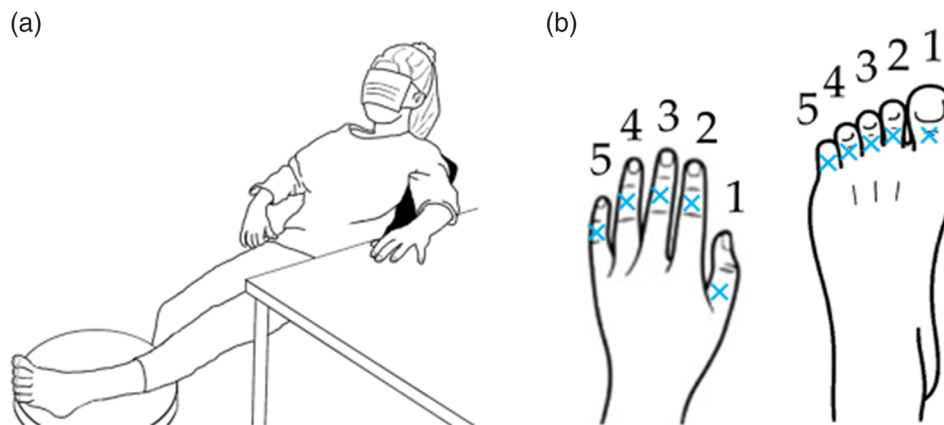


FIGURE 1 (a) Schema of the tactile localization task for one subject. (b) Supporting figure provided to participants to map the numbers to each finger and toe during the tactile localization task.

approval by the National Ethics Committee (CPP No. 2019-A02700-57)) and was conducted in accordance with the ethical standards outlined in the Declaration of Helsinki. Children received games or stuffed animals as compensation for their participation in the experiment.

2.2 | Procedure

Participants performed two tasks: first, a sensory tactile localization task, where they were asked to verbally identify a finger or toe (on the hand and on the foot) based on blindfolded tactile stimulation; and then, a finger movement production task, where they were asked to raise a finger based on a color cue.

2.2.1 | Sensory stimulation task

In the sensory task, we chose to test the hand and foot to replicate the protocol used by Manser-Smith et al. (2019) in order to assess whether the results in NT adults and children replicate previous results. In order to limit the impact of the visuo-spatial reference frame for localizing tactile stimuli (Bremner et al., 2008), in the current study all participants performed the sensory tactile localization task without vision. Participants were seated comfortably in a large chair with their left arm resting on the table and their left foot resting bare on a stool (Figure 1a). To begin, the experimenter explained the task: the experimenter would gently touch a random finger on the participant's left hand and a random toe on their left foot, and then the participant would be asked to identify (using a number) the touched finger and toe as accurately as possible. The numerical correspondence between a finger/toe and a number was established by following the most frequent use of finger and toe numbering in France (e.g., for the fingers, Thumb = 1, Index = 2, Middle = 3, Ring = 4, Little = 5, Figure 1b). To ensure that each number was correctly mapped to each finger and toe for all participants, a figure (Figure 1b) showing the labels was

presented to the participants. This figure was not available during the testing part of the experiment. The participant was first asked to indicate the numbers associated with the stimulated fingers with vision of their fingers over 10 training trials. All participants obtained 100% correct responses on this training, and no participant reported any difficulty in using this numbering scheme. To apply a reproducible amount of force to the skin surface of the fingers or toes, stimulation was administered using a retractable monofilament stylus to the medial phalanx of the finger or proximal phalanx of the thumb, and between the metatarsophalangeal joint (at the base of the toe) and the interphalangeal joint (in the middle of the toe), or the medial phalanx of the finger or proximal phalanx of the thumb (see blue section on Figure 1b). Stimulation was applied to the dorsal aspect of the hand and the dorsal part of the toes. A training session with masked eyes was performed before the task, with ten trials (2 per finger/toe). This training session was to be replicated if the accuracy was not above 95%, but this was never the case.

During each trial of the task, the experimenter applied a one-second stimulation to the hand, followed by a one-second stimulation to the toe, with each stimulation spaced one second apart. Each trial was spaced 5 seconds apart to allow the experimenter to enter the response into the computer and identify the next stimulation sequence. Finger labels were recorded according to the numerical correspondence presented in Figure 1a (e.g., for the fingers, Thumb = 1, Index = 2, Middle = 3, Ring = 4, Little = 5). For the testing phase, participants performed 200 trials.

2.2.2 | Motor production task

In this task, both hands were tested. we reasoned that, the left-hand performance is of special interest since it is less likely to be affected by a ceiling effect in this right-handed population. Participants sat in front of a screen placed horizontally on a table. To begin, the experimenter explained the task: the participant places their hands on the screen, and when they see a color light up under one of their fingers,

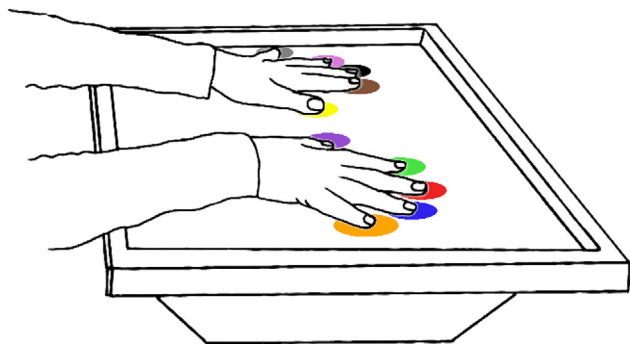


FIGURE 2 Experimental set-up of the motor production task representing the set of all possible stimuli at the same time. During the task, each color appears randomly one after the other one and the subject must lift the finger above it.

they have to raise that finger, and only that finger, as accurately as possible. Apart from this instruction, their hand and fingers had to remain motionless above the target area (Figure 2). Hands were resting on the screen when participants did not have to move a finger. The participant then placed their hands on the screen at the point representing the expected position of their two hands and fingers (for comfort, the position and size of the hands were adjusted for each participant).

For a given trial, the instruction and response period lasted 2000 ms, during which participants received the instruction and had to lift their fingers as quickly as possible. The inter-trial rest period lasted 250 ms. A Logitech® HD Pro C920 webcam using a 1920 × 1080 image resolution placed at finger height recorded the finger movements.

Regarding the motor task, a color-coded input was presented to the participants on the tablet screen beneath the finger to be moved (2000 ms display). The use of a color code allowed participants to determine which finger to raise based also on categorical information, rather than solely on spatial location information. Indeed, participants were instructed that each color was associated with a finger (Figure 2) and that they should raise the finger associated with that color when presented on the screen as quickly and accurately as possible.

Before each test phase, 20 practice trials were performed (2 trials for each finger) to help participants understand the task and become familiar with the instructions. The training phase was repeated if the accuracy was below 95%. In this training phase, all participants achieved 95% accuracy on the trials. For the testing phase, participants performed 100 trials. Each finger was tested 10 times, and the trials were presented in the same pseudorandom order for all participants. The total duration of the task averaged 15 min.

2.3 | Data processing

2.3.1 | The sensory stimulation task

Verbal responses were coded online by the experimenter for each trial. Subsequently, offline, if the participant produced an anticipated

response, it was categorized as correct; otherwise, it was considered incorrect. For each participant, sensory accuracy was computed as the proportion of correct responses for each finger. This response proportion was utilized to form a response matrix (also referred to as a confusion matrix), which not only presents the accuracy of responses on the main diagonal but also displays the distribution of errors around the diagonal (refer to Figure 3).

2.3.2 | The motor production task

Motor responses were videotaped and coded offline by the experimenter. Responses were considered if they occurred during the entire duration of a trial (instruction and response: 2000 ms) or during the inter-trial period (250 ms) for a total period of 2250 ms.

During this interval, the experimenter recorded the initial executed movement and also noted whether any other fingers were raised or not during this movement. If the participant produced the anticipated response, it was classified as accurate; otherwise, it was marked as inaccurate.

This proportion of responses was used to construct a confusion matrix (see sensory stimulation section for construction). Note that errors represent synkinesis (Figure 5), raising more than one finger at a time during this period was defined as synkinesis. For every trial, we quantified synkinesis by counting the number of extra fingers raised during the trial (only in cases of correct responses), and we measured the extent of synkinesis as the greatest distance to the target finger (only in trials with a correct response and synkinesis observed).

3 | RESULTS

The values of the dependent variables, namely, sensory accuracy, sensory error amplitude, motor accuracy, synkinesis production, and synkinesis amplitude, are presented as mean and standard deviations (SD). As all data exhibited non-normal distribution, we conducted non-parametric analyses (Mann-Whitney U or Wilcoxon) for all dependent variables. The effect size for Mann-Whitney test and Wilcoxon test is represented by the biserial rank correlation.

Hence, the analyses were consistent for both the sensory task and the motor task.

The statistical analysis was structured to first assess differences between groups, comparing NT adults (ADU), NT children (NT), and children with DCD, and then to test whether a limb effect occurred for all participants (i.e., hand versus foot in the sensory task, and left versus right hand for the motor task). Statistical significance was attributed to differences with a p-value below 0.05. All p-values were adjusted using the Bonferroni correction.

As a subsequent step, we conducted multiple linear regressions (backward stepwise regression) to ascertain whether accuracy or errors (production errors or amplitude of errors) in one task (motor or sensory) effectively predicted accuracy or errors (production errors or

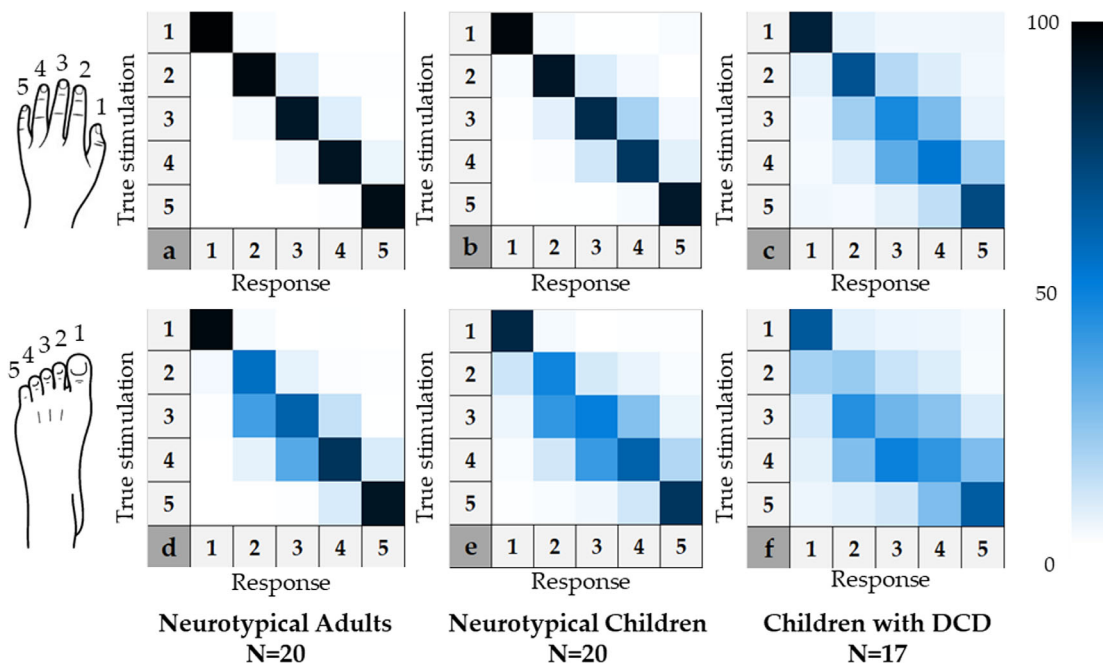


FIGURE 3 Percentage of each possible response in the sensory task (between 0, white, to 100%, dark blue) for each finger or toe according to the location of the true stimulation to the participants' left hand (a–c) and left foot (d–f) for NT adults (left graphs), NT children (middle graphs) and children with DCD (right graphs).

amplitude of errors) in the alternative task. These encompassed models to predict sensory accuracy and sensory error amplitude utilizing variables such as age, group membership, motor accuracy, synkinesis production and synkinesis amplitude. For the motor production task, the models that predicted motor accuracy, synkinesis production, and synkinesis amplitude were formulated with age, group membership, sensory accuracy, and sensory error amplitude as inputs. In each regression, we exclusively report the models featuring the most robust adjusted R^2 .

3.1 | Neuropsychological characteristics

Standardized scores from neuropsychological assessments were compared, and no statistically significant differences were observed between neurotypical children and adults (similarities subtest: $t(38) = 1.09$, $p > 0.05$; matrix subtest: $t(38) = -2.34$, $p > .05$; digital memory subtest: $t(38) = -0.43$, $p > .05$). As anticipated, the comparison between neurotypical and DCD children revealed no significant differences on the similarity subtest ($t(35) = 0.578$, $p > 0.05$). However, differences were found on the matrix subtest ($t(35) = 2.96$, $p < 0.05$) and the working memory subtest (digits, $t(35) = 3.49$, $p = 0.001$), favoring the neurotypical children. Children with DCD had greater impairment scores on the M-ABC subtest ($t(35) = 4.99$, $p < 0.001$) than neurotypical children-related difficulties. Additionally, children with DCD displayed lower scores on the EVSP test ($t(35) = -11.66$, $p < 0.001$) (Table 1).

3.2 | Sensory performance

For the NT adult and children participants, the confusion matrices for both the arm and hand were nearly diagonal (Figure 3), however those of the children with DCD had strong off-diagonal components, suggesting an increased tendency to make errors in the sensory task. Indeed, children with DCD had lower sensory accuracy ($M = 56.16$, $SD = 10.80$) than NT children ($M = 75.90$, $SD = 8.77$; $U = 314.00$, $p < 0.001$, $r_{rb} = 0.85$), who were less accurate than adults ($M = 86.13$, $SD = 5.60$; $U = 341.00$, $p < 0.001$, $r_{rb} = 0.71$; Figure 4a,c). Moreover, children with DCD made errors further away from the target ($M = 1.37$, $SD = 0.17$) than the NT children ($M = 1.19$, $SD = 0.08$; $U = 48.00$, $p < 0.001$, $r_{rb} = -0.72$) who made errors further away than the adults ($M = 1.08$, $SD = 0.05$; $U = 46.50$, $p < 0.001$, $r_{rb} = -0.77$; Figure 4b,c). Across groups, sensory accuracy was lower (foot: $M = 1.21$, $SD = 0.17$; hand: $M = 63.70$, $SD = 15.30$; $W = 1431.00$, $p < 0.001$, $r_{rb} = 1.00$) and sensory error amplitude was greater (foot: $M = 83.50$, $SD = 15.98$; hand: $M = 1.20$; $SD = 0.22$; $W = 587.00$, $p = 0.18$, $r_{rb} = -0.28$) for the foot than the hand.

To examine the potential influence of working memory on the observed outcome, we conducted an ANCOVA analysis. This analysis aimed to assess the presence of a group effect on sensory accuracy and amplitude of sensory error while controlling for the covariate of working memory. Our findings revealed a substantial group effect ($F_{\text{accuracy}}(2, 52) = 31.01$, $p < 0.001$; $F_{\text{error amplitude}}(2, 52) = 27.15$, $p < 0.001$), and post-hoc comparisons with Bonferroni correction demonstrated significant differences between each group, even when

TABLE 1 Scores obtained on average by each group, M: Mean; SD: Standard deviation (WISC-IV/WAIS-IV are standard score range = 0–20; EVSP are raw score, range = 0–72; M-ABC are raw degradation score, range = 0–40).

	Adults, N = 20		NT children, N = 20		Children with DCD, N = 17	
	M	SD	M	SD	M	SD
Similarities subtest (WISC IV/ WAIS IV)	13.60	2.04	12.70	3.06	12.13	2.85
Matrix subtest (WISC IV/ WAIS IV)	10.05	2.76	11.95	2.35	9.50*	2.61
Digit memory subtest (WISC IV/ WAIS IV)	12.50	2.40	12.80	1.99	10.06**	2.72
EVSP test	\	\	66.35	3.33	57.00***	7.57
M-ABC	\	\	3.20	2.65	22.94***	6.99

*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

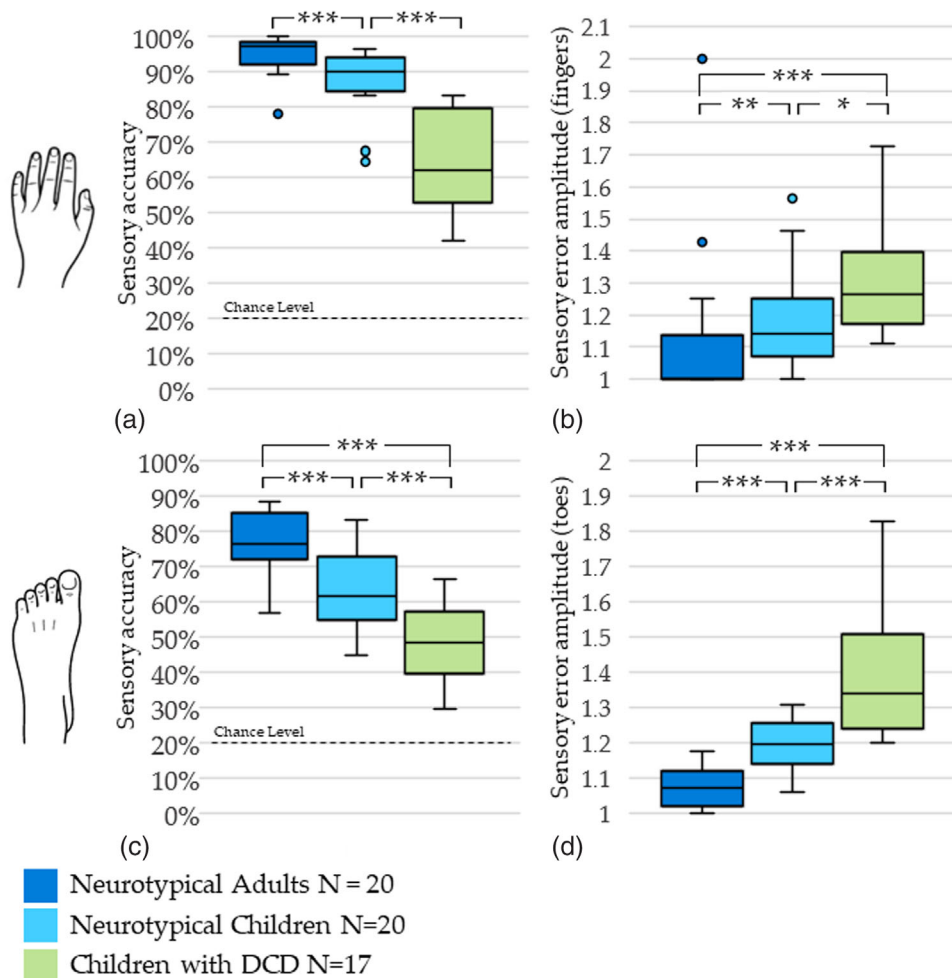


FIGURE 4 Sensory task mean performance for NT adults (dark blue), neurotypical children (NT, light blue) and children with Developmental Coordination Disorder (DCD, green). (a) Sensory accuracy of the hand. (b) Error amplitude between true stimulation location and response location for the hand expressed as a number of fingers. If the amplitude of the sensory error is equal to 2, this means that, on average, the participant committed an error located at a distance of 2 fingers from the true stimulation. (c) Sensory accuracy of the foot, expressed as a number of toes. (d) Error amplitude between true stimulation location and response location for the foot. *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$. Error bars display standard error. The small circles represent outliers' performances from two standard deviations from the mean. Chance level is marked with a dotted line.

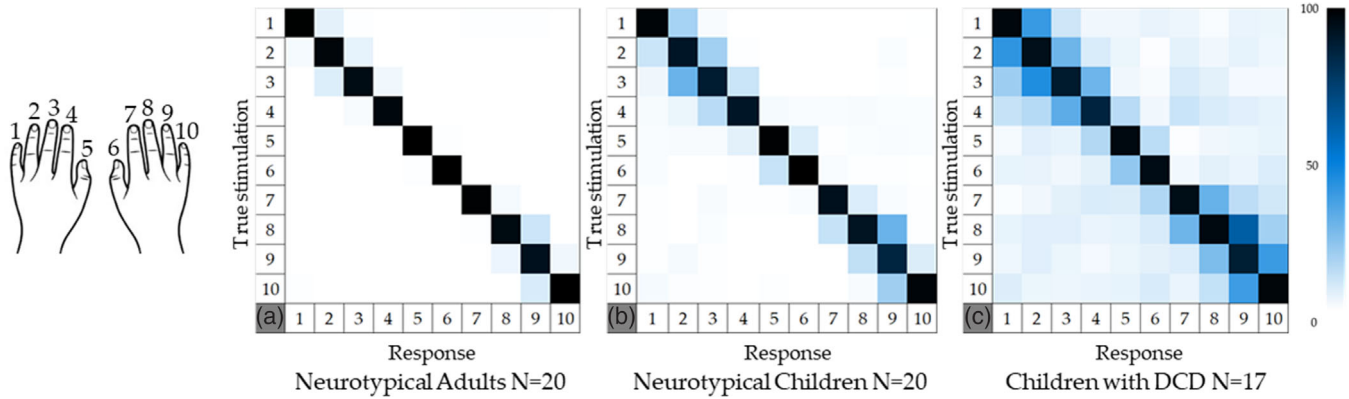


FIGURE 5 Accuracy of movements for each finger as a function of the true stimulation to the left-hand fingers (1,2,3,4,5) and right-hand fingers (6,7,8,9,10) hands for NT adults (a), the NT children (b) and the children with DCD (c).

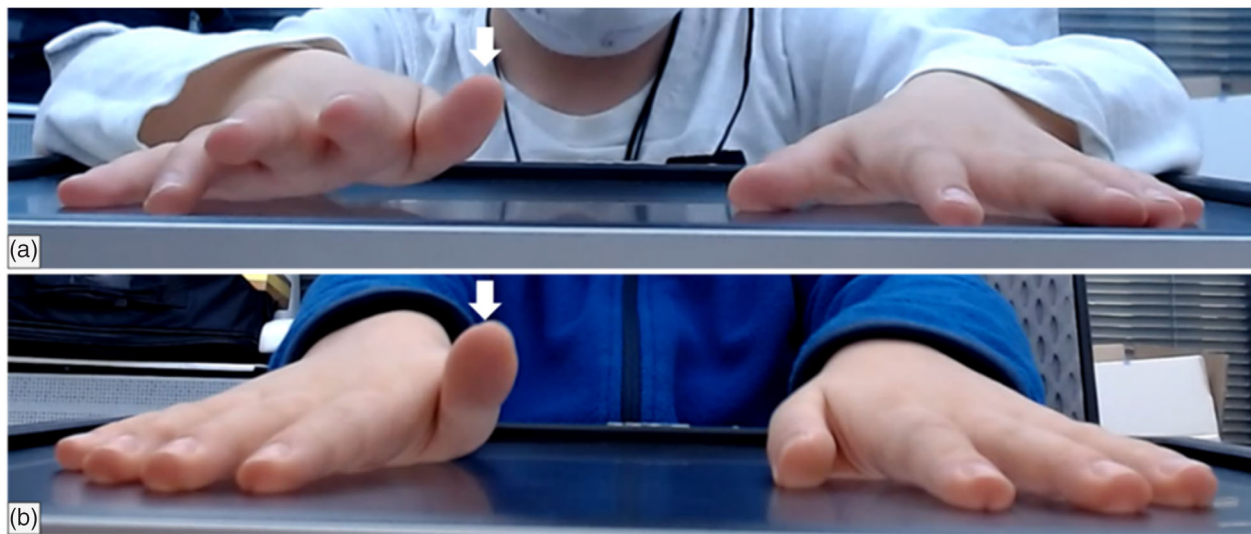


FIGURE 6 Motor production during the fourth stimulation in the motor task. (a) shows a child with DCD aged of 9 years and (b) shows a neurotypical children aged of 9 years.

controlling for working memory abilities (all $p < 0.001$). The covariate showed a significant effect only on the amplitude of confusion ($F(1, 52) = 12.04, p < 0.05$) but not on the accuracy ($F(1, 52) = 7.57, p = 0.79$). These findings suggest that the observed group differences in our study cannot be explained by differences in working memory capacity.

3.3 | Motor performance

Similar to the sensory task, adult and NT confusion matrices for the motor task were nearly diagonal, while those for the children with DCD were less so (Figure 5). This indicates that children with DCD were more likely to make synkinesis errors due to moving adjacent fingers (Figure 6). However, because children with DCD were also actually producing the expected finger movements (a movement consistent with the anticipated response), there was no overall difference in motor

accuracy between children with DCD ($M = 93.53, SD = 5.85$) and NT children ($M = 93.95, SD = 4.97; U = 165.50, p = 0.90, r_{rb} = -0.03$). Yet, NT children were less accurate than adults ($M = 97.95, SD = 0.89; U = 334.50, p < 0.001, r_{rb} = 0.67$; Figure 7a). There was no difference in accuracy between the left hand ($M = 94.87, SD = 5.52$) and right hand ($M = 95.60, SD = 4.74; W = 722.00, p = 0.86, r_{rb} = -0.03$).

The off-diagonal pattern of the children with DCD confusion matrix suggests increased synkinesis. Indeed, children with DCD performed more movements with synkinesis ($M = 93.35, SD = 5.98$) than the NT children ($M = 93.84, SD = 4.80; U = 61.0, p < 0.001, r_{rb} = -0.64$), who had more synkinesis than the adults ($M = 97.89, SD = 0.97; U = 60.0, p < 0.001, r_{rb} = -0.70$; Figure 7b). Children with DCD also exhibited more severe synkinesis, with erroneous movements of fingers farther away from the instructed finger ($M = 2.23, SD = 0.95$) than the NT children ($M = 1.42, SD = 0.64; U = 75.0, p < 0.01, r_{rb} = -0.56$), who exhibited larger amplitude synkinesis than adults ($M = 0.85, SD = 0.68; U = 71.50, p < 0.001, r_{rb} = -0.64$; Figure 7c). There was no difference

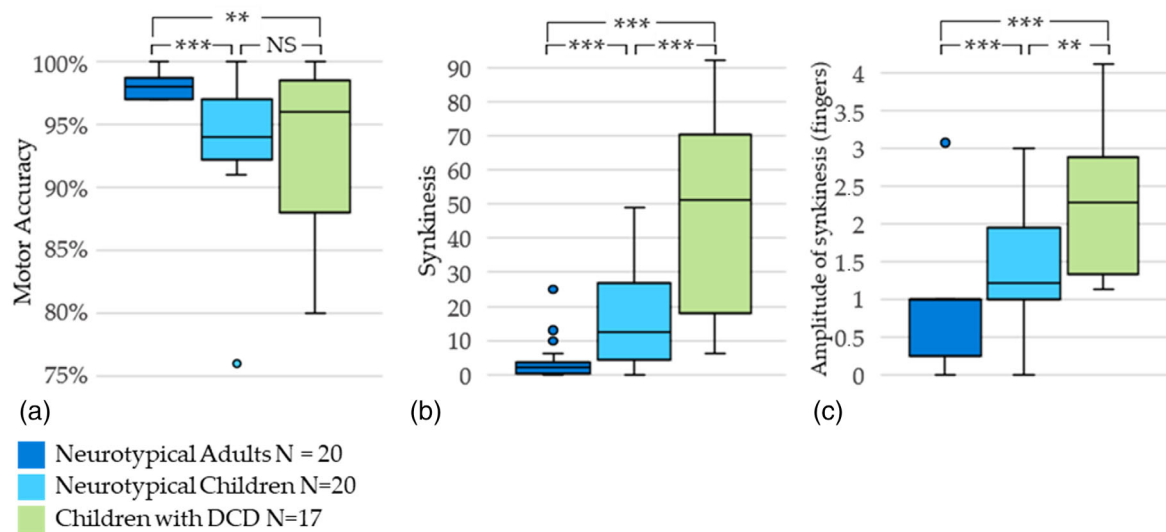


FIGURE 7 Motor task mean performance for NT adults (dark blue), neurotypical children (NT, light blue) and children with Developmental Coordination Disorder (DCD, green). (a) Accuracy for both hands. (b) Proportion of synkinesis averaged across both hands. (c) Amplitude of maximum synkinesis, expressed in number of fingers, for both hands. If the amplitude is 2, this means that, on average, the farthest of the participant's synkinesis is two fingers away from the target finger. *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$. Error bars display standard error. The small circles represent outliers' performances from two standard deviations from the mean.

between the left hand and right hand in terms of the amount (left: $M = 9.43$, $SD = 10.80$; right: $M = 9.05$, $SD = 11.55$; $W = 441.00$, $p = 0.48$, $r_{tb} = 0.13$) or magnitude of synkinesis (left: $M = 0.97$, $SD = 0.55$; right: $M = 0.98$, $SD = 0.55$; $W = 288.50$, $p = 0.89$, $r_{tb} = 0.03$).

To investigate the potential influence of cognitive inhibition (as assessed by the BRIEF questionnaire, only in children, Gioia et al., 2014) on the observed motor performance, we carried out an ANCOVA analysis. This analysis aimed to assess the presence of a group effect between children on motor synkinesis and amplitude of motor synkinesis while controlling for the covariate of cognitive inhibition. Our results revealed a significant group effect between children with and without DCD ($F_{\text{synkinesis number}}(1, 34) = 12.07$, $p < 0.01$; $F_{\text{synkinesis amplitude}}(1, 34) = 3.97$, $p = 0.05$). The cognitive inhibition covariate showed no significant effect either on the number and amplitude of synkinesis ($F_{\text{synkinesis number}}(1, 34) > 1$, $p = 0.99$; $F_{\text{synkinesis amplitude}}(1, 34) = 1.10$, $p = 0.3$). These findings imply that the noted group differences in our study cannot be accounted for solely by variations in inhibition capacity, at least in the case of children.

3.4 | Multiple linear regression models

3.4.1 | Sensory

Multiple linear regression models were employed to predict sensory accuracy and sensory error amplitude, incorporating variables such as age, group (DCD children, NT children, adults), motor accuracy, synkinesis production, and synkinesis amplitude (sensory accuracy: $F(2, 54) = 60.11$, $p < .001$, adjusted $R^2 = 0.68$; sensory error amplitude: $F(3, 53) = 24.56$, $p < .001$, adjusted $R^2 = 0.56$). Sensory accuracy during stimulation was significantly predicted by both participant group

($\beta = -0.64$, $t = -6.06$, $p < .001$) and synkinesis production ($\beta = -0.25$, $t = -2.35$, $p = 0.02$), and sensory error amplitude was predicted by participant group ($\beta = 0.71$, $t = 6.23$, $p < .001$) and motor accuracy ($\beta = 0.21$, $t = 2.10$, $p = 0.04$), but not synkinesis amplitude ($\beta = 0.17$, $t = 1.52$, $p = 0.13$).

3.4.2 | Motor

Similarly, multiple linear regression was also used to motor accuracy, synkinesis production, and synkinesis amplitude from age, group, sensory accuracy, and sensory error amplitude (motor accuracy: $F(3, 53) = 5.64$, $p = 0.002$, adjusted $R^2 = 0.20$; synkinesis production: $F(3, 53) = 21.47$, $p < .001$, adjusted $R^2 = 0.52$; synkinesis amplitude: $F(2, 54) = 15.92$, $p < .001$, adjusted $R^2 = 0.35$). Motor accuracy was not found to be predicted by age ($\beta = 0.35$, $t = 1.71$, $p = 0.09$), group ($\beta = -0.32$, $t = -1.29$, $p = 0.20$), or sensory error amplitude ($\beta = 0.30$, $t = 1.71$, $p = 0.09$). Synkinesis production was predicted by group ($\beta = 0.59$, $t = 2.79$, $p = 0.007$) and sensory accuracy ($\beta = -0.35$, $t = -2.22$, $p = 0.031$), but not by age ($\beta = 0.22$, $t = 1.41$, $p = 0.17$). On the other hand, synkinesis amplitude was predicted by group ($\beta = 0.46$, $t = 2.92$, $p = 0.005$), but not by sensory error amplitude ($\beta = 0.18$, $t = 1.16$, $p = 0.253$).

4 | DISCUSSION

4.1 | Children with DCD have an altered body representation

The quality of body representation in DCD has recently become a subject of interest, due to its potential role in impaired internal mod-



eling (Gomez & Sirigu, 2015; Martel et al., 2022). This study aimed to assess the inaccuracies of body representation among children with DCD, examining its effects on perception and action by comparing adults, neurotypical children and children with DCD. One intent of the study is to quantify imprecision in body representation imprecision using sensory and motor performance data. For this purpose, we assessed accuracy (the extent of conformity to an absolute response) and response precision (the variability of performance around the expected response, i.e. amplitude of errors or associated movements respectively) within each domain.

In the sensory task, children with DCD were less accurate than their peers, and when they performed sensory errors, the amplitude of this error was larger compared to their peers. In the motor task, conspicuously, associated movements (synkinesis) in neighboring fingers or/and contralateral ones interfered with their motor performance. It is worth noting that in this task, children with DCD did not have lower accuracy scores than their peers. We know that movements are usually executed at a rate that is limited by individual biomechanics and factors such as the type of joint, size, weight (Wolpert et al., 1998). The learned relationship between input and output signals, known as an internal model, allows the individual to predict the behavior of the system under similar constraints. These learned sensory and motor maps allow the individual to perform and synchronize movements, and are thought to be altered in children with DCD (Wilson et al., 2013).

However in the present study, similar to previous research (Adams et al., 2016; Plumb et al., 2008), we show that children with DCD can attain comparable accuracy in motor tasks to their peers. Yet, we show that their movement is hampered by synkinesis, which can be seen as a behavioral signature of a more imprecise internal body representation in the motor domain. We argue that this imprecision in body representation, both sensory and motor, is at the root of constructing deficient internal representations of action. Indeed, the accumulation of inaccurate sensory information in body representation models would lead, according to the principle of internal model theory (Wolpert et al., 1998), to inaccurate predictive models and efference copies (Wolpert & Kawato, 1998). Yet, like for every sensorimotor learning task, and unlike what is found in patients with apraxia, children with DCD performed the task with the correct action goal, but with a coarse representation of what effectors should be used. As a consequence, as observed in our task and in other studies (Adams et al., 2016; Plumb et al., 2008), if the action complexity is low, children with DCD perform as accurately as their peers. Yet, when asked to show precision in their body representation their performance is impaired. It could explain why more time is needed to master and automatize motor coordination in DCD.

Addressing whether the motor production task involves an element of inhibition is pivotal to our investigation. Inhibition can be understood at different levels, including cognitive and neuronal levels, and it is important to note that these definitions may not directly overlap. In the realm of motor inhibition, it is well-established that multiple forms of inhibition occur during human behavior (MacLeod, 2007 for the cognitive inhibition level and Wood et al., 2017 for the inhibitory interneurons control of sensory processing and Ziemann,

2020 for inhibitory models of interneurons in the motor cortex). We have addressed the cognitive control aspect of inhibition by measuring it using the BRIEF battery in our sample, ensuring that it does not confound our interpretation. The results indicate that cognitive inhibition does not contribute to the occurrence of synkinesis, and even after controlling for cognitive inhibition, significant group differences in synkinesis remain between children with DCD and typically developing peers. This suggests the involvement of factors beyond cognitive inhibition in the manifestation of motor impairments. Considering neuronal inhibitory mechanisms operating at the level of motor areas representation of body parts may be crucial for maintaining the specificity and precision of motor responses, as discussed below. The association of neuronal inhibitory effects with somatotopy remains an open question (See Duque et al. for a feature review, 2017), and further studies are needed to investigate these mechanisms at both cognitive and neuronal levels, exploring their interplay and distinct contributions to motor difficulties in DCD.

Our results are congruent with Martel et al.'s (2022) results, showing that children and young adolescents with DCD have preserved motor learning capacity, but altered body representation updating abilities. In their study, Martel et al. (2022) argued that a previously neglected aspect of internal models is this body estimate, a representation of the body for action, that allows monitoring the position and size of different effectors (de Vignemont, 2010; Head & Holmes, 1911; Martel et al., 2016). Altogether, our results provide solid evidence in favor of such an interpretation, and this interpretation offers a largely unexplored cognitive mechanism to explain faulty internal representations in DCD.

Many motor learning models (Bernstein, 1967; K. Newell, 1996; Thelen & Smith, 1994) suggest that during initial motor skill development, individuals do not separate actions performed by different body parts to reduce complexity, that is, the degrees of freedom to control (e.g., young children initially move the arm-wrist-hand as a unit when writing before separating each body part). However, expertise leads to increased independence of each body part or muscle until achieving expert-level movement (e.g. skiing, Vereijken et al., 1992, learning to write with the non-dominant, hand Newell & van Emmerik, 1989, in children, Jensen et al., 1995). To attain motor expertise, it is essential that the system effectively distinguishes between body parts or muscle groups during motor control (and also during sensory perception for feedback). In other words, the motor program parameters must allow precise activation and inhibition of these body segments to be identified and parametrized, extending more or less widely over the body based on spatial or functional proximity. Currently, we have limited knowledge about how this separation occurs in childhood and in children with DCD.

4.2 | Altered body image or body schema in DCD?

A question regarding body representation that was addressed by Martel and collaborators was whether only the plasticity of body schema or also the plasticity of body image was altered in DCD.

In their study, Martel et al. (2022) predicted that children with DCD should show a less plastic body schema estimate than their peers, but that the body image and its plasticity should be preserved since body image has not been linked to motor control. However, in the context of neurodevelopmental disorders, we argue that it is very unlikely that body image plasticity is independent of body schema plasticity, especially during the intense period of change of that these representations undergo in adolescence.

Indeed, the study by Martel et al. (2022), itself is a good demonstration of the strong relationship between body image and body schema plasticity: the manipulation of a tool in space modifies the body representation for action which in turn modifies the explicit judgment of body images (i.e., the conscious forearm representation is reduced after tool use). This indicates that the two representations are not fully dissociable, and that plasticity of the body schema is linked to plasticity of the body image in the relatively short-term. In the longer-term (developmental trajectory), we have shown in the current study that the precision and accuracy of body representations for action are good predictors of the precision and accuracy of body representations for perception in our groups, with the reverse also being true. For example, we show that the more synkinesis a participant performed (motor task), the more inaccurate and imprecise they would be in the sensory task, and vice versa. Thus, our results provide further evidence that body image and body schema are not independent during development.

Therefore, we have good reason to argue that in the long-term, a deficient body schema in DCD may induce children with DCD to develop an inefficient body image of themselves and that the overall body representation of children with DCD is altered. Previous indirect evidence had already pointed to impaired multisensory body representations by showing weaker somatosensory localization in participants with DCD (Elbasan et al., 2012; Johnston et al., 2017), which is inconsistent with the prediction of a preserved body image in children with DCD. However, Martel et al. (2022) did show that when asked to estimate their arm length, children with DCD do not differ from their peers in their ability. In the present study, we show instead that the body image is altered in the sensory task. Therefore, our data support the conclusion that both body representation for action and perception are imprecise in children with DCD.

One interpretation of these a priori conflicting results is that due to the large variability in arm length estimation, Martel and collaborator failed to observe a stronger initial overestimation bias in body image in children with DCD compared to their peers: thus, these results call for a pre-registered replication study. However, it is also likely that plasticity of the body schema is altered, but not plasticity of the body image as Martel and collaborator have shown. Nevertheless, because of cascading and interacting effects between these two systems, children with DCD should exhibit an altered body image in the long-term. Because such an interpretation could have clinical implications, replications are needed.

4.3 | Body representations gradually develop with expertise following spatial proximity and contralateral inhibition principle

The developmental trajectory provided by the comparison between adults and neurotypical children shows that neurotypical children still have immature sensory and motor accuracy in finger localization and finger movement tasks as previously reported (Benton, 1955; Chinello et al., 2013). Our results are consistent with the literature demonstrating that the body schema develops quite gradually until age 8 (Assaiante et al., 2014), and motor anticipation functions are not yet fully mature at age 8 (Schmitz et al., 2002).

However, our results also suggest that learning of finger representation is a more continuous process than previously suggested: learning of body representation does not occur in a categorical way when introducing labels related to finger knowledge but rather reflect a gradual individualization of fingers with learning and development. This observation is relevant to research focusing on the relationship between finger knowledge and mathematical skills in children (Butterworth, 1999a, 1999b; Noël, 2005). Indeed, mathematical learning should not be reduced to categorically correct or incorrect knowledge, but involves refinement of body representations that mimics the refinement from an approximate number sense to a categorical label.

It is probable that changes in body representations during development result from cerebral plasticity, itself dependent on the sensorimotor experience of the children. Indeed, as a child ages, they will experience various sensorimotor activities. This notion of induced cerebral plasticity aligns with what we know about the somatotopic organization of the cortex. Cortical body map plasticity is thought to play a crucial role in motor control learning. Penfield demonstrated the somatotopic organization of sensorimotor regions at the cortical level, where each body part occupies a distinct cortical space (Lotze et al., 2000; Penfield & Boldrey, 1937). Despite considerable inter-individual variability of these cortical maps (Desmurget et al., 2014), the leg is typically represented medially in S1, followed by the trunk, arm and face. These develop postnatally through complex interactions between genetic and environmental signals and continue to reorganize throughout life (Vargas et al., 2009). We know that such sensorimotor organization is plastic (Azañón & Longo, 2019; Tamè et al., 2012) and changes based on the use or disuse of body parts (Hlustik, 2001; Penfield & Boldrey, 1937). For instance, violin players who engage in extensive finger movements exhibit enlarged areas representing each finger in sensory and motor regions compared control subjects (Gentner et al., 2010). The adage “like attracts like” summarizes the principles of topographical organization in the cerebral cortex: the cortex minimizes the distance between body parts with spatial (thumb-index) and functional similarity (thumb-mouth, synchrony of action) (Aflalo & Graziano, 2006; Graziano & Aflalo, 2007). This cortical distance and overlap among body regions serve as a marker of neuronal specificity between body parts. Despite numerous studies on this organization in adults, somatotopic organization during development, particularly in humans, remains largely unexplored (but, see Gordon



et al., 2023). These principles of topographical organization and plasticity are pertinent to computational and theoretical models of motor control, and our results can shed light on whether these principles hold true. In addition to the developmental trend mentioned earlier, we also observed a limb-related effect on motor and sensory tasks likely reflecting limb expertise across all groups and measures, indicating a substantial effect (see [supporting information](#)).

Moreover, the confusion matrix also provides an effective way to observe how the principles describing topographic organization may map onto the type of errors performed in both tasks. For instance, in the amplitude of error and the type of synkinesis performed in all 3 groups, we observed that when errors were performed, they occurred on proximal parts (thumb-index) and contralateral parts (left thumb-right thumb, see Gordon et al., 2023), reflecting a spatial proximity and contralateral inhibition principle. We did not observe strong evidence in favor of the functional similarity principle: no differences were observed in the amplitude of sensory errors, yet for synkinesis and their amplitude (i.e., on the motor task), we observed slightly lower levels of errors for fingers sharing a functional gesture such as precision grasping (See [supporting information](#)). Interestingly, the types of error performed by children with DCD were not different in nature or atypical compared to neurotypical children, but they were greater in intensity and amplitude. Overall, this study of error types helps to understand the nature of body representation organization during development of motor coordination and to disentangle what is specific to motor abilities and what is specific to cerebral development. Future studies assessing these principles at the brain level, in children with DCD, would be important for developing future models of motor development. In turn, knowledge about body representation plasticity in typical development could inform relevant training studies for children with DCD targeting body representation in a remediation perspective.

4.4 | Clinical perspectives

Understanding the mechanisms underlying this pathology may lead to improved screening, detection, and management and thus to improved quality of life for individuals with this disorder Smits-Engelsman et al., 2001). As discussed in the section on body image and body schema, further studies are needed to confirm these results which could have relevant clinical implications. Indeed, if children with DCD fail to form a precise body representation for action that causes an internal modeling deficit, but have a reliable body image plasticity, as suggested by Martel, that can, in turn, refine their body schema. We can therefore assume that remediation targeting the body image might help them refine their overall body representation, despite low body schema plasticity, and increase the precision of their internal models through the use of more accurate body estimates. We assert that if it is confirmed that body image plasticity is preserved, then this could be a priority target for intervention. We could imagine exercises designed to sensorially stimulate a part of the body and provide the participant with feedback on the error produced, thus improving the sensitivity and accuracy of the participants' body image.

In a second phase, two possibilities are conceivable: either the representation of the body schema improves spontaneously, or the association between these two representations is increased by providing feedback during a motor task based on the body image (this image should be more accurate following the previous training). Indeed, one could assume that trainings aimed at driving attention toward the incongruity between body image and body schema could help children adapt their body schema in line with their body image.

Finally, another line of research involves using training in the integration of these body representations (image and schema) as a preventive strategy before the body schema falls below what is expected for an age group. To this end, it would seem useful to replicate this study in a sample of young children with DCD (aged 4–5). If the deficits have not yet set in, it may then be appropriate to train body representations in a response-to-intervention model at school, rather than in a remediation model in the face of an established deficit. Moreover, since body representation is a precursor to internal models, relevant training targeting body representation in a preventive way could be relevant, not only for children for DCD, but for all children.

4.5 | Limitations of the study

In the present study, children with DCD and NT children had different levels of working memory abilities. We have thus taken into consideration the potential influence of working memory as one of the confounding factors in the sensory stimulation task, as it could impact participants' accuracy. However, this could be explained by an unexpectedly high working memory ability in NT children, as children with DCD had performance in the normal range and showed no sign of working memory overload during the task, such as failure to provide an answer. Moreover, our analysis using working memory load as a covariate in an ANCOVA indicated that it did not significantly influence the group effect on sensory response accuracy or error amplitude. These results support our conclusion that the observed deficit in sensory localization is related to the motor difficulties experienced by participants rather than working memory limitations.

5 | CONCLUSIONS

In this study, we have presented evidence supporting the idea that body representation matures gradually with age and motor expertise. Furthermore, as theorized at the brain level, we show that, during development, behavioral errors in body representation also follow the principles of spatial similarity and contralateral inhibition. With respect to the clinical population, we showed that children with DCD have an imprecise body representation compared to their neurotypical peers, providing additional support for our hypothesis (Gomez & Sirigu, 2015) that inaccurate body estimates impair the ability of children with DCD to form internal models of movements. Contrary to previous findings (Martel et al., 2022), our results do not provide evidence that

body representation for perception is preserved, yet we discuss the possibility that body image plasticity may still be effective in DCD. From a clinical perspective, we suggest that future early remediation targeting body representation in general may be effective. Previous studies have shown that a body education program (i.e., ENCOR) integrated into school programs and conducted independently by teachers can improve body representation and motor performance in preschool children (Cojan, 2022; Patriau et al., 2022). Future studies may wish to test the impact of such low-cost prevention strategies by focusing on body image plasticity, which may retain a high level of plasticity in DCD (Martel et al., 2022).

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data are available on OSF registry: https://osf.io/7e9fk/?view_only=ca7337dd27184dbbbf0ab40195a68fe7

ETHICS STATEMENT

All participants or their legal representatives provided written informed consent before the experiment. The experiment was approved by the National Ethics Committee (CPP No. 2019-A02700-57) and conducted in accordance with the ethical standards of the Declaration of Helsinki.

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ENDNOTE

¹Several studies have reported a noisy sensorimotor performance of children with DCD, giving rise to the "noise hypothesis" of DCD in the motor domain (Golenia et al., 2018; Smits-Engelsman et al., 2008; Smits-Engelsman & Wilson, 2013). However, the relationship between performance variability and motor control is not a trivial question, as noise may originate from different sources (Churchland et al., 2006; Desmurget et al., 1995; Latash et al., 2002).

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SUPPORTING INFORMATION

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