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Title

Motor deficits in autism differ from that of developmental coordination disorder

Running title

Motor deficits differ in ASD and DCD

Authors

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Abstract

Autism Spectrum Disorders (ASD) and Developmental Coordination Disorders (DCD) are both associated with sensorimotor impairments, yet their nature and specificity remain unknown. In order to clearly distinguish the specificity between the two disorders, children with ASD or DCD presenting the same degree of motor impairment, thus homogenous profiles, were examined in a reach-to-displace paradigm, which allows the integrity of two main aspects of motor control (anticipation/feedforward control and movement correction/feedback control) to be separately interrogated. We manipulated children's previous knowledge of the weight of the object they were to displace: when known, participants could anticipate the consequences of the weight when reaching for the object, prior to contact with it, thus allowing for feedforward control. Conversely, when unknown prior to contact, participants had to cope with the object weight in the displacing phase of the movement, and use feedback control. Results revealed a preserved feedforward control, but an impaired movement execution (atypical slowness) in children with DCD, while children with ASD displayed the opposite pattern with an impaired feedforward control, but a preserved feedback one. These findings shed light on how specific motor impairments might differently characterise developmental disorders and call for motor rehabilitation programmes adapted to each population.

Keywords

Autism Spectrum Disorder; Developmental Coordination Disorder; feedforward control; feedback control; internal models; action representation, kinematics

Introduction

In addition to the typical pattern of impaired communication, social interaction and behavioural stereotypies (DSM-5: American Psychiatric Association, 2013), children with ASD also experience fine and gross motor troubles, clumsiness, and atypical sensorimotor development, with a prevalence of over 50% (Bauman, 1992; Downey & Rapport, 2012; Hirata et al., 2015; Miyahara et al., 1997; Paquet et al., 2016; Provost et al., 2007; Whyatt & Craig, 2012). Almost 80% of people with ASD live, indeed, with varying degrees of motor difficulties that impact on their daily functioning (Lai et al., 2014). Meanwhile, Developmental Coordination Disorders (DCD) is another neurodevelopmental condition diagnosed on the basis of impaired motor skills in absence of any intellectual disability nor neurological injury (DSM-5: American Psychiatric Association, 2013). Children with DCD experience general clumsiness, poor balance (Geuze, 2005b), associated with coordination and handwriting problems which negatively impact their academic and life achievements (Geuze, 2005a; Paquet et al., 2016; Smits-Engelsman et al., 2001; Van der Linde et al., 2015; Van Waelvelde et al., 2006). A study on a cohort of almost 12000 American families affected by ASD from the SPARK database (Bhat, 2020) observed that 87% of the sample had motor impairments according to the DCD-Questionnaire (thus qualified as at risk for DCD; Schoemaker et al., 2006). Similarly, over 97% of a group of children with ASD scored below the 16th percentile on the M-ABC (Miller et al., 2021). A diagnosis of ASD and DCD being recognized by the DSM-5 (American Psychiatric Association, 2013), any child with ASD screened as DCD with the typical tests (M-ABC, Henderson et al., 2016; DCD-Q, Schoemaker et al., 2006) could be diagnosed as ASD+DCD. However, while the symptoms at the behavioural level, as indicated by the evaluation scales, might look similar, it is not clear that they are of the same nature. For instance, gesture to command and imitation of meaningful gestures have been found to distinguish ASD from DCD, even when controlling for social deficits (Kilroy et al., 2021, 2022). This strongly urges for disentangling the pattern of motor deficits pertaining to ASD from those pertaining to the DCD populations, as they might not be managed in the same way during motor interventions. ,

Motor control is not a unitary function but instead relies on two modes of control: the feedforward and the feedback. While the latter corrects the movement already launched, the former, also called

anticipatory, defines in advance the motor command according to the build-up of a sensorimotor representation of the characteristics of the object, the effector, the relationship between the two, such as the distance from the body. Once the movement starts and somatosensory information is available, it is compared to that predicted by the so-called forward model. Any mismatch will lead to corrective commands, hence feedback control, and an update of the model to improve the action performance (see, for review, Desmurget & Grafton, 2000). In typically developing children, it has been established that almost a decade was necessary to reach adult-like patterns in reach and lifting tasks (Forssberg et al., 1992; Martel et al., 2020; Roy et al., 2013; Schneiberg et al., 2002). Regarding atypical development, the literature has not reached a consensus. ASD individuals are known for experiencing difficulties in executive planning, but some discrepancy persists regarding motor planning abilities and motor execution (see Rinehart, Bradshaw, Brereton, & Tonge, 2001 for preserved motor execution and Forti et al., 2011; Glazebrook, Elliott, & Szatmari, 2007; Glazebrook, Gonzalez, Hansen, & Elliott, 2009 for impaired movement execution). The complexity of the task sometimes determines the ability of ASD individuals in movement planning. They seem able to plan their movement when the information is directly accessible, however when asked to anticipate a movement on an uncertain target, they fail to adopt an optimal starting position (Glazebrook et al., 2007) and display different kinematic signatures than TD children (Cavallo et al., 2021) as if self-generated planning was disrupted in the ASD population. Fabbri-Destro and collaborators (2008) asked children with ASD to reach for an object and to place it in a specific container, that could be either large (easy task) or small (difficult task). Children with ASD failed to modify their reaching movement kinematics as a function of the difficulty, suggesting that they could not take into account the movement goal (Fabbri-Destro et al., 2008). This view is supported by patients' inability to perform the end-state comfort bar task (Hughes, 1996). Indeed a lack of anticipation (feedforward control) has been repetitively observed (Bäckström et al., 2021; Cattaneo et al., 2007; Hughes, 1996; Mari et al., 2003; Martineau et al., 2004; Rinehart et al., 2001; Schmitz et al., 2003; Stoit et al., 2013). In a reach-to-grasp paradigm, Mari and collaborators (2003) observed a lack of coordination between the reaching and the grasping phases in ASD, especially in those with lower IQ. Yet, recent studies challenged this view reporting a disrupted feedforward and feedback control in ASD individuals (Mosconi et al., 2015; Shafer et al., 2021; Wang

et al., 2015; see also Ming, Brimacombe, & Wagner, 2007; Sacrey, Germani, Bryson, & Zwaigenbaum, 2014 for review). Previous studies reported that adding a visual distractor to a task influenced both feedforward and feedback control of typical children, but not of children with ASD (Dowd et al., 2011), highlighting their preference for proprioceptive over visual feedback (Lidstone & Mostofsky, 2021; see also Glazebrook et al., 2009 for visuo-proprioceptive integration).

The nature of motor impairment in DCD is also debated. Jover and collaborators (2010) observed a lack of effectiveness of feedforward control in a paradigm where posturo-motor coordination was at stake. When considering voluntary movements, children with DCD appeared able to program their movement accurately in easy end-state-comfort tasks, while they displayed difficulties in complex tasks (Adams et al., 2016; Noten et al., 2014; Smyth & Mason, 1997). In visually-guided reaching tasks, their initial direction error has been found unaffected attesting of preserved feedforward control, while the path length could be longer in children with DCD than in TD children suggesting that they reached for a longer than necessary distance, which could highlight deficits in integrating visual information and online control (Grohs et al., 2021). Regarding the feedback control, children with DCD were found impaired in Rapid Online Control (ROC) through double step paradigms (Hyde & Wilson, 2011a, 2011b; but see Adams et al., 2016 for absence of ROC deficit). This impaired feedback control is generally attributed to a difficulty in integrating error signals between what is predicted and what is actually felt (Kagerer, Bo, Contreras-Vidal, & Clark, 2004; Kagerer, Contreras-Vidal, Bo, & Clark, 2006; see for reviews Adams, Lust, Wilson, & Steenbergen, 2014; Gomez & Sirigu, 2015; Smits-Engelsman & Wilson, 2013; Zwicker, Missiuna, Harris, & Boyd, 2012). Children with DCD would have a deficit in their internal modelling function and reduced visuo-motor processing (e.g. Fuelscher et al., 2015; Reynolds et al., 2015; for review, Steenbergen et al., 2020). Finally, some authors support the hypothesis of a maturational delay as compared to age-matched typical children rather than structural impairment (Hyde & Wilson, 2013; Li et al., 2015; Zoia et al., 2002). Recently, using a tool-use paradigm we probed body representation plasticity and found a deficit in children with DCD and adolescents thus favoring the internal model deficit hypothesis (Martel et al., 2022).

From this short review, it seems that DCD and ASD motor impairments share some characteristics but might have distinct profiles, which was confirmed by several reviews focusing on the differences and similarities between the two populations (Caçola et al., 2017; Kilroy et al., 2019; Piek & Dyck, 2004). However, very few studies directly compared DCD and ASD groups of children on motor tasks. To date, most of them focused on action imitation or observation and found both similarities and differences in performance (Dewey et al., 2007; Gauthier et al., 2018; Green et al., 2002; Paquet et al., 2019; Xavier et al., 2019). In a small sample of children, Miller and collaborators (2019) observed that children with DCD and ASD differed in their speed profile in a dynamic postural control task.

Studies investigating voluntary movements in children with DCD or ASD, without taxing visuo-spatial performance or imitation skills are scarce and call for homogeneous inclusion criteria. Some studies considered the dual diagnosis DCD + ASD when children with ASD scored below the 15th percentile at the M-ABC, thus showing motor impairments (Caeyenberghs et al., 2016). Others compared ASD and DCD groups with different levels of motor impairments (Dewey et al., 2007; Gauthier et al., 2018; Green et al., 2002; Paquet et al., 2019) and some did not consider the level of motor impairment in their groups (Miller et al., 2019; Xavier et al., 2019). Here we sought to identify the fingerprint of the ASD and DCD motor impairment, to this aim children motor deficits were matched for their severity (using a gold-standard test).

We chose an ecological paradigm that allowed investigating both feedforward and feedback mechanisms in one single task (Martel et al., 2020; Roy et al., 2013), without highly taxing the visual system. The task consisted in reaching for an object and displacing it to a different location. We manipulated a non-visible property of the object namely the object weight, and the knowledge the child had about it before starting the movement. When the weight was known, the reaching phase allowed investigating feedforward control as the reaching phase could be adapted to the weight of the object. Adults and children older than 7-8 years old (Martel et al., 2020; Roy et al., 2013) reach faster for a heavy object, in order to compensate for the consequences of the upcoming weight. In kinematics, reaching faster translates in peaks of acceleration or velocity showing an increased amplitude and /or an anticipated latency. Once the object in hand (during the Displace phase), a major

weight would typically slow down the movement as evidenced by delayed peaks of smaller amplitudes. Based on our above review of the literature, we hypothesized feedforward control to be preserved in children with DCD, that is a reaching phase adapted to the weight of the upcoming object as observed in TD peers. On the contrary, we hypothesized that children with ASD would fail using a proper anticipatory control feedforward control and would display a very similar profile (namely undifferentiated peak latencies and amplitudes) whether they were reaching for a light or a heavy weight. Complementarily, when the weight was unknown, the displacing phase allowed investigating feedback control. Indeed, in this case, the participants had no means to anticipate the weight of the object, and thus had to wait until they receive somatosensory feedback once the object in hand to adapt their movement to the weight. Adults and children around 11-12 years old have an optimal feedback control and are able to erase the consequences of the weight before the end of the movement (Roy et al., 2013). Younger children display consequences of a heavy weight on their movement for the entire displacing phase time-course (Martel et al., 2020). In light with previous work, we hypothesized that children with DCD would be impaired in feedback control and would display a different performance when compared to their TD peers in the Displace phase when the object weight was unknown. On the contrary, children with ASD should perform similarly to TD children given that our task does not require a high level of visual processing.

Material and methods

Participants

Using the same paradigm in typically developing children (Martel et al., 2020) we reported consistent and large effects with groups of 10 participants. To account for variability in atypical populations we increased the sample size in each group up to 14 children. We recruited 3 groups of 14 participants aged between 7 and 12 years old: children with ASD (with no official diagnosis of DCD; 2 left-handed; 2 girls; mean age \pm SD = 10 years \pm 1 year 5 month), children with DCD (3 left-handed; 6 girls; mean age \pm SD = 10 years 7 months \pm 1 year 4 month), and a control group of TD children (1 left-handed; 4 girls; mean age \pm SD = 10 years 5 months \pm 1 year 6 months), all matched for age

($F(2,39) = .624$; $p = .541$). All of the children were schooled in their age class in typical school system. IQ was determined according to the standardized procedures of the fourth version of the Wechsler intelligence scale for children (WISC-4) (Wechsler, 2003). None of the children had any cognitive disabilities (IQ score > 70); note that some data is missing for a few participants as they dropped out before having their IQ test. Both atypical groups (available data 11/14 for the ASD, 12/14 for the DCD) had a similar verbal (VCI) but not perceptive (PRI) IQ, with the ASD group scoring better at PRI (VCI \pm SD for DCD and ASD groups respectively: 106 ± 10 ; 113 ± 18 ; $p = .131$; PRI \pm SD for DCD and ASD groups respectively: 91 ± 15 ; 103 ± 14 ; $p = .037$). While a score at the WISC-4 was already available for some, most of the TD children underwent a shorter IQ test providing us with a global score. Crucially, we paired the two atypical groups in terms of motor skills (see below), to investigate the nature of impairments associated with qualitatively equivalent motor impairment in each disorder. Participants scores are summed up in Table 1.

The ASD group was referred to us by the national reference centre for ASD of Lyon. Note that children with ASD were included for another study which required an fMRI and a MEG. They were thus screened by a psychiatrist who ensured they could undergo this second study, which excluded comorbidities such as ADHD, anxiety, and mood disorders. There was no other community involvement in this work. All children were diagnosed with ASD by a trained team of specialists, following the DSM-5 (American Psychiatric Association, 2013; IQ, ADI-ADOS). Importantly, they had no official diagnosis of DCD. They were also screened on the French adaptation of the Movement ABC (Henderson & Sugden, 1992; Soppelsa & Albaret, 2004) and we used this score to match both the ASD and DCD groups in terms of M-ABC mean score (DCD: 22.8 ± 6.3 ; ASD: 18.5 ± 8.9 ; $t(26) = -1.50$; $p = .147$). Ten out of fourteen scored under the 5th percentile, one scored below the 15th percentile but under the 5th percentile for manual dexterity subcategory, and the last two children were above the 15th cut-off. Thus, despite not being diagnosed as DCD, most of the children with ASD exhibited serious motor difficulties.

The children with DCD were referred to our lab by parents' associations as well as by the health network Dys/10 (specialized in the care of developmental disorders, from diagnosis with a

multidisciplinary team to follow-ups with schools). All children were diagnosed DCD according to the DSM-5 (American Psychiatric Association, 2013), and accordingly had no neurological condition nor intellectual disability. Children with DCD were additionally screened on the Movement ABC by a trained physical therapist, as part of the inclusion criteria. To be included in the study, children had to score below the 5th percentile (12 children) or below the 15th percentile but under the 5th percentile for manual dexterity (2 children). Comorbidity of other troubles (e.g. dyslexia, ADHD...) was not an excluding criteria, except for Developmental Language Disorder (DLD) as we previously showed specific motor disorders on the task we used in this population (Roy et al., 2013).

TD children were recruited from neighbouring schools and had no known neurodevelopmental disorders; they were not the siblings of any included children with developmental disorders. Each child scored above the 15th percentile on the M-ABC (mean score \pm SD = 2.8 \pm 1.5). Their mean score significantly differed from the two other groups ($F(2,39) = 38.7$; $p < .001$; TD vs DCD: $p < .001$; TD vs ASD: $p < .001$).

All parents and children gave written informed consent to participate in the study and were naïve to its purpose. The local ethics committee (CPP Sud-Est II) approved this study. After completion of the tasks, children received a board game.

Table 1. Individual score for the typically developing (TD), Developmental Coordination Disorder (DCD) and Autism Spectrum Disorder (ASD) groups. The scores on manual dexterity, ball skill and balance are the three subtests of the M-ABC. The scores \leq 5th percentile are in bold, and those \leq 15th percentile in italic. The scores for the VCI (Verbal Comprehension Index), PRI (Perceptual Reasoning Index), WMI (Working Memory Index) and PSI (Processing speed Index) are subtests of IQ test. Missing data for IQ score indicated that we lost contact with the families before we could have them get an IQ test.

ID	Age	Manual	Ball	Balance	Total M-ABC	VCI	PRI	WMI	PSI
TD group									
TD01	8.6	0	1	0	1	Total IQ = 129			
TD02	12.1	0	1.5	1	2.5	Total IQ = 120			
TD03	11.1	3	0	0	3	130	102	112	127
TD04	12.1	1	1	1	3	Total IQ = 122			
TD05	10.6	2.5	0	0	2.5	110	99	103	90
TD06	9.1	2	0	0	2	Total IQ = 118			
TD07	9.2	2.5	2	0	4.5	128	126	103	109
TD08	8.1	2.5	0	0	2.5	99	114	112	100
TD09	11.9	3	3	0	6	120	107	109	100
TD10	11.7	0	2.5	2	4.5	Total IQ = 111			
TD11	8.1	0	0	0	0	Total IQ = 107			
TD12	9.9	1	1	0	2	NA			
TD13	11.0	2	0	0	2	Total IQ = 95			

TD14	12.0	1.5	0.5	1	3	Total IQ = 104			
DCD group									
DCD01	12.3	11.5	8	1	20.5	103	84	100	78
DCD02	12.2	8.5	3.5	12	24	122	128	97	96
DCD03	10.7	4.5	1.5	10	16	118	114	100	88
DCD04	10.1	15	8	7.5	30.5	99	86	82	86
DCD05	10.9	11.5	1	9	21.5	116	96	82	86
DCD06	9.9	10.5	9	8	27.5	114	84	88	81
DCD07	9.5	12	3	1.5	16.5	NA	NA	NA	NA
DCD08	10.4	6	10	7	23	94	81	103	103
DCD09	8.8	11.5	7	14	32.5	NA	NA	NA	NA
DCD10	8.9	14	6	10	30	106	90	88	86
DCD11	12.3	15	8	5	28	110	94	94	73
DCD12	9.0	14	0	0	<i>14</i>	96	79	70	71
DCD13	10.9	10	0	3	<i>13</i>	98	88	97	106
DCD14	12.3	14.5	1	7	22.5	90	73	94	78
ASD group									
ASD01	7.9	5.5	2	7	14.5	96	90	97	93
ASD02	10.1	4.5	8	4	16.5	116	92	73	64
ASD03	12.3	10.5	10	9	29.5	NA	NA	NA	NA
ASD04	11.7	4	4	1	9	135	96	112	103
ASD05	8.5	5.5	9.5	2.5	17.5	130	104	100	88
ASD06	9.6	0	4	0	4	130	114	106	93
ASD07	9.3	10	10	10.5	30.5	110	99	94	55
ASD08	9.6	13	0	6.5	19.5	NA	NA	NA	NA
ASD09	11.2	10	8	7	25	NA	NA	NA	NA
ASD10	9.08	3	0	12.5	15.5	84	114	82	76
ASD11	8.1	0.5	3	8.5	<i>12</i>	122	124	121	76
ASD12	11.4	12.5	10	8	30.5	84	82	103	69
ASD13	11.1	13	8	6	27	118	94	97	71
ASD14	10.2	1.5	3	3	7.5	114	124	76	116

Apparatus

Children were comfortably seated in a quiet room, in front of a table. A bottle was located at 25cm aligned with the participants' midline. A predefined position was marked at 15cm in the frontal axis of the target object (on the right for right-handed and on the left for left-handed children). The objects were two visually identical white opaque bottles (250mL), one termed hereafter "light" (50g) and the other termed hereafter "heavy" (500g). Prior to the experiment, participants were asked to familiarize themselves and verbally characterize the perceived difference between the two target objects. All the participants manipulated the same weight to allow direct comparisons.

Performance measures were derived from infrared markers displacement via an optoelectronic high-resolution motion-tracking device (Optotrak 3020; Northern Digital Inc; see below).

Procedure

Participants started each trial with their dominant hand resting in a pinch grip position on a starting point placed on the edge of the table, in front of their body midline. Upon hearing an acoustic Go signal, children had to reach and grasp the object with their dominant hand at a comfortable speed and displace it to the predefined position. At the end of each trial, participants were back to the starting position, their finger in a pinch grip position, waiting for the next trial. To ensure a uniformly sized grasp surface across participants, children were required to grasp the object by its blue cap (40mm). Training trials with both weights were provided until the child moved naturally without being confused by the markers. The non-dominant hand was kept under the table, on the ipsilateral thigh. We assessed two conditions in block, with a short break in between:

- ***Known object weight:*** it was proposed first and allowed for feedforward control assessment. Each child had to perform 15 trials in a row with an object and then 15 trials with the other, the weight being counterbalanced between participants. The block design ensured the child could use her optimal strategy based on stabilized internal representation.
- ***Unknown object weight:*** it allowed for feedback control assessment after lifting the object. Here, light and heavy objects were pseudo-randomly presented ($n = 15$ each). The experimenter's manipulation was concealed and it was emphasized to the child that she should not try to guess the object weight.

The order of the two conditions (known and then unknown) was kept the same for all children, as we wanted to ensure that children had enough experience with the two bottles and their different weights before performing the Unknown object weight condition. The performed action consisted of two different phases: the Reach phase (before contact with the object) and the Displace phase (lifting and displacing the object). When known, the object weight representation could shape the Reach phase before any physical contact with the object thus opening a window on the feedforward control efficiency. When unknown, the object weight was physically perceived in the Displace phase thus testifying on the feedback processing efficiency (Martel et al., 2020).

Movement recordings and data processing

The positions of 6 active infrared markers were recorded during the movement. Markers were positioned on the wrist at the styloid process of the radius, on the nail of the thumb and on the nail of the index, as well as on the experimental table to reconstruct the movement in a 3D referential (sampling rate at 300 Hz; spatial resolution: 0.1 mm). Two additional markers were placed on the target objects to measure the height at which they were lifted. Data pre-processing consisted in applying a second-order Butterworth dual pass filter (cutoff frequency: 10Hz), and then kinematics parameters were analysed with a custom Matlab software developed in the ImpAct Team (CRNL - INSERM U1028 - CNRS UMR5292). The kinematics values were extracted semi-automatically, each trial was manually checked.

The extracted kinematic variables were the following:

- Reach phase (8 parameters): numbers are indicated on Figure 1 when possible
 - o (1) Latency and amplitude of the maximum wrist acceleration
 - o (2) Latency and amplitude of the maximum wrist velocity
 - o (3) Latency and amplitude of the maximum wrist deceleration
 - o (4) Latency and amplitude of the maximum finger aperture

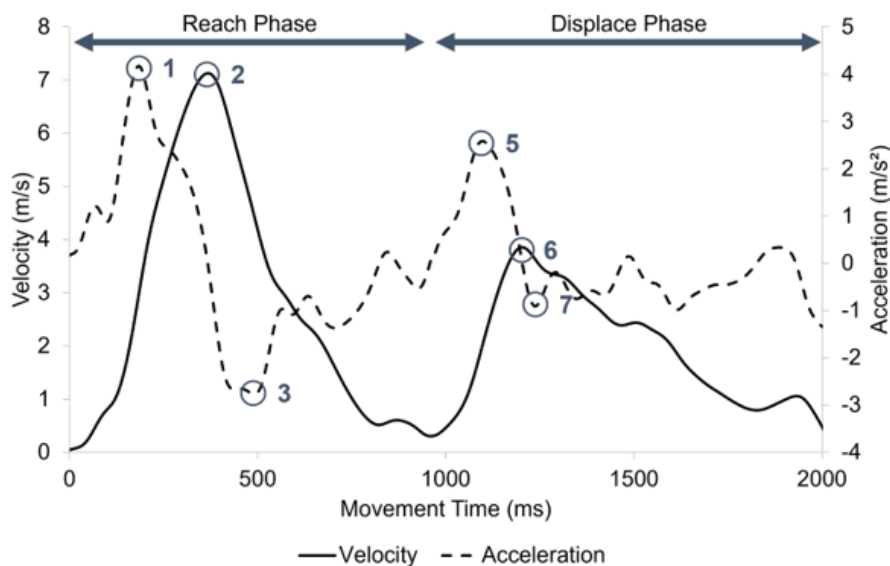
Carrying a heavy object slows down the movement (i.e. longer latencies and smaller amplitudes) in the Displace phase. Thus, a typical feedforward control would consist in anticipating this speed reduction by going faster before grasping the object, in order to minimize the consequences of the weight once the object is in hand. This translates into shorter latencies and higher amplitudes in the Reach phase. Note that as the amplitude of the deceleration is negative, higher amplitude for this parameter means more negative. Anticipation might also be visible on the maximum finger aperture during the movement and its latency, participants opening their fingers less, and earlier for a heavy known weight. Any of the 8 parameters of the Reach phase could be modified, but a similar number of parameters modified in each group along the same direction speak for a consistent and trustworthy pattern. Conversely, the absence of modulation, or an opposite one (namely faster reaching for the light object) according to the known weight in the Reach phase would indicate atypical feedforward control.

- Displace phase (7 parameters):
 - (5) Latency and amplitude of the maximum wrist acceleration
 - (6) Latency and amplitude of the maximum wrist velocity
 - (7) Latency and amplitude of the maximum wrist deceleration
 - (8) Height at which the object was lifted. This is chronologically the last parameter of the movement.

As described earlier, carrying a heavy object slows down the movement (i.e. longer latencies and smaller amplitudes) in the Displace phase. When the weight is not anticipated in the Reach phase, the consequences of the weight are maximized in the Displace phase. This translates into earlier and higher peaks for an unknown light object, which does not slow down the movement, and later and smaller peaks for an unknown heavy object which slows the movement to a great extent. Optimal feedback control aims at reducing these differences, which might be completely compensated by the end of the Displace phase (Height parameter). Atypical feedback control would be visible in larger differences between light and heavy weight compared to a TD group, or through a larger number of parameters impacted in the Displace phase.

Main parameters as recorded from a single trial on the wrist are illustrated in Figure 1.

[insert Figure 1.]



Statistical analysis

Similarly to our previous studies (Martel et al., 2020; Roy et al., 2013), we performed the statistical analysis only on the last eight trials per weight and condition to guaranty a more stable representation. Analyses were performed with “R” (R Core Team, 2018) and missing values were ignored. We performed mixed model analyses on participants’ individual trials for each kinematic parameter. In terms of interpretation, linear mixed models are similar to ANOVAs, but more adequate for our study as they account for relatively small sample size with (relatively high) variability (Boisgontier & Cheval, 2016). We used the “lme4” (Bates et al., 2015) and “lmerTest” (Kuznetsova et al., 2017) packages. For each model, we opted for the maximal random structure (Barr et al., 2013) that still allowed the model to converge.

We ran three different types of models, investigating three different aspect of motor control:

- **Movement execution** (i.e. Reach phase with no object in hand, and no possible anticipation): we compared the performance of each group, neglecting the weight factor, in the Reach phase of the unknown condition only. We used mixed models to assess the effect of *Group* (TD/DCD/ASD; fixed effect), while taking into account participants’ variability (random intercept). This analysis allowed to investigate movement execution when not influenced by internal representations of the weight (since the weight is unknown) nor the weight itself (since the object is not in hand).
- **Feedforward and feedback modes of control**: we examined the effects of *Knowledge* (Known/Unknown), *Weight* (Light/Heavy), *Group* (TD/DCD/ASD), and their interactions (fixed effects), as well as the intra and inter-individual variability of weight and knowledge effect (random slopes) in all the conditions. We particularly focused on triple interactions $Weight \times Group \times Knowledge$ between the TD and any of the other group, in each phase of the movement (Reach phase for feedforward control; Displace phase for feedback control). In short, here to investigate feedforward control we compared the three groups during the Reach

phase to determine the presence of weight effects when it was known (and the absence of any weight effects when it was unknown). To investigate feedback control, we compared the three groups during the Displace phase of an unknown weight to evaluate whether the weight consequences would be reduced over time.

- **Internal sensorimotor representation of the weight:** we focused on any group which showed impaired feedforward control (we hypothesised it would concern only the ASD group), and modelled the effects of *Weight* (Light/Heavy) and *Knowledge* (Known/Unknown) and their interaction (fixed effects), as well as the intra and inter-individual variability of weight and knowledge effect (random slopes; maximal random effects for each parameter). We particularly focused on the interaction *Weight* × *Knowledge*. This analysis specifically allowed to investigate whether despite an absent feedforward control (no modulation of the Reach phase for a known object weight), feedback control once the object in hand would benefit of knowing the weight in advance, attesting of the building of a correct sensorimotor representation of the weight.

Results

Movement execution (Reach phase – Unknown weight)

As a global index of movement execution, we examined the differences between groups when reaching for an unknown object weight. By examining movement without any object in hand, we assessed the characteristics of simple motor execution for each group.

During the Reach phase, the latencies and amplitudes of acceleration, velocity, and deceleration of the wrist (parameters 1-3) never differed between the TD group and the ASD group (all $p > .28$), neither did the latency and amplitude of the maximum finger aperture (all $p > .29$, parameter 4). This suggests that both groups displayed a similar kinematic pattern when reaching for an object of unknown weight, indicating a preserved movement execution in ASD. The DCD group was slower than the TD group, displaying delayed wrist (velocity latency: $t = 2.09$, $p = .043$; deceleration latency: $t = 2.43$, $p = .020$, parameters 2 and 3 respectively) and finger aperture latencies (maximum finger aperture latency: $t =$

2.96, $p = .006$, parameter 4), as well as reduced amplitudes (acceleration: $t = -2.10$, $p = .042$; deceleration: $t = 2.19$, $p = .035$; parameters 1 and 3 respectively). The DCD group tended to be slower than the ASD group on several parameters ($p < .09$ on 4/8 parameters), however the results reached significance only for the maximum finger aperture latency ($t = 3.17$, $p = .003$; see Table S1, parameter 4). In sum, the DCD group was specifically atypically slow in their movement execution, even with no constraints to slow them (i.e. no object in hand).

Feedforward and feedback modes of control

Reach phase and feedforward strategy

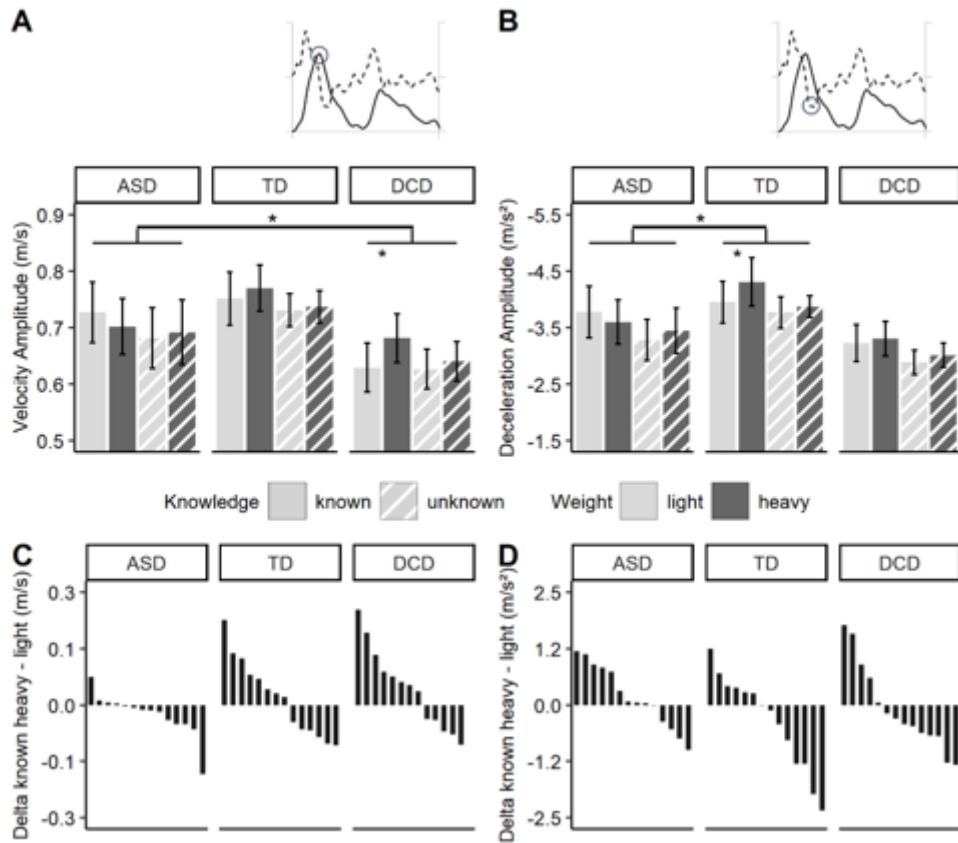
When the object weight was unknown, as expected, the latencies and amplitudes of the acceleration, velocity, and deceleration of the wrist, as well as the latency and amplitude of the maximum finger aperture during the Reach phase did not significantly differ as a function of object weight (parameters 1-4: all $p > .430$ for the TD group; all $p > .328$ for the DCD group; all $p > .143$ for the ASD group; Figure 2, dashed bars; see Table S2 for all the means and statistic). This comparison does not inform us on feedforward strategy but constitutes a sanity check that none of the children tried to anticipate the weight of the object in the Reach phase when they did not know it. In contrast, when the object weight was known, informing us about feedforward control, both the TD and DCD groups adapted their Reach phase to the upcoming object weight (Figure 2, solid bars), but not the ASD group. This different behaviour of the ASD group was confirmed by significant triple interactions *Group* \times *Weight* \times *Knowledge* between TD children and children with ASD (parameter 1: acceleration amplitude: SE = 387, $t = -2.35$, $p = .019$) as well as between children with DCD and children with ASD (parameter 2: velocity amplitude: SE = 29.4, $t = -2.26$, $p = .024$). Conversely, the TD and DCD groups never differed from each other on their latencies and amplitudes of wrist acceleration, velocity, and deceleration, neither on their latency and amplitude of maximum finger aperture (parameters 1-4: all $p > .380$; Figure 2; see Table S3 for all the means and statistic).

Specifically, the ASD group did not significantly modulate their latencies and amplitudes of wrist acceleration, velocity and deceleration, neither their latency and amplitude of maximum finger

aperture during the Reach phase as a function of object weight (parameters 1-4: all $p > .126$). By contrast, TD and DCD groups anticipated the heavy object by increasing either their velocity (parameter 2; DCD: $SE = 17.4$, $t = 2.57$, $p = .012$; Figure 2A and C) or their deceleration (parameter 3; TD: $SE = 179$, $t = -1.99$, $p = .050$; Figure 2B and D). In addition, TD children exhibited a smaller finger aperture (parameter 4; $SE = 1.51$, $t = 2.11$, $p = .040$) when reaching for the heavy object (see Table S2 for all the means and statistic). Importantly, this pattern was consistent among most children in each group, as can be seen in Figure 2C and D: TD and DCD groups displayed a positive (for the velocity) or negative (for the deceleration) difference, indicating an increased amplitude for a heavy known weight, while children with ASD did not consistently modulate their peaks. This pattern of increasing amplitudes for a heavy weight is consistent with what has been reported previously and indicates efficient feedforward control (Martel et al., 2020; Roy et al., 2013), compensating in advance the consequences of the heavy object on the movement.

In sum, these results point towards a similar feedforward mode of control for the TD and DCD groups, reaching faster for a heavy object, while children with ASD did not modulate their movement according to the object to reach. This pattern was consistent among most children, showing homogeneity in the different profiles.

[insert Figure 2.]



Displace phase and online control

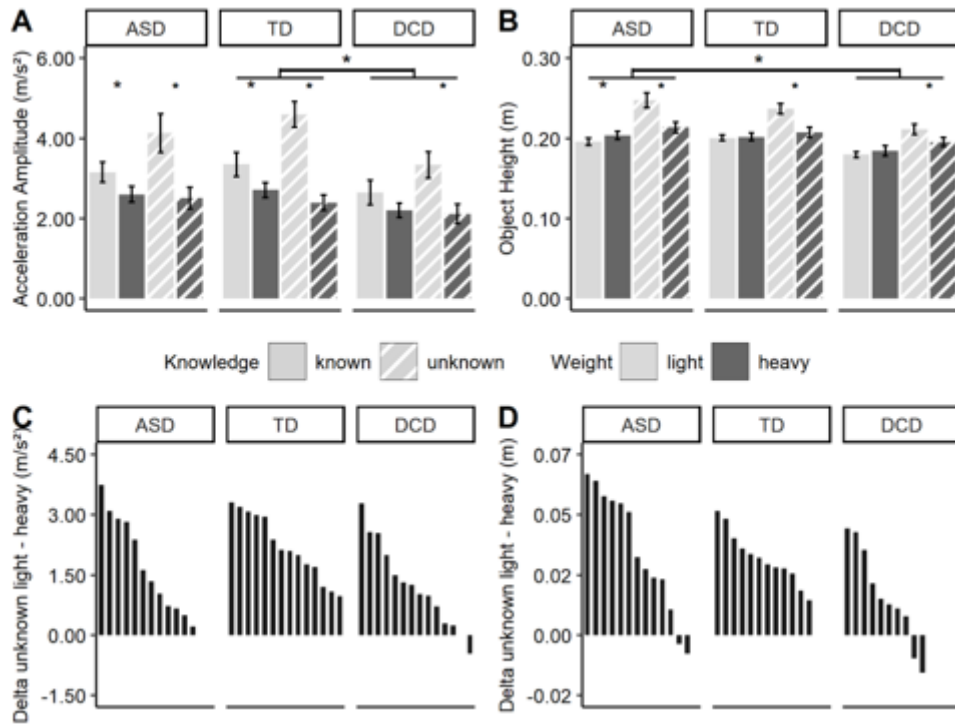
Once in hand, a heavy object slows down the movement (longer latencies and smaller amplitudes for parameters 5,6,7), especially in the unknown condition when the reach phase could not anticipate the effect of object weight. Efficiency of feedback control is indicated by the number of parameters altered by the weight disparity (the more efficient, the least parameters from the end of the movement), and by the quantitative difference between light and heavy objects (the smaller, the better the feedback control).

In the unknown condition, as the weight could not be anticipated, its effect was observable in each of the groups, with reduced amplitudes and longer latencies for the heavy weight compared to the light one (see Table S4). However, significant triple interactions *Group* × *Weight* × *Knowledge* underlined the peculiar behaviour of children with DCD with respect to TD children (parameter 5; acceleration amplitude: SE = 281, $t = -2.86$, $p = .004$; Figure 3A) and to children with ASD (parameter 6 and 8

respectively; velocity amplitude: $SE = 21.2$, $t = 2.76$, $p = .006$; height: $SE = 5.95$, $t = 3.36$, $p < .001$; Figure 3B). Children with DCD were less impacted by an unknown light weight on their Displace phase as compared to both TD and children with ASD: when the weight could not be anticipated, both groups got carried away by the unexpected light object, displaying higher amplitudes while the DCD group was less affected. TD and ASD groups in turn did not differ among them, displaying the same difference in amplitudes and latencies between an unknown light and heavy object (see Table S3 for all the means and statistic). Such reduced difference in the DCD group could in theory highlight a better feedback control than both the other groups, but this is highly unlikely. Indeed, we showed earlier that children with DCD were slower during their Reach Phase: with a slower movement, there is more time to update and react to an unexpected light weight, explaining the reduced amplitudes compared to TD children and children with ASD. Importantly, this pattern was consistent among most children in each group, as can be seen in Figure 3C and D: most children displayed a positive acceleration or height difference, indicating that they were a bit carried away by a light unknown weight. Children with DCD seem overall the least affected, as shown by the reduced differences when compared to children with ASD and TD children.

Overall, our results point to a general slowness in children with DCD associated with a reduced effect of the object weight in the Displace phase when unknown. Conversely, both TD and ASD groups displayed a preserved online control and were able to adapt efficiently to the unknown weight of the object. This pattern was consistent among most children, showing homogeneity in the different profiles.

[insert Figure 3.]



Internal sensorimotor representation of weight in the ASD group

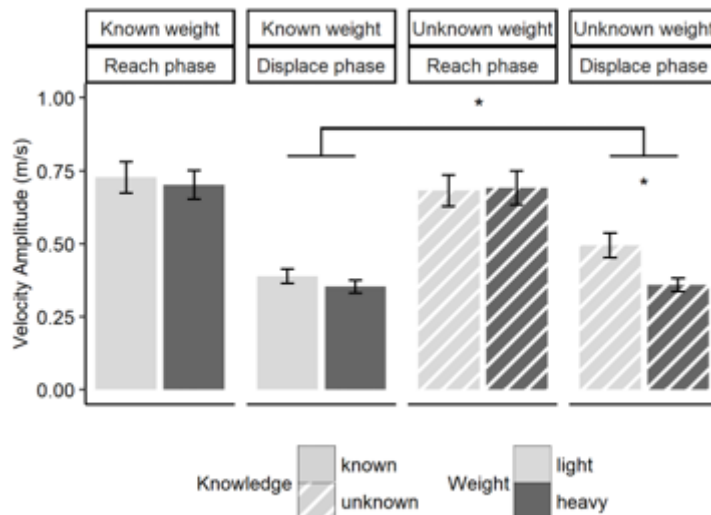
In the group with ASD, mixed models indicated no interaction between *Weight* and *Knowledge* on any of the parameters of the Reach phase (see Table 2). This is consistent with the absence of feedforward control described above. Noteworthy, interactions were present on most of the parameters of the Displace phase: children with ASD performed better in the Displace phase when the weight was previously known, despite not having anticipated the weight in the Reach phase. The cost of the weight (difference between light and heavy) in the Displace phase was reduced for a known weight compared to an unknown one, suggesting that they were able to take the weight information in consideration after all (see Figure 4 for an illustration with the velocity amplitude).

Table 2. Interaction *Weight* × *Knowledge* of all the parameters from the Reach phase and the Displace phase in the group with ASD. P values are in bold when significant. SE = Standard Deviation of the estimates. Numbers in bracket refer to Figure 1 and to numbers in the Methods.

Reach Phase	Weight × Knowledge			Displace Phase	Weight × Knowledge		
	SE	t	p		SE	t	p
(1) Acceleration Latency	15.8	-0.53	.597	(5) Acceleration Latency	56.7	-2.09	.037
(1) Acceleration Amplitude	370	-1.51	.132	(5) Acceleration Amplitude	238	4.79	<.001
(2) Velocity Latency	17.1	.624	.533	(6) Velocity Latency	57.3	-1.81	.071
(2) Velocity Amplitude	24.4	-1.44	.152	(6) Velocity Amplitude	19.2	5.57	<.001

(3) Deceleration Latency	23.0	.288	.773	(7) Deceleration Latency	67.7	-0.92	.357
(3) Deceleration Amplitude	251	1.31	.190	(7) Deceleration Amplitude	207	-2.68	.008
(4) Finger aperture Latency	31.2	-0.43	.671	(8) Height	4.83	9.29	< .001
(4) Finger aperture Amplitude	1.62	.449	.654				

[insert Figure 4.]



Discussion

This study aimed at determining the nature and specificity of motor control impairments in Autism Spectrum Disorders as compared to Developmental Coordination Disorders. In order to clearly distinguish between feedforward and feedback modes of control, we manipulated a non-visible characteristic of object in a reach to displace paradigm. Feedforward control was quantifiable in the known weight condition during the Reach phase that is before any haptic feedback. Conversely feedback processing was assessed during the Displace phase that is after the contact with the object. Our findings highlight a preserved feedforward control, but an impaired movement execution in children with DCD, in sharp contrast children with ASD displayed a preserved feedback, online control but an impaired feedforward control, i.e. they failed to anticipate the object's weight during the Reach phase. Interestingly, we were able to state that they were nevertheless able to build a representation of the weight.

An impaired motor execution in DCD but not in ASD patients

Interestingly, children with ASD exhibited an intact motor execution. While we did not replicate the findings of several authors who observed atypical slowness in ASD (Forti et al., 2011; Glazebrook et al., 2007, 2009), our results are instead close to those of Rodgers and colleagues, who found no increase in movement time in young children with ASD grasping an object (Rodgers et al., 2019). Their study also revealed, in older children with ASD, that atypical movement slowness emerges with increased task complexity. Here the reach-to-grasp task did not present any difficulty for them, which could explain the absence of such slowness. Importantly, in the present study participants with ASD had an IQ within normal range and indeed Mari and colleagues reported a link between IQ and motor coordination, low IQ being more impaired (Mari et al., 2003). In the DCD group, on the contrary, most of the movement parameters were delayed, and the amplitudes reduced; such an atypical slowness has been reported in the literature (Ameratunga et al., 2004; Biancotto et al., 2011; Maruff et al., 1999; Plumb et al., 2008). Having controlled for IQ and motor impairment severity, our findings show unambiguously that this atypical slowness characterizes the motor execution of children with DCD.

Opposite pattern of feedforward control between ASD and DCD

As previously reported on the same paradigm (Martel et al., 2020; Roy et al., 2013), the typically developing group used an anticipatory strategy to avoid or minimize the weight effects of the object. They modulated their Reach phase increasing their amplitudes before the grasp of the heavy object. This strategy of speeding up the Reach phase is meant to increase load force, hence preventing the lengthening of the Displace phase (Johansson & Westling, 1988). An efficient feedforward control may result in a total disappearance of the weight effects in the Displace phase of the movement, as shown in healthy adults and 11 years old children in our paradigm (Roy et al., 2013). Children up to 10 years old display a not fully mature feedforward control in lifting tasks (Forsberg et al., 1991, 1992; Kuitz-Buschbeck et al., 1998, 1999; Martel et al., 2020; Olivier et al., 2007; Paré & Dugas, 1999). Hence, as our group was constituted of children from age 8 to 12 years old, the Displace phase protraction was still observable. Importantly, children with DCD exhibited a similar strategy, when

knowing the weight, they went faster prior to contact with the heavy object, increasing their peaks amplitudes. This testified of their preserved ability to use feedforward control (Adams et al., 2016; Noten et al., 2014; Smyth et al., 2001) and witnessed the accuracy of their object representations in the case of ecological and easy planning tasks. Yet, this preserved feedforward control in voluntary movements contrasts with the immaturity found in postural control (Jover et al., 2010). This discrepancy may find an explanation in terms of time constraints. Indeed, children with DCD displayed an atypical slowness in our study, and postural anticipation relies on a timely muscular inhibition. As pointed out by Jover and colleagues (Jover et al., 2010, p. 854), the “precise mastering of timing parameter is one of the key factors in the development of anticipatory postural adjustments during childhood”. Our findings nicely extend the results reported by Jover and co-workers in postural control highlighting that individuals with DCD may not suffer from an impaired anticipatory control per se but rather present a marked deficit when time matters (Nobusako et al., 2018). Nevertheless, our study suggests that children with DCD are able to accurately build internal representations, which are correctly turned into a motor command similarly as TD individuals.

By contrast, children with ASD showed no trace of feedforward control, as they did not modulate any parameters in the Reach phase when the weight was known. This recalls results in postural control, in which children with ASD from 6 to 10 years old exhibited an absence of feedforward control (Martineau et al., 2004; Schmitz et al., 2003), while anticipatory adjustments have been observed in the same task as early as age 4 in typical population (Schmitz et al., 2002). This study thus confirms the presence of a feedforward deficit in ASD (see also Foster et al., 2020). Notably, despite a similar Reach phase in the known and unknown weight condition, we observed a more efficient Displace phase when the weight was known, indicating that children with ASD were able to build a weight representation. As soon as they had the object in hand, they were able to integrate the somatosensory feedback, and could only then benefit from their weight representation, which enabled them a better control during the Displace phase. It would seem that they can use this somatosensory information when it is immediately available to them, but the maintenance of this information in memory, in the form of a representation used to scale the kinematics in advance, seems to be lacking. Altogether, these results are in line with recent theories of impaired predictive processes in ASD (see Haker et al.,

2016 for review). Under the general hypothesis that the brain entails an internal model of its environment, which forms and updates predictions, a variety of mechanistic explanations have been provided to account for differences in prediction processes in ASD. Among those, imprecise internal models, or priors, have been put forward to account for their altered perception (Pellicano & Burr, 2012). In the context of action prediction, this would also imply that people with ASD would favour the use of proprioceptive information over reliance on internal models.

Integrity of feedback control in ASD

Remarkably the ASD group displayed an online control similar to that observed in the TD group. This echoed back to the preferential use of feedback control over feedforward control in postural tasks (Schmitz et al., 2003; Somogyi et al., 2016). Our results tend to converge with the literature arguing for a preserved feedback control in children with ASD, as observed in adaptation tasks (Foster et al., 2020; Gidley Larson et al., 2008; Masterton & Biederman, 1983). Given that online control skills have been shown to predict the abilities on the M-ABC test (Blanchard et al., 2017), we cannot totally rule out the fact that some children with ASD with more severe motor impairments might show difficulties with feedback control. The variability of motor abilities present in individuals with autism, and the relatively small size of our sample, call for caution in generalising the preservation of this online control. However, TD children and children with ASD seemed to have similar patterns of feedback control despite their drastically M-ABC scores, which would rather argue against this possibility.

Children with DCD were less affected by the unexpected light object than the other two groups of children who lifted the object too high when it was unexpectedly light, resulting in large amplitudes. Rather than a better online control in children with DCD compared to the ASD and TD groups, these results should be interpreted as the reflect of the marked slowness characterizing DCD movements. It is unlikely that children with DCD used slowness as a strategy: indeed, slowness was observed in each phase of the movement, whether children had the object in hand or not, and whether they knew its weight or not. Such a slowness strategy has on the contrary been observed in children with ASD to gain sensory feedback in a postural task (Schmitz et al., 2003). Thus, we could not confirm our prediction that children with DCD show atypical feedback control. Nevertheless the atypical sensory

processing (Elbasan et al., 2012; Ringold et al., 2022; Schoemaker et al., 2001) observed in children with DCD could be a factor affecting feedback control.

Clinical implications of this work

Distinct pattern of motor impairment found in our sample of children with ASD or DCD despite similar scoring on the standard M-ABC assessment highlights the fact that this clinical test makes a quantitative assessment of motor skills, but not a qualitative one. Accordingly, machine learning approaches to classify diagnosis as ASD or DCD failed to use motor features from the M-ABC and other standard tests as a criterion to differentiate ASD and DCD (Harrison et al., 2021). Yet, using the M-ABC score as a criterion to group children in terms of having DCD, ASD or ASD + DCD (i.e. ASD diagnosis with impaired motor skills), Caeyenberghs and collaborators observed low overlap between DCD and ASD in terms of structural brain networks' topological properties (Caeyenberghs et al., 2016). Abnormalities would be disorder-specific, and the comorbid DCD + ASD would depict a unique neural signature with topological changes that were more widespread than in only DCD. In sum, current standard tests do not always inform clinicians on the nature of impairments but give a necessary overview of life-impacting motor difficulties in each child so that they can benefit from support and rehabilitation.

Our results suggest that children with ASD would benefit from rehabilitation aiming at improving their feedforward control, maybe through the support of their preserved representations and use of sensory information. This could for instance be done through tasks that would encourage children to use a feedforward strategy, but that would be motivating and engaging enough so they could benefit from practice. Complementarily, because children with ASD were able to build a correct representation of the weight, and to use it once the object in hand, verbalisation and conscientisation could be beneficial. In our paradigm, this would translate by having them take the heavy object in hand, and explain to them that the object is heavy so they need more strength to carry it compared to the light one, and so by going faster when reaching for it, the movement would be easier. Verbalising the consequences of a non-anticipated movement would achieve a similar goal, to explain that they would have struggled less if they had anticipated the movement beforehand.

Conclusion

In sum, our work has highlighted that despite similar impairments level as evaluated by the M-ABC, children with ASD and DCD exhibit different patterns of motor deficits in a simple ecological reaching paradigm that does not tax the visual system. Children with ASD would lack feedforward control, in line with a more general hypothesis of impaired predictive processes, while children with DCD would be comparable to age-matched TD peers. Children with ASD would instead have a preserved online control and motor execution, while the picture was blurrier for those with DCD. Notably, so far our paradigm allowed to differentiate the motor disorders of populations with DCD, ASD and DLD (Roy et al., 2013). Finally, our study also indicates that while it is important to rehabilitate the motor skills of a large majority of children with ASD, it is equally important to identify their strengths (such as the use of feedback control) and weaknesses (such as the use of feedforward control) in order to adapt and target motor skills training, which is clearly different from that of children with DCD.

Data availability

All data and code used in this study will be available on the website of the Open Science Framework (OSF) once it is accepted for publication.

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Figure Legends

Figure 1. Kinematic data of a single trial from a TD child, separated in a Reach and a Displace phase. Circled peaks are extracted for the wrist profile analyses, both in amplitudes (m/s or m/s²) and in latencies (ms). Two parameters are missing in the figure because they are extracted from different markers namely parameter 4, the finger aperture and parameter 8 referring to the object height when lifted. Numbers are referred to in the methods and results.

Figure 2. A/Triple interactions *Group × Weight × Knowledge* for the maximal wrist velocity amplitude in the Reach phase of the movement. B/Triple interactions *Group × Weight × Knowledge* for the maximal wrist deceleration amplitude in the Reach phase of the movement. When they knew the weight, both TD children and children with DCD modulated their Reach phase by going faster (increased amplitudes) to anticipate the consequences of the weight once the object in hand. This suggests efficient feedforward control in both groups. Conversely, children with ASD did not display a marked anticipation, with no difference between a light and a heavy weight indicating that they were unable of using feedforward control. Bar graphs illustrate mean values for each group \pm sem. **C/Individual performance ordered by size for the velocity amplitude in the known condition.** Positive values indicate that the amplitude increased for a heavy weight (efficient feedforward control), while negative values indicate reduced amplitude. Most of the children in the TD and DCD groups displayed increased amplitudes for a heavy weight (8/14 in each group), while children with ASD barely modulated their reach (only 1/14 correctly modulated their reaching amplitude). **D/Individual performance ordered by size for the deceleration amplitude in the known condition.** Negative values indicate that the amplitude increased for a heavy weight (efficient feedforward control), while positive values indicate reduced amplitude. Most of the children in the TD and DCD groups displayed increased amplitudes for a heavy weight (respectively 6/14 and 8/14), while the pattern was more random for children with ASD (only 4/14 modulated their deceleration amplitude in the right direction).

Figure 3. A/Triple interactions *Group × Weight × Knowledge* for the maximal wrist acceleration amplitude in the Displace phase. B/Triple interactions *Group × Weight × Knowledge* for the maximal height of the bottle in the Displace phase of the movement. Children with DCD displayed different behaviour from the TD and ASD groups, with less difference between a light and a heavy object. While this would in theory indicate a better feedback control for children with DCD, these results were likely to be due to their slowness, which hid any potential impairment. TD children and children with ASD display similar patterns of performance indicating a preserved feedback control in ASD. Bar graphs illustrate mean values for each group \pm sem. **C/Individual performance ordered by size for the acceleration amplitude in the unknown condition.** Positive values indicate that the amplitude increased for a light weight, sign of a poorer online control. All the children were carried away by the light unknown weight, with most of the children with DCD displaying reduced weight cost. **D/Individual performance ordered by size for the height to which the object was raised in the unknown condition.** Positive values indicate that the light unknown weight was raised higher, as seen in most of the children. Children with DCD displayed overall reduced weight cost.

Figure 4. Illustration of interactions *Weight × Knowledge* on the velocity amplitude of the Reach phase (object not in hand) and the Displace phase (object in hand) when the weight was known or unknown by the children with ASD. Despite no modulation of the kinematics according to the weight in the Reach phase, children with ASD controlled the object better once in hand when its weight was previously known, as shown by a significant interaction. This suggests that they were nonetheless able to build a correct weight representation and use it, but only when they received

feedback confirming their predictions (object in hand). Bar graphs illustrate mean values for each group \pm sem.