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Finger counting to relieve working memory in children with developmental coordination disorder: Insights from behavioral and three-dimensional motion analyses

Maëlle Neveu [a,b,*], Cédric Schwartz [c], Laurence Rousselle [a]

[a] Research Unit for a Life-Course Perspective on Health & Education, University of Liège, B-4000 Liège, Belgium
[b] National Fund for Scientific Research (F.R.S.–FNRS), B-1000 Bruxelles, Belgium
[c] Laboratory of Movement Analysis (LAM)–Motion Lab, University of Liège, B-4000 Liège, Belgium

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A limited number of studies have attempted to understand how motor deficits affect numerical abilities in children with developmental coordination disorder (DCD). The purpose of this study was to explore the functionality of finger-counting (FC) in children with DCD. The participants, 15 children with DCD and 15 typically developing (TD) children matched on school level and fluid reasoning abilities, were asked to use FC to solve an ordinal task with high working memory (WM) load. Behavioral measures supplemented with biomechanical measures, from three-dimensional motion analysis synchronized to a voice recording were used to assess children's performance and FC functionality (total duration, interfinger [IF] transition, IF variance, finger/voice synchronization, and automatization of FC movements). Children with DCD were less accurate than TD children in using FC to solve ordinal problems with high WM load. This group difference could not be accounted for by poor FC skills given that FC movement turned out to be as functional in children with DCD as in their TD peers. When added to the model as a covariate, WM captured a greater proportion of intergroup variability than manual dexterity, further suggesting that their difficulties would be better accounted for by limited WM resources than by fine motor skills.

* Corresponding author.
E-mail address: mneveu@uliege.be (M. Neveu).

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Introduction

In many cultures around the world, children use their fingers to deal with numbers (Bender & Beller, 2012; Fuson, 1988). From 3 years of age, they begin to use finger-counting (FC) in a variety of numerical contexts. In Western countries, each finger is raised individually, in one-to-one correspondence with a number word, ending with a number gesture that provides a cardinal representation of the last number word stated. A growing body of evidence suggests that intrinsic properties of FC play a key role in the development of children's mathematical skills (Alibali & DiRusso, 1999; Gelman & Gallistel, 1978; Gibson et al., 2019; Graham, 1999; Thevenot et al., 2014). In their developmental model, Roesch and Moeller (2015) explained how these properties contribute to the development of early numerical and arithmetic skills. FC supports the segmentation of the verbal number sequence and emphasizes the order in which number words should be recited by associating each raised finger with a specific number word (Beller & Bender, 2011; Crollen, Seron, et al., 2011; Roesch & Moeller, 2015). Furthermore, number gesture produced during FC provides an iconic representation of the quantity supporting the understanding of cardinality of verbal symbols (Di Luca & Pesenti, 2008; Gunderson et al., 2015; Krinzinger, 2011; Neveu, Schwartz, et al., 2023; Wasner et al., 2015).

Building on the development of early numerical skills, FC forms the basis on which young children rely to acquire their first arithmetic abilities (Bartelet et al., 2014; Major et al., 2017). Because fingers are used as an external support to visualize and combine the quantities involved in computations (Baroody, 1987; Björklund et al., 2019; Kullberg & Björklund, 2020), they are often described as an ideal tool for relieving the load on working memory (WM) inherent in this type of task (De Chambrier et al., 2018; Passolunghi & Cornoldi, 2008). As such, when solving numerical problems with high WM load (e.g., solving additive problems with carrying such as 23 + 18, performing advanced counting such as enumerating the number of items between two elements in an ordered sequence), children use FC to keep track of the counted items, thereby relieving their WM (Crollen, Mahe, et al., 2011; Kullberg & Björklund, 2020). Finger-counting can be used as an offloading technique until adulthood to deal with cognitively demanding numerical problems (e.g., listing the number of elements, calendar calculation, syllable counting; Hohol et al., 2018; Lucidi & Thevenot, 2014). Mainly used in young children with low WM resources, FC gradually decreases during the elementary school years when children have sufficient cognitive resources to switch from FC to more powerful mental calculation strategies (Geary et al., 1991; Jordan et al., 2008; Poletti et al., 2022). This transition has been found to occur later in children with mathematical learning disabilities (MLDs) who have limited WM resources (De Smedt et al., 2013; Mazzocco et al., 2011). These children have been shown to make more extensive use of concrete supports such as fingers, which provide them with a physical representation of numbers while reducing the WM load in the task (Noël, 2005, 2009; Passolunghi & Cornoldi, 2008). Therefore, children with MLDs continue to use FC over a longer period from Grade 1 to Grade 3 and use fewer mental strategies (e.g., arithmetic fact retrieval, decomposition of numbers) compared with their typically developing (TD) peers (Geary et al., 1991; Jordan et al. 2003; Neveu, Geurten, & Rousselle, 2023; Wylie et al., 2012).

Naturally, FC relies on fine motor skills. The FC speed and FC regularity are important parameters for achieving fluid finger gestures, synchronized with the recitation of the verbal number sequence, and sufficiently automated so as not to consume too many executive resources. When too slow and irregular, FC could induce unintended pauses that could lead to a desynchronization of recitation and finger movements. When too fast, the finger/voice synchronization could be compromised, leading to one-to-one correspondence errors. When in between, finger/voice synchronization efforts could add an additional cognitive load, making this tool ineffective in relieving WM. Thus, the effectiveness of FC is directly linked to its automatization, which may depend on several parameters of finger gestures such as speed of execution, regularity of movement, and finger/voice synchronization, turning fingers into a powerful tool to relieve the cognitive load in WM. Interestingly, some children with MLDs were found to exhibit fine motor skills impairment similar to those observed in children with developmental coordination disorder (DCD), which could impede their FC movement (Pieters et al., 2015). Surprisingly, in children with DCD who are known to suffer from severe and persistent motor impairment (Wilson et al., 2012), the functionality of FC has not yet been examined. However, in addition to their motor disorder, these children have also been found to have poor WM resources (Alloway & Archibald, 2009; Rigoli et al., 2013). Therefore, they could be doubly penalized when performing arithmetic operations with, on the one hand, limited resources in WM and, on the other, restricted possibilities for using FC strategies to relieve their WM.

Little is known about the characteristics of mathematical difficulties in children with DCD. An initial series of investigations provided evidence of poor number sense in children aged 7 to 10 years (Gomez et al., 2015, 2017). Moreover, their counting skills were found to be limited, an impairment that could be due to the oculomotor dysfunction reducing their ability to track targets by pointing (Gomez & Huron, 2020). Difficulties in executing calculation procedures have also been reported in 9-year-old children with DCD, particularly when associated with severe motor impairments (Pieters, Desoete, Waelvelde, et al., 2012). Some authors have suggested that their difficulties might result from poor knowledge of the numerical system or a lack of automatization of calculation procedures (Pieters, Desoete, Waelvelde, et al., 2012), but another source of impairment could be their difficulty in deploying functional FC movements in relevant mathematical tasks.

Thus, the main aim of this study was to investigate the functionality of FC in children with DCD. First, we examined whether children with DCD could use FC efficiently to solve a task with high WM load (named the N^{th}-After task). Children with DCD were asked to use FC to determine what the n^{th} element is after a target in an ordered sequence. Because children with DCD present a higher risk of arithmetic learning difficulties (Pieters, Desoete, Roeyers, et al., 2012), FC was implemented in a simple ordinal task with high WM load to avoid potential confounding factors with arithmetic disability. Moreover, the task needed to be performed with numerical versus non-numerical ordered sequences to examine the influence of the type of sequence on performance. If fine motor impairments reduce children's ability to use efficient FC strategies to relieve WM, children with DCD should be less accurate than their TD peers in the ordinal task whatever the condition (letters or numbers).

Finger-counting functionality was further explored using three-dimensional (3D) motion analysis combined with voice recording. Four different biomechanical parameters were assessed to examine FC functionality, namely total duration and inter-finger (IF) transition providing global and local measures of FC execution speed, variance of IF transitions as a measure of FC regularity, and finger/voice synchronization as a measure of one-to-one correspondence. Contrasting with the N^{th}-After task, FC was further examined using two control FC tasks with lower WM demands to determine whether FC functionality in each group was influenced by the WM requirements of the task. The two control tasks involved no demand (i.e., execution of finger-like counting movement with no recitation) and low demand (i.e., FC up to 10) in WM, respectively. If FC is cognitively demanding in children with DCD, increasing the WM load of the task should deteriorate FC functionality (as assessed through the four biomechanical parameters) in the DCD group in comparison with TD children. In this case, FC is expected to be less functional in the N^{th}-After task than in the two other tasks in children with DCD when compared with their TD peers. Conversely, if FC is automatized and effortless in children with DCD, FC functionality should be similar whatever the WM load of the task.

Method

Participants

A total of 30 French-speaking children participated in the experiment: 15 children with DCD (mean age = 8.6 ± 0.74 years) and 15 TD children in the control group (mean age = 8.4 ± 0.95 years). All children were enrolled in mainstream elementary school. Following Lakens et al.'s (2022) approach, power analyses were performed to estimate the sample size for the current study. G*Power software (Version 3.1.9.7) was used, considering repeated-measures analyses of variance (ANOVAs) and *t* tests, two analyses commonly used to show group differences. A sample size of 30 children (15 per group) was required to provide strong statistical power ($\geq$.80) and bring out the expected large effect sizes (i.e., similar to those found in Gomez et al., 2015, or in Ferguson et al., 2015; f > .40 for ANOVAs and d > .80 for t tests).

Children were recruited between September 2020 and July 2022 through newsletters distributed by teachers in local schools and by therapists practicing in multidisciplinary centers. Short letters were also published on social network sites. Initially, 62 parents answered the call (21 children with DCD and 41 TD children). After contacting them, children were met for a first time to ensure that they satisfied the inclusion criteria of the study. All children were asked to complete the three manual dexterity subtests of the Movement Assessment Battery for Children–Second Edition (MABC-2; i.e., Placing Pegs, Threading Lace, and Drawing Trail; Henderson et al., 2007) and the four verbal comprehension and fluid reasoning subtests of the Wechsler Intelligence Scale for Children–Fifth Edition (WISC-V; i.e., Similarities, Vocabulary, Matrix Reasoning, and Figure Weights; Wechsler, 2016). Parents of all participants were invited to complete an anamnestic questionnaire about their children. Only parents of children with DCD completed the MABC-2 motor questionnaire.

The current study used strict inclusion criteria to ensure that all children included in the DCD group actually had a clear clinical diagnosis of DCD. As such, all children in the DCD group met the five criteria of the *Diagnostic and Statistical Manual of Mental Disorders–Fifth Edition* (DSM-5; American Psychiatric Association, 2013). Each criterion was assessed through objective measurement. To be included in the DCD group, children needed to exhibit poor fine motor skills with a manual dexterity index of the MABC-2 below the 10th percentile (DSM-5 Criterion A). The motor impairment needed to interfere with children's daily activities, as evidenced by an MABC-2 motor questionnaire score below the 5th percentile or motor difficulties reported in the anamnestic questionnaire filled out by parents (DSM-5 Criterion B). Moreover, their motor disorder could not be explained by other medical conditions (e.g., epilepsy, hydrocephalus, cerebral palsy; DSM-5 Criterion C). This was confirmed by the anamnestic questionnaire. Finally, children needed to have WISC-V verbal comprehension and fluid reasoning indexes above 80 (DSM-5 Criterion D). Note that for 13 of 15 children in the DCD group, the diagnosis has been confirmed by a physician. Among the 21 children with DCD who answered the call, 4 did not meet one of the four criteria of the DSM-5 based on the objective measurements and were excluded from the sample (3 of them had a manual dexterity index above the 10th percentile [from P16 to P25], and 1 child was excluded because the parents reported hydrocephalus at birth. The parents of 2 children withdrew from the study because they were unable to attend the second test session.

The 15 selected TD children were matched with participants in the DCD group on the basis of their school level and their fluid reasoning abilities as assessed with the Figure Weights subtest of the WISC-V, a subtest with low visuospatial processing requirements (Van Dyck et al., 2022; maximum 2 points difference in standard score with the DCD participants). To be included in the control group, children needed to score above the 25th percentile on the MABC-2 manual dexterity index and to have no history of motor difficulties, learning disabilities, or attention-deficit disorder as reported by parents in the anamnestic questionnaire.

The anamnestic data collected through questionnaires revealed that 12 of the 15 children included in the DCD group had comorbidities (i.e., developmental language disorder [n = 6], reading disability [n = 1], and/or attention-deficit/hyperactivity disorder [n = 8]), and 10 were followed by a speech or occupational therapist at the time the study was conducted. The socioeconomic status of the families, collected with the International Standard Classification of Occupation (ISCO-08; International Labour Organization, 2008), was heterogeneous, with 36.7% of parents working as managers or in an intellectual profession, 30% as factory workers, and 20% as administrative employees or technicians. Of the remaining families, 10% of parents reported not having an occupation and the socioeconomic status of 3.3% was unknown.

This study was not preregistered, and the research was approved by the local ethics committee. The parents of participants, as well as their children, gave written informed consent. Each child was informed orally about the research and consented to it.

Tasks

The experimental protocol included three FC tasks with different WM demands. A 3D motion measurement device was used to collect biomechanical data in the three FC tasks. Working memory and knowledge of ordered numerical and non-numerical sequences were also assessed in two additional control tasks.

N^{th}-After task

Adapted from Crollen et al. (2011), the N^{th}-After task was administered to assess the ability to use FC to solve problems involving ordered numerical and non-numerical sequences. Specifically, the children were asked to identify the n^{th} item after a target item using two types of ordered sequences. The task involved the verbal number sequence in the numerical condition (i.e., "What is the n^{th} number after x?") and the alphabetical sequence in the non-numerical condition (i.e., "What is the n^{th} letter after x?"). Children were explicitly asked to count on their fingers from the term $x + 1$ and to continue until n fingers were raised according to the following instruction: "Now I'm going to ask you what is the n^{th} number/letter after x? To answer this question, you will put x in your head and continue to count/recite the alphabet from $x + 1$ by raising one finger for each number/letter. You will stop when you have raised n fingers." The experimenter made a first demonstration and then invited the children to do it in turn. Thus, the task was designed to place a high load on WM (i.e., memorizing the starting point and the number of steps and then reciting the sequence until the target was reached), making FC a relevant strategy for relieving WM. Children were asked to state their answer aloud. In each condition, the task consisted of two sets of eight ordinal problems requiring the children to raise two to nine fingers (i.e., 16 items by condition). Half of the items involved two to five fingers and could be done with one hand, whereas the other half involved six to nine fingers and required the use of both hands. Three training trials involving the raising of one, two, and three fingers, respectively, were conducted before starting the task to ensure that the instructions had been accurately understood. One point was given for each correct answer. To make sure that the instructions were understood, participants needed to succeed in six training trials (three per condition) to move on to the test phase.

Finger-counting

To assess FC, participants were asked to count from 1 to 10 on their fingers, starting with their dominant hand. This task only required coordinating finger movements with the recitation of the verbal number sequence and thus placed a lower load on WM. Participants needed to complete the FC sequence three times to obtain a stable measure of their performance.

Counting-like finger movement

This task was designed to assess counting-like finger movement with no recitation and thus involved no cognitive load in WM. Children needed to perform an ordered sequence of finger movements simulating FC (i.e., starting with the hand closed and raising fingers one by one following the order of their anatomical position: thumb, index, middle, ring, and pinky fingers), starting with their dominant hand. Participants were asked to complete the sequence of counting-like finger movements three times to obtain a stable measure of their performance.

Ordered sequences

This task assessed the children's knowledge and level of development of ordered sequences, which were considered as prerequisites for the N^{th}-After task. First, children were asked to recite the numerical sequence (from 1 to 30) and the alphabetical sequence (from a to z). Second, they needed to perform *advanced recitation,* that is, reciting the ordered sequences between two benchmarks (e.g., for the numerical sequence "Can you count between 5 and 13?", for the alphabetical sequence "Can you recite the alphabet between e and m?"). This ensured that children reached the breakable chain level of knowledge for each sequence (Fuson, 1988), an ability that is fundamental to performing the N^{th}-After task. For each type of sequence, 5 trials were carried out, 1 for the sequence recitation and 4 for advanced recitation between two targets, for a total of 10 trials. One point was awarded for each correct answer. To be included in the study, children needed to be able to recite perfectly both the numerical (up to 30) and the alphabetical sequences and to be able to recite each sequence between two benchmarks (i.e., minimum 3 of 4 trials succeeded for advanced recitations for each sequence, with 1 error tolerated for each sequence).

Working memory

Working memory abilities were assessed using a backward letter span task. The stimuli consisted of a set of 21 sequences of letters of increasing length (i.e., two to nine letters). Participants needed to repeat a letter sequence read aloud by the experimenter in the reverse order. The task began with 2 trials of two-letter sequences. Participants needed to succeed in 2 trials of the same length to be presented with span + 1, with a maximum of 3 trials per span. Two training trials of two-letter length were administered before starting the task. Each correct answer was credited with 1 point.

3D motion acquisition and processing

Data acquisition

Four units of a Codamotion 3D optoelectronic system (Charnwood Dynamics, Rothley, UK) were used to localize, with millimeter precision (Schwartz et al., 2015), the eight 3D markers placed on each participant's hand (i.e., one on the distal phalange of each finger, one on the proximal phalange of the index finger, one on the middle finger metacarpal, and one on the distal wrist crease). Acquisitions were performed at a frequency of 200 Hz. Voice recording was captured by a microphone placed close to the mouth on the participants' clothing, synchronized with the 3D motion acquisition.

Data processing

Data processing was performed on MATLAB R2017a software. As illustrated in Fig. 1, processing consisted of (1) targeting, from 3D motion analysis, the precise time at which the child started to lift each finger; (2) targeting, from the acoustic recording, the time at which the child started to recite each term of the ordered sequence; and (3) mapping the signals to each other.

Four different indexes were extracted from biomechanical data to assess movement functionality in each of the tasks involving finger movements (i.e., N^{th}-After task, FC, and counting-like finger movement), namely *total duration, IF transition, IF variance,* and *finger/voice synchronization indexes.* No synchronization index was extracted for the counting-like finger movement task, which involved no recitation, because the calculation of the synchronization index required both acoustic and motor signals.

First, a *total duration index* was calculated to measure the overall time of execution of finger movements. For each item, the total duration index was calculated as the time interval between the beginning of the motor signal of the first finger raised and the beginning of the motor signal of the last finger raised. Second, an *IF transition index* was considered as the average of the time intervals between consecutive finger raises (i.e., the time interval between the beginning of the motor signal of each finger and the beginning of the motor signal of the next finger). Third, an *IF variance index* was extracted to measure the regularity with which the participant raised his or her fingers. For each item, the regularity index was calculated as the standard deviation of the time intervals between consecutive raised fingers. Higher indexes reflected poor regularity in finger movement. Fourth, a *finger/voice synchronization index* was computed to assess the child's ability to synchronize the raising of each finger with the recitation of the ordered sequence. For each item, an index was computed as the average of the time intervals (in milliseconds) between the instant at which the child began to raise each finger and the instant at which he or she began to enunciate each term in the ordered sequence. To facilitate data interpretation; the synchronization index for each item was transformed using the function $f(x) = -x$. Positive values indicated that the voice occurred before the raising of fingers, whereas negative values reflected the reverse situation. The closer the index got to zero, the better the synchronization.

Procedure

The entire protocol required two 1-h sessions. The first individual session took place at the children's homes and was dedicated to the IQ, WM, and fine motor skills assessment to confirm that the participants met the inclusion criteria of the current research. At the end of the first session, the experimenter showed the participants the 3D device and placed demonstration markers on their fingers, to make them familiar with the equipment.

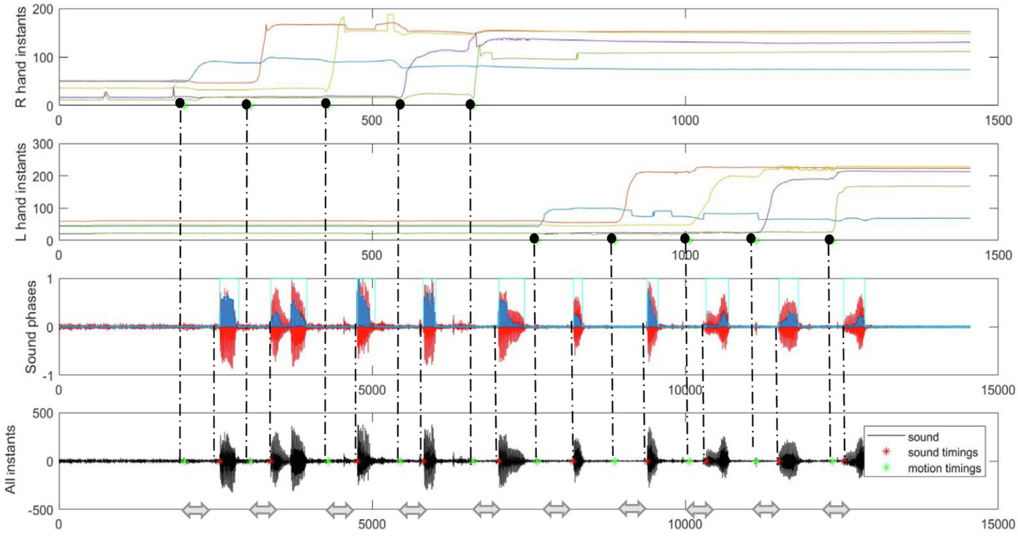

Fig. 1. Example of data processing where acoustic and motor signals have been mapped. The gray arrows represent the time intervals between the moments when the participants started to lift their fingers and the moment when they started to speak. L, left; R, right.

The second session was conducted in the Motion Laboratory of the local university to assess the children's ability to use FC. After a time of familiarization with the environment, children were invited to sit on a chair placed at a school table in the center of the four units of the 3D system. Markers were then placed on both of their hands. A blank trial was conducted before starting the session to ensure that the markers did not interfere with the participants' finger movements and that the children felt comfortable with the equipment. Children were asked to inform the experimenters if they felt uncomfortable, and when necessary the markers were repositioned. None of the participants reported persistent discomfort. Assessment started with the administration of the counting-like finger movements task, followed by the FC task. Then, the two conditions of the N^{th}-After task were conducted in a counterbalanced order. Participants were offered a break for a few minutes between the two tasks. This second session was also recorded with a two-dimensional (2D) camera.

Analyses

Results were analyzed in three stages using Jamovi 2.4.11 computer software. First, chi-square and paired-sample *t* tests were performed to provide descriptive information on each group. Then, behavioral and biomechanical data were analyzed using generalized linear mixed models (GLMMs). Known to be more powerful than the paired-sample *t* tests and repeated-measures ANOVAs, GLMMs are particularly recommended for the statistical processing of small sample sizes (Meteyard & Davies, 2020; Wiley & Rapp, 2019). Moreover, such models make it possible to consider missing data resulting from a lack of visibility of 3D markers during the experimental phase. All items were individually encoded. The final GLMMs were selected based on the lowest Akaike information criterion (AIC) scores, reflecting a good fit with data. Binomial GLMMs were used for analyzing behavioral data (i.e., performance on the recitation and N^{th}-After tasks), whereas gamma GLMMs were used for the biomechanical data (i.e., measures obtained from the four functionality indexes). Odds ratios (ORs) have been reported as a measure of effect size. According to Cohen (1988), Odds ratios in the ranges of 1.44 to 2.49, 2.50 to 4.31, and ≥4.32 were considered as small, moderate, and large effect sizes, respectively. For all analyses, Bayesian factors (BFs) have been indicated. BF10 indicates evidence in favor of the alternative hypothesis (H1) over the null hypothesis (H0), while BF01 reflects the opposite situation. According to Jeffreys (1961), a BF less than 1 provides no evidence, whereas BFs in the ranges of 1 to 3, 3 to 10, 10 to 30, 30 to 100, and > 100 provide anecdotal, moderate, strong, very strong, and extreme evidence in favor of the expected effect, respectively. Bayesian analyses were conducted considering settings of the Cauchy prior distribution.

Results

Descriptive information

Table 1 shows descriptive information in DCD and control groups, mean performance in IQ, manual dexterity, WM, Nth-After task, and *t* test performed for group comparisons. The DCD group included 6 girls and 9 boys, whereas the control group included 9 girls and 6 boys. Both groups had equivalent socioeconomic status (χ^2 = 8.26, p = .31). Although 2 children with DCD repeated a grade, the two groups were balanced in terms of age (p = .57).

As expected, *t* tests confirmed that children in the DCD group were significantly weaker than TD children in all three manual dexterity subtests of the MABC-2 (Placing Pegs: p = .005; Threading Lace: p < .001; Drawing Trail: p < .001) and in the manual dexterity index (p < .001). Crucially, no group difference was found in the fluid reasoning index (based on mean standard scores in the nonverbal subtests, p = .25) or in the Figure Weights (p = .56) and Matrix Reasoning subtests (p = .10), confirming that both groups had similar nonverbal reasoning abilities. By contrast, group comparisons showed that the verbal comprehension index (based on mean standard scores in the verbal subtests) and the Similarity subtest scores were significantly lower in children with DCD compared with their peers (*p*s = .008 and .008, respectively), whereas no difference was found in the Vocabulary subtest (p = .08). However, it is important to note that this group difference did not reflect a verbal weakness in the DCD group, whose mean standard scores were perfectly in the average range (M = 10, SD = 3; see Table 1), but rather reflected a verbal strength in the control group, whose verbal standard scores fell within the upper limit of the average range.

Behavioral data

Behavioral data were analyzed to examine whether children with DCD were able to use FC when solving an ordinal task with high WM load (i.e., Nth-After task). A first GLMM was conducted to compare accuracy between groups (control vs. DCD) across the two experimental conditions (numerical vs. alphabetical sequence) of the Nth-After task. Therefore, group, condition, and the group-by-condition interaction were added to the model as first-, second-, and cross-level predictors, respectively. Participants and items were treated as random effects.

The results revealed that group [SE = .61, t(879) = 3.40, p < .001, OR = 8.03; large effect size] was a strong significant predictor of accuracy, reflecting that children with DCD had lower accuracy than the control group in the Nth-After task. The condition effect suggests no advantage of the alphabetical or numerical condition [SE = .24, t(879) = 0.84, p = .40, OR = 1.22]. The group-by-condition interaction was not significant [SE = .41, t(879) = −0.38, p = .71, OR = 0.86]. To determine whether the group effect could be explained by WM and/or manual dexterity, performance in the backward letter span task and manual dexterity index (MABC-2) were added to the model. In this case, the majority of the variability was captured by these covariates, making the group effect nonsignificant [SE = 1.04, t(879) = 0.93, p = .35, OR = 2.63]. Working memory shared a significant part of variance with the group effect [SE = .23, t(879) = 2.22, p = .03, OR = 1.65; small effect size], whereas manual dexterity did not [SE = .02, t(879) = 0.24, p = .81, OR = 1.01]. This suggests that group differences in the Nth-After task would be more related to WM than to manual dexterity.

In addition, errors made by participants during the Nth-After task were analyzed using 2D video-recording. Seven categories of errors could be distinguished among the 218 errors identified.[1] Examples of each type of error in response to the question "What is the 7th number after 4?" are provided in parentheses.

[1] Note that errors could cumulate the characteristics of two different categories and thus were counted twice.

Table 1
Descriptive information regarding IQ scores, fine motor skills, working memory, and the Nth-After task in the DCD and control groups

	Control group (n = 15)		DCD group (n = 15)		Group comparisons	Effect size
	Mean (*SD*)	Range (min–max)	Mean (*SD*)	Range (min–max)	$t(15)$	d
Age (in months)	101.00 (11.40)	74–119	103.00 (8.89)	84–119	−0.58	−0.15
Gender (M/F)	6/9		9/6			
School level (G1/G2/G3/G4)	1/4/7/3		1/4/7/3			
IQ (WISC-V)						
Fluid Reasoning index[a],[b]	10.90 (2.55)	6.5–16	9.73 (2.53)	5.5–15	1.20	0.31
Matrix Reasoning[a]	10.70 (2.25)	7–14	9.07 (2.91)	5–15	1.76	0.45
Figure Weights[a]	11.10 (3.42)	5–18	10.40 (2.50)	5–15	0.59	0.15
Verbal comprehension index[a],[b]	12.50 (1.76)	10–16	10.00 (2.21)	6.5–13	3.06**	0.79
Similarity[a]	13.40 (2.23)	8–17	10.40 (2.75)	6–15	3.07**	0.79
Vocabulary[a]	11.50 (2.26)	7–16	9.67 (2.35)	5–14	1.90	0.49
Manual dexterity (MABC-2)						
Manual dexterity index[a],[b]	10.30 (1.21)	9–13	5.67 (1.42)	3–8	8.73***	2.26
Placing Pegs[a]	10.20 (2.54)	7–15	7.13 (2.53)	3–12	3.30**	0.85
Threading Lace[a]	10.60 (1.99)	8–13	6.27 (2.31)	3–11	5.56***	1.44
Drawing Trail[a]	10.00 (2.67)	4–12	3.60 (2.95)	1–12	5.51***	1.42
Working memory						
Backward letter span	5.40 (1.24)	4–8	3.40 (1.30)	2–6	4.97***	1.28
Nth-After task						
Total	28.10 (5.71)	9–32	17.40 (11.40)	1–32	3.61**	0.97
Numerical sequence	14.70 (2.02)	9–16	9.79 (5.49)	1–16	3.56**	0.95
Alphabetical sequence	13.40 (3.94)	0–16	7.64 (6.22)	0–16	3.16**	0.84

Note. DCD, developmental coordination disorder; M, male; F, female; G, Grade; WISC-V, Wechsler Intelligence Scale for Children–Fifth Edition; MABC-2, Movement Assessment Battery for Children–Second Edition.
[a] Standard note: M = 10, SD = 3.
[b] Fluid reasoning, verbal comprehension, and manual dexterity indexes were calculated as the mean standard notes of the individual subtests.
** $p \leq .01$.
*** $p \leq .001$.

A first category was referred to as *FC errors,* which were related to the execution of the FC movements (i.e., observable lack of synchronization between finger lifts and enunciation). A second category of errors included *stop errors* due to an incorrect number of fingers raised during FC (i.e., raised fewer or more fingers than required). The third type referred to *initiation error* when the participant initiated the FC with a term other than x or $x + 1$ (e.g., the child started to count from 8 instead of from 5). Because all children demonstrated their ability to recite the numerical and alphabetical sequences between two targets before starting the task, the initiation errors could not be interpreted as an inability to initiate the recitation from an arbitrary entry point. Rather, stop and initiation errors could be interpreted as reflecting WM errors related to difficulties in maintaining the instruction in WM during the processing of the Nth-After task. As a result, children started their counting from a false starting point or raised an incorrect number of fingers (sometimes even stopping their counting only after having raised all their fingers).

Fourth, *instruction errors* were related to the execution of the instruction. An error was classified in this category when the child initiated his or her counting from the term x instead of the term $x + 1$ despite the explicit instruction given before starting the task (e.g., the child initiated the counting from

4 instead of from 5). The fifth category encompassed *enunciation errors,* which were related to an incorrect enunciation of the verbal numerical or alphabetical sequences (i.e., mainly errors caused by omissions of a term from the ordered sequence). A sixth type of error consisted of *reversal errors* when the child reversed the number from which to start (i.e., term x) and the number of fingers to be raised (i.e., term n) (e.g., the child started to count from 8 and raised four fingers instead of starting from 5 and raising seven fingers). Finally, the last category concerned *unclassified errors* related to a lack of response or to errors that could not be classified in any other category. Instructional, enunciation, and reversal errors were grouped with the unclassified errors under the heading of "other errors." Because these errors occurred occasionally, they can be interpreted as manifestations of inattention. They reflected neither a lack of understanding of the instructions nor a poor mastery of the ordered sequences given that before starting the Nth-After task all participants had been able to perform the three training trials and recite the ordered sequences.

Table 2 summarizes the distribution of errors in each group in the Nth-After task. Taking a closer look at WM and FC errors, children in both groups made a greater number of WM errors than FC errors, but the distribution of these two types of errors did not differ between groups (χ^2 = .53, p = .47). Children with DCD made significantly more WM errors [t(28) = 2.38, p = .02) than TD children. Indeed, children with DCD made about three times more WM errors than children in the control group (75.7% vs. 24.3% of all WM errors, respectively). Most FC errors were made by 3 children with severe fine motor impairment (manual dexterity index $\leq$ 1st percentile for 2 of them and at the 9th percentile for the third child).

Biomechanical data

The four functionality indexes (i.e., total duration, IF transition, IF variance, and finger/voice synchronization indexes) were analyzed to examine the functionality of finger movements during FC. Three tasks with different WM loads were analyzed: counting-like finger movement with no WM load, FC with low WM load, and the Nth-After task with high WM load. Only the numerical condition of the Nth-After task was taken into account to make it comparable to the two control tasks. Moreover, the Nth-After task involved the raising of two to nine fingers, whereas the two control tasks required the raising of all ten fingers. Given these methodological differences in data collection, the group effect was analyzed separately in each task.

In the counting-like finger movement task, three GLMMs were run to compare (1) total duration, (2) IF transition, and (3) IF variance indexes across groups. For each of the three models, group was added as the main predictor, whereas participants and items were considered as random effects. Results revealed that neither total duration [SE = .67, t(58) = −1.51, p = .13, OR = 0.36], IF transition [SE = −.12, t(58) = −1.56, p = .12, OR = 0.88], nor IF variance indexes [SE = .06, t(58) = −0.92, p = .36] was significantly predicted by group. These results suggested that the three functionality indexes did not differ between groups when the FC movements were executed with no requirement for coordination with the verbal recitation.

In the FC task, four GLMMs were run to compare (1) total duration, (2) IF transition, (3) IF variance indexes, and (4) finger/voice synchronization across groups. For each model, group was added as the main predictor, whereas participants and items were considered as random effects. Results revealed that group significantly predicted IF variance [SE = .01, t(69) = −54.20, p < .001, OR = 0.94; small effect size] but not total duration [SE = .58, t(69) = −0.02, p = .98, OR = 0.98], IF transition index [SE = .11, t(69) = −0.96, p = .34, OR = 0.90], or finger/voice synchronization [SE = .08, t(69) = −0.01, p = .99, OR = 0.99]. This indicated that FC movements in coordination with the verbal number sequence were less regular in children with DCD compared with the control group.

In the Nth-After task, four GLMMs were run to compare (1) total duration, (2) IF transition, (3) IF variance, and (4) finger/voice synchronization indexes across groups. For each model, group and item accuracy in the Nth-After task (success vs. failure) and the group-by-item accuracy interactions were added to the model as first-, second-, and cross-level predictors, respectively. Participants and items were treated as random effects. Neither group [SE = .06, t(686) = 0.03, p = .97, OR = 1.00], item accuracy [SE = .01, t(686) = 1.48, p = .14, OR = 1.02], nor their interaction [SE = .03, t(686) = 1.62, p = .11, OR = 1.05] predicted total duration. Furthermore, the IF transition index was predicted by item accu-

Table 2
Distribution of errors in each group during the Nth-After task

Category of errors	DCD group	Control group	Total[a]	Error description
FC errors	11	2	13	Lack of synchronization between fingers and verbal enunciation
WM errors				
Stop	81	27	108	Number of fingers raised other than *n*
Initiation	31	9	40	Initiation of FC with a term other than *x* or *x* + 1
Total	112	36	148	
Other errors				
Instruction	3	4	7	Initiation of FC from the term *x* instead of *x* + 1
Enunciation	6	5	11	Omission of a term in the verbal sequence
Reversal	32	2	34	Permutation of the terms *x* and *n*
Unclassified	3	2	5	Lack of response and errors not classified
Total	44	13	57	

Note. DCD, developmental coordination disorder; FC, finger-counting; WM, working memory. Errors were described in response to the question, "What is the n^{th} number/letter after [*x*]?"
[a] "Total" refers to all errors made by participants of each group.

racy [SE = .05, t(686) = 2.97, p = .003, OR = 1.15; small effect size], whereas the group effect [SE = .22, t(686) = 0.60, p = .55, OR = 1.14] and group-by-item accuracy interaction [SE = .09, t(686) = 0.81, p = .42, OR = 1.08] were nonsignificant predictors. The GLMM also provided evidence that item accuracy [SE = .29, t(686) = 2.43, p = .01, OR = 2.03; small effect size] was a significant predictor of the IF variance index, whereas group [SE = .79, t(686) = 0.12, p = .90, OR = 1.10] and the group-by-item accuracy interaction [SE = .58, t(686) = 1.08, p = .28, OR = 1.87] did not. Finally, finger/voice synchronization was predicted by item accuracy [SE = .15, t(686) = 2.42, p = .02, OR = 1.44; small effect size], whereas neither group [SE = .44, t(686) = −1.05, p = .29, OR = 0.63] nor the group-by-item accuracy interaction [SE = .30, t(686) = 0.90, p = .37, OR = 1.31] was a significant predictor. Altogether, these findings reflected that FC movements made during failed trials were less regular, were less synchronized with the recitation, and exhibited longer IF transition speed compared with FC movements executed during successful trials. Crucially, these features were not specific to one of the groups given that none of the indexes was predicted by either group or the group-by-item accuracy interaction. Therefore, children with DCD did not differ from their peers on execution speed, IF transition speed, regularity, and finger/voice synchronization when using FC in a task with high WM load (Nth-After task) whether the trial succeeded or failed.

Bayesian analyses

Given the absence of significant effects in the analysis of biomechanical data, Bayesian paired-sample t tests were conducted to determine whether the absence of significant group differences in the GLMMs was conclusive and supported the null hypothesis (H_0: no difference between groups).

In the counting-like finger movement task, the data were equally likely to be observed under the null hypothesis (H_0) and the alternative hypothesis (H_1: significant difference between groups), providing anecdotal evidence in support of each model whatever the FC functional parameters under consideration (total duration: n = 14, BF_{01} = 0.91, BF_0 = 1.10; IF transition: n = 14, BF_{01} = 0.91, BF_{10} = 1.10; IF variance: n = 14, BF_{01} = 0.67, BF_{10} = 1.49). This indicates a lack of evidence to support either the absence or presence of significant group differences in functionality indexes when participants must perform stand-alone counting-like finger movement.

In the FC task, overall, the data were more likely to be observed under the null hypothesis (H_0) compared with the alternative model (H_1) (total duration: n = 12, BF_{01} = 3.36; IF transition: n = 14, BF_{01} = 2.59; IF variance: n = 14, BF_{01} = 2.19; finger/voice synchronization; n = 12, BF_{01} = 3.46; all BF_{10} < 1). Evidence supporting the null effect remained anecdotal for IF transition and IF variance indexes but were moderate for total duration and finger/voice synchronization indexes. For both indexes, the data were three times more likely considering the absence of group differences compared with the alternative model, suggesting that children with DCD were as fast and synchronized as their peers while executing FC in coordination with the verbal recitation. However, no conclusive evidence was found in support of either the H_1 or H_0 hypothesis with regard to finger movement transition speed and regularity.

Finally, in the N^{th}-After task, the data provide moderate evidence for the null hypothesis (H_0) against the alternative hypothesis (H_1) (total duration: n = 14, BF_{01} = 3.68; IF transition: n = 15, BF_{01} = 3.76; IF variance: n = 14, BF_{01} = 3.39; finger/voice synchronization; n = 15, BF_{01} = 7.27; all $BF_{10} < 1$). For all parameters, the observed data were three to seven times more likely under a model with no difference between groups compared with a model with a significant group effect. These results support the conclusion that children with DCD did not differ from their peers on execution speed, transition speed, regularity, and finger/voice synchronization when using FC in a WM-loaded task (N^{th}-After).

Discussion

The purpose of this study was to investigate the functionality of FC in children with DCD using behavioral and biomechanical data. At the behavioral level, we examined whether children with DCD use FC efficiently to solve a task with high WM load, named the N^{th}-After task. At a biomechanical level, different aspects of FC functionality were examined in the light of four parameters captured from 3D motion analysis to determine whether FC movements were as fast, regular, and synchronized with voice in children with DCD as in TD children. Contrasting with the N^{th}-After task, FC movements were further examined in two control FC tasks with lower WM demands to determine whether FC functionality in each group was influenced by the WM demands of the task.

The results of behavioral analyses showed that, compared with the control group, children with DCD were less accurate in the N^{th}-After task. This group effect was not modulated by the condition (i.e., letters or numbers), indicating that it was related to the task and not to the type of ordered sequence. The group difference could not be explained by a lower level of elaboration of these sequences in the DCD group either given that all children who participated reached the breakable chain level of knowledge for the alphanumeric sequences used in the study. Interestingly, when WM and manual dexterity were added to the model, the group effect disappeared. Only WM emerged as a significant covariate, suggesting that WM inter-individual differences could account for at least some of the variance of the group effect in this task, whereas manual dexterity did not. Indeed, the N^{th}-After task was designed to place heavy demands on WM so that FC was not only compulsory but also useful for the task at hand. To solve the task, the children needed (1) to maintain instructions in WM, including the starting point and the number of fingers to be raised, and (2) to coordinate the finger raising with the sequence recitation to keep track of counting. In TD children, the use of fingers gives the WM sufficient room to ensure that these different processes run smoothly (Crollen, Mahe, et al., 2011). Here, analysis of errors reported in the N^{th}-After task showed that the most common errors in both groups involved the maintenance of instructions (i.e., initiation or stop errors) and that these errors were about three times more frequent in children with DCD. They could be related to their weaknesses in WM, an impairment that has been reported multiple times in children with DCD (Alloway & Archibald, 2009; Lachambre et al., 2021; Sartori et al., 2021).

Interestingly, Dupont-Boime and Thevenot (2018) showed that 6-year-old children with low resources in WM make less use of FC to solve calculations than children with better resources. To explain this difference, the authors suggested that the discovery and implementation of FC as a relevant strategy to solve additions would require high levels of resources in WM. When these resources are lacking, WM can be overloaded by FC, leading children with limited resources to use other more error-prone strategies. For children with DCD who experience fine motor impairment (Barnett & Prunty, 2021; Biotteau et al., 2019; Huau et al., 2015), FC might be demanding, especially in dual-task situations. Indeed, when motor and cognitive tasks need to be handled simultaneously, children with DCD have been found to prioritize the cognitive task over the motor task, resulting in a degradation of their motor performance, which could reflect a lack of automatization of motor processes

(Laufer et al., 2008; Tsai et al., 2009). Similarly, the use of FC in the Nth-After task is a dual-task situation that not only requires the coordination of recitation and finger movements but also requires maintaining in WM the number where to start and the number of fingers to be raised. If FC is demanding in WM (i.e., FC gestures are cognitively effortful or not adequately automatized at a basic level), children with DCD might be pushed to commit a considerable amount of WM resources in FC at the expense of maintaining instructions.

This assumption is called into question by the analyses conducted on biomechanical data, which showed no group differences on any of the functionality indexes. Evidence in the counting-like finger movement task was anecdotal and thus failed to be conclusive, leaving open the possibility that the null effect could be linked to a lack of statistical power. However, in the two other tasks, Bayesian statistics provided moderate evidence in support of the absence of group differences on a significant number of parameters. When FC movements needed to be executed in coordination with verbal counting, Bayesian statistics provided moderate evidence in support of the null effect, suggesting that children with DCD were as fast and synchronized as the control group in this task. Importantly, in the Nth-After task that was more demanding in terms of WM resources, the null hypothesis was again the most likely model for all parameters, suggesting that children with DCD produced FC movements as functional as their peers. Considering the frequency of FC errors (a number that was quite marginal compared with the number of other errors, n = 11 vs. n = 207), it could still be argued that children with DCD made more FC errors than their peers and that item accuracy was predicted by FC functionality. However, this effect was not modulated by group membership, providing no evidence that the errors made by children with DCD resulted from poorer FC functionality.

Altogether, these results challenge the assumption that FC movements would be cognitively demanding for children with DCD. Indeed, the current results highlight a similar impact of WM load on execution speed and finger/voice synchronization in children with DCD compared with their TD peers, at least in the context of the current tasks. It is still possible that children with DCD, equipped with the markers as they were in the motion lab, had prioritized FC and devoted available WM resources to finger movements, as required by the Nth-After task, to the detriment of the instructions to be held in WM, resulting in a significant number of WM errors. Further research is necessary to examine FC automatization in other cognitively demanding numerical tasks before concluding that children with DCD might have reached a certain level of automatization in performing FC movements. In this respect, it would be interesting to track FC functionality longitudinally in dual-task situations contrasting different WM loads (i.e., low, medium, and high) to examine the developmental trajectory of FC automatization (as attested by a lower dual-task effect on FC functionality) in children with DCD compared with TD children.

To sum up, the current study failed to find functional limitations of FC movements in children with DCD. However, the implementation of FC could have consumed resources in WM and could have led children with DCD to commit a high number of WM errors in a task with high WM load. This first set of results would need to be corroborated with a large-scale sample to reach higher statistical power and detect a smaller effect size. The future investigations could contrast FC/no-FC conditions in arithmetic tasks with various WM loads to examine the extent to which FC offers tangible help for these children. Such a comparison would provide insightful evidence for the interplay among WM, finger use, and arithmetic difficulties in children with DCD. Specifically, we would expect group differences in this arithmetic task to be greater as WM load increases, an interaction that would be modulated differently by FC condition depending on whether FC helps or not.

Future investigations are also needed to determine whether the current findings are specific to DCD or whether they could be the consequence of some of the comorbidities in the current sample (i.e., learning disabilities and/or attention-deficit disorder). In addition to a motor disability, children with DCD are known to be at greater risk of attention-deficit/hyperactivity disorder (Lino & Chieffo, 2022; Wilson et al., 2020) or mathematical learning disabilities (Pieters, Desoete, Waelvelde, et al., 2012), two conditions that are themselves frequently associated with a WM deficit (De Smedt et al., 2013; Mazzocco et al., 2011). As such, a straight comparison of children with mathematical learning disability in a task similar to the Nth-After task would be particularly interesting because so far they have been found to benefit from FC to compensate for their WM deficits in numerical processing (Noël, 2005, 2009; Passolunghi & Cornoldi, 2008), unlike children with DCD in the current study. Interestingly, the limited number of FC errors were made exclusively by 3 children with severe fine motor impairment. Given that the cognitive profile of children with DCD is extremely heterogeneous (Van Dyck et al., 2022), it is possible that some of them present difficulties severe enough to hinder effective finger recitation coordination during FC. It would be interesting to compare different profiles in larger samples of children with DCD to determine whether certain profiles are more at risk of presenting finger recitation coordination difficulties. Our current study could also be extended to assess the FC functionality of children with DCD in other numerical contexts. For example, it would be interesting to examine the spontaneous use of FC to solve arithmetic problems to determine whether children with DCD feel comfortable enough with FC to use it as a functional tool in arithmetic tasks.

Conclusion

The current findings show that children with DCD are less accurate than TD children in an FC task that puts heavy demands on WM. The current results suggest that these difficulties could be more closely related to a limitation of WM resources than to dysfunctional FC movements. In the current work, FC functionality in children with DCD was investigated using 3D motion analysis, an innovative technique providing a high level of precision that cannot be obtained through straightforward behavioral observations. Three-dimensional motion analysis opens many new perspectives on understanding the issues relating to embodied numerical cognition. This technique should make it possible to focus on the functionality of the gestures involved in numerical and arithmetic processing (FC and cardinal number gestures). Currently, studies that have questioned the role of fine motor skills in mathematical cognition development have focused on motor tasks that were far removed from the gestures performed in numerical contexts (i.e., pegboard, tying shoelaces, and stacking cubes; for reviews, see Barrocas et al., 2020; Neveu, Geurten, Durieux, et al., 2023). From a functionalist point of view, future works should focus more closely on fine motor skills, which are more proximal to those used in numerical contexts, to gain a better understanding of their involvement in typical and atypical numerical and arithmetic development.

CRediT authorship contribution statement

Maëlle Neveu: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Cédric Schwartz:** Validation, Software, Methodology, Formal analysis, Data curation. **Laurence Rousselle:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Data availability

Data will be made available on request.

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