Finger-counting to relieve working memory in children with developmental coordination disorder: Insights from behavioral and 3D motion analysis.

Abstract

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. Fifteen 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 a high working memory load. Behavioral measures supplemented with biomechanical measures, from 3D motion analysis synchronized to a voice recording, were used to assess children's performance and FC functionality (total duration, inter-finger transition, regularity, finger/voice synchronization, and automatization of FC movements). Children with DCD were less accurate than typically developing children in using FC to solve ordinal problems with high working memory load. This group difference could not be accounted for by poor FC skills, as 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, working memory captured a greater proportion of intergroup variability than manual dexterity, further suggesting that their difficulties would be better accounted by limited working memory resources than by fine motor skills.

Keywords: developmental coordination disorder, finger-counting, working memory, 3D motion analysis.

1. Introduction

In many cultures around the word children use their fingers to deal with numbers (Bender & Beller, 2012; Fuson, 1988). From the age of three, 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 (Roesch & 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; Wasner et al., 2015).

Building on the development of early numerical skills, FC forms the basis which young children rely on to acquire their first arithmetic abilities (Bartelet et al., 2014; Major et al., 2017). Since 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 to 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 or 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 thus relieving their WM (Crollen, Mahe, et al., 2011; Kullberg & Björklund, 2020). Finger counting can be used as an off-loading 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 as children have sufficient cognitive resources to switch from FC to more powerful mental calculation strategies (Geary & Brown, 1991; Jordan et al., 2008; Poletti et al., 2022). This transition has been found to occur later in children with mathematical learning disabilities (MLD) who have limited WM resources (De Smedt et al., 2013a; Mazzocco et al., 2011a). These children have been shown to make more extensive use of concrete supports such as fingers, which provide them with a physical representation of number while reducing the WM load in the task (Noël, 2005, 2009; Passolunghi & Cornoldi, 2008). Therefore, children with MLD continue using FC over a longer period between grades one to three, and use fewer mental strategies (i.e., arithmetic facts retrieval, decomposition of numbers) compared to their typically developing peers (Geary & Brown, 1991, Jordan et al. 2003, Wylie et al. 2012).

Naturally, FC relies on fine motor skills. The FC speed as well as 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. Too slow and irregular, FC could induce unintended pauses which could lead to a desynchronization of recitation and finger movements. Too fast, the finger/voice synchronization could be compromised, leading to one-to-one correspondence errors. In between, finger/voice synchronization efforts could add an additional cognitive load, making this tool ineffective in relieving working memory 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 cognitive load in working memory. Interestingly, some children with MLD 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 (P. H. Wilson et al., 2012), the functionality of FC has never 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). They could therefore be doubly penalized when performing arithmetic operations with, on the one hand, limited resources in WM and, on the other hand, 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 seven to ten years old (Gomez et al., 2015, 2016). Moreover, their counting skills were found to be limited, an impairment which could be due to oculomotor dysfunction reducing their ability to track targets by pointing (Gomez & Huron, 2020). Difficulties in executing calculation procedures has also been reported in nine-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 Nth-After task). Children with DCD were asked to use FC to determine what is the n^{th} element after a target in an ordered sequence. As 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 had to be performed with numerical *vs.* 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 typically developing peers in the ordinal task, whatever the condition (letters or numbers).

Finger-counting functionality was further explored using 3D motion analysis combined with voice recording. Four different biomechanical parameters were assessed to examine FC functionality, namely: total duration and inter-finger transition providing global and local measures of FC execution speed, variance of interfinger transitions as a measure of FC regularity and finally, finger/voice synchronization as a measure of one-to one correspondence. Contrasting with the Nth-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 respectively involved no- (i.e. execution of finger-like counting movement with no recitation) and low- (i.e. FC up to ten) demand in WM. 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 to typically developing children. In this case, FC is expected to be less functional in the Nth-After task than in the two other tasks in children with DCD when compared to their typically developing peers. Conversely, if FC is automatized and effortless in children with DCD, FC functionality should be similar whatever WM load of the task.

2. Method

2.1. Participants

Thirty French-speaking children participated in the experiment: 15 children with DCD (Mean age = 8.6 ± 0.74 years) and 15 typically developing children in the control group (Mean age = 8.4 ± 0.95 years). All children were enrolled in mainstream elementary school. Following Lakens' (2022) approach, power analyses were performed to estimate the sample size for the present study. G*Power software (version 3.1.9.7) was used, considering repeated-measures 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, 41 typically developing children). After contacting them, children were met 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 MABC-2 (Henderson et al., 2007. i.e., placing pegs, threading lace, drawing trail) and the four verbal comprehension and fluid reasoning subtests of the WISC-V (Wechsler, 2016.; i.e., similarities, vocabulary, matrix reasoning, figure weights). Parents of all participants were invited to complete an anamnestic questionnaire about their child. Only parents of children with DCD completed the MABC-2 motor questionnaire.

The present 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 DSM-5. Each criterion was assessed through objective measurement. To be included in the DCD group, children had 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 had to interfere with their daily activities, as evidenced by a 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 had to have WISC-V verbal comprehension and fluid reasoning indexes above 80 (DSM-5 criterion D). Note that for 13 on 15 children in the DCD group, the diagnosis has been confirmed by a physician. Among the 21 children with DCD who answered the call, four did not meet one of the four criteria of the DSM-5 based on the objective measurements and were excluded from the sample: three of them had a manual dexterity index above the 10th percentile (from P16 to P25), and the last child was excluded as parents reported hydrocephalus at birth. The parents of two children withdrew from the study because they were unable to attend the second test session.

Fifteen typically developing children were selected and 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 visuo-spatial processing requirement (Van Dyck et al., 2022; max 2 points difference in standard score with the DCD participant). To be included in the control group, children had to score above the 25th percentile on the MABC-2 manual dexterity index and must 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 an occupational therapist at the time the study was conducted. The socio-economic status of the families, collected with the International Standard Classification of Occupation (ISCO-08; International Labour Organization [ILO], 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. 10% of parents reported not having an occupation and the socio-economic status of 3.3% was unknown.

This study was not pre-registered and the research was approved by the local ethics committee (reference number: 1920-116). 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.

2.2 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.

Nth-After task. Adapted from (Crollen, Mahe, et al., 2011), the N$^{\text{th}}$-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?”). The 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, the number of steps and then reciting the sequence until the target was reached), making FC a relevant strategy for relieving WM. The 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 while the other half involved six to nine fingers and required the use of both hands. Three training trials involving respectively, the raising of one, two and three fingers 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 the instructions were understood, participants had to succeed six training trials (3 per condition) to move on 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. The participants had 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. The children had 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 finger), starting with their dominant hand. The 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 pre-requisite for the Nth-After task. First, the children were asked to recite the numerical sequence (from 1 to 30) and the alphabetical sequence (from a to z). Second, they had 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 which is fundamental to performing the N^{th}-after task. Five trials were carried out for each type of sequence, one for the sequence recitation and four for advanced recitation between two targets, for a total of ten trials. One point was awarded for each correct answer. To be included in the study, children had 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. min. three on four trials succeeded for advanced recitation for each sequence; one 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). The participants had to repeat a letter sequence read aloud by the experimenter in the reverse order. The task began with two trials of two-letter sequences. Participants had to succeed in two trials of the same length to be presented with span+1, with a maximum of three trials per span. Two training trials of two-letter length were administered before starting the task. Each correct answer was credited with one point.

2.3. 3D motion acquisition and processing

Data acquisition. Four units of a Codamotion 3D optoelectronic system (Charnwood Dynamics Ltd, 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 index, 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, this was synchronized with the 3D motion acquisition.

Data processing. Data processing was performed on Matlab R2017a software. As illustrated in Figure 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 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.

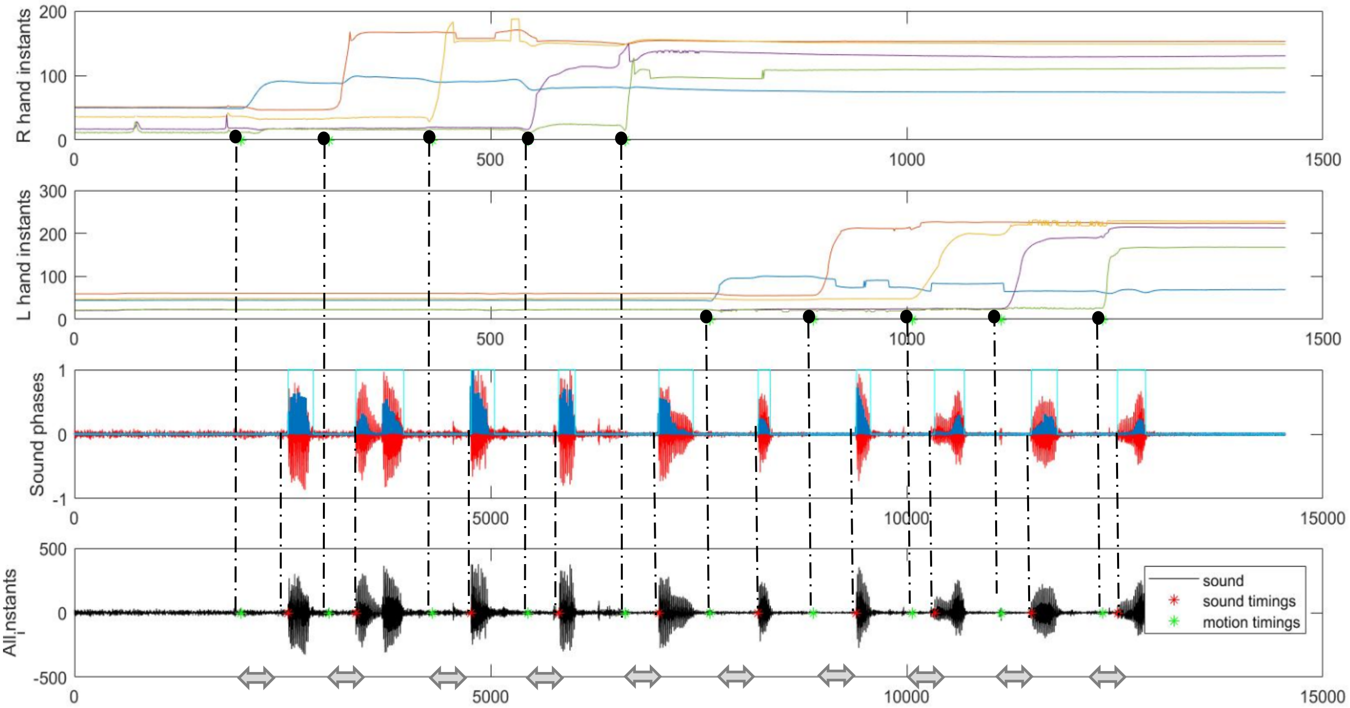

Figure 1: Example of data processing where acoustic and motor signals have been mapped. The grey arrows represent the time intervals between the moments when the participant started to lift their fingers and the moment when he/she started to speak.

Four different indexes were extracted from biomechanical data to assess movement functionality in each of the tasks involving finger movements (i.e., Nth-After task, finger-counting and counting-like finger movement), namely *total duration, inter-finger (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 speed 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 their 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/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 while negative values reflected the reverse situation. The closer the index gets to zero, the better the synchronization.

2.4. Procedure

The entire protocol required two one-hour sessions. The first individual session took place at the child's home and was dedicated to IQ, working memory and fine motor skills assessment, to confirm that the participant 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.

The second session was conducted in the Motion Laboratory of the local university to assess 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 children felt comfortable with the equipment. The children were asked to inform the experimenters if they felt uncomfortable and, when necessary, the markers were repositioned. None of the children reported persistent discomfort. Assessment started with the administration of the counting-like finger movements task followed by the finger-counting task. Then, the two conditions of the N^{th}-After task were conducted in a counterbalanced order. Participants were offered a few minutes break between the two tasks. This second session was also recorded with a 2D camera.

2.5. Analyses

Results were analyzed in three stages using Jamovi 2.4.11 computer software. First, chi-squares 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 AIC scores, reflecting a good fit with data. Binomial GLMMs were used for analyzing behavioral data (i.e., performance on the recitation and the Nth-After tasks) while 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), ORs in the ranges [1.44 - 2.49], [2.50 - 4.31] and ≤ 4.32 were considered as small, moderate and large effect sizes respectively. Finally, Bayesian paired-sample t-tests were performed to assess further the null results from the GLMMs. For all analyses, Bayesian factors (BF) were reported, BF_{10} indicates evidence in favor of H_1 over H_0, while BF_{01} reflects the opposite situation. According to Jeffrey 1961, a BF less than 1 provide no evidence while BF in the ranges [1-3], [3-10], [10-30], [30-100], > 100 respectively provides anecdotal, moderate, strong, very strong, and extreme evidence in favor of the expected effect. Bayesian analyses were conducted considering settings of the Cauchy prior distribution.

3. Results

3.1. Descriptive information

Table 1 shows descriptive information in DCD and control groups, mean performance in IQ, manual dexterity, working memory, Nth-After task and t-test performed for group comparisons. Six girls and nine boys were part of the DCD group, whereas the control group included nine girls and six boys. Both groups had equivalent socioeconomic status (χ^2=8.26, *p*=.31). Although two 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 typically developing children in all three manual dexterity subtests of the MABC-2 (Placing pegs: *p*=. 005; Threading a shoelace: *p*<.001; Drawing a 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), nor in 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 subtests scores were significantly lower in children with DCD compared to their peers (*p*=.008 and .008 respectively), while no difference were 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 a verbal strength in the control group whose verbal standard scores fell within the upper limit of the average range.

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 (11.4)	74 - 119	103.00 (8.89)	84 - 119	-.58	-.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 ^{ab}	10.90 (2.55)	6.5 - 16	9.73 (2.53)	5.5 - 15	1.20	.31
Matrix reasoning ^{a}	10.70 (2.25)	7 - 14	9.07 (2.91)	5 - 15	1.76	.45
Figure Weights ^{a}	11.10 (3.42)	5 - 18	10.40 (2.50)	5 - 15	.59	.15
Verbal Comprehension index ^{ab}	12.50 (1.76)	10 - 16	10.00 (2.21)	6.5 - 13	3.06**	.79
Similarity ^{a}	13.40 (2.23)	8 - 17	10.40 (2.75)	6 - 15	3.07**	.79
Vocabulary ^{a}	11.50 (2.26)	7 - 16	9.67 (2.35)	5 - 14	1.90	.49
Manual Dexterity (MABC-II)						
Manual Dexterity index ^{ab}	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**	.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**	.97
Numerical sequence	14.70 (2.02)	9 - 16	9.79 (5.49)	1 - 16	3.56**	.95
Alphabetical sequence	13.40 (3.94)	0 - 16	7.64 (6.22)	0 - 16	3.16**	.84

Note. G = grade; M = male; F = female.

^{a} standard note: Mean=10, *SD*=3.

^{b}Fluid Reasoning, Verbal Comprehension and Manual Dexterity indexes were calculated as the mean standard notes of the individual subtests.

* $p \leq .05$; ** $p \leq .01$; ***$p \leq .001$.

3.2. 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 model 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 group-by-condition interaction were added to the model respectively as first, second- and cross-level predictors. Participants and items were treated as random effects.

The results revealed that the 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 on the numerical condition (SE=.24, $t(879)=.84$, $p=.40$, OR=1.22). The group-by-condition interaction was not significant (SE=.41, $t(879)=-.38$, $p=.71$, OR=.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 in the model. In this case, the majority of the variability was captured by these covariates, making the group effect non-significant (SE=1.04, $t(879)=.93$, $p=.35$, 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), while manual dexterity did not (SE=.02, $t(879)=.24$, $p=.81$, OR=1.01). This suggests that group differences in the Nth-After task would be more related to WM than to manual dexterity.

Additionally, 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 to the question *What is the 7th number after 4?* are provided between brackets.

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 (i.e., the child started to count from eight instead of five). Since 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/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 four instead of five). 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

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

to count from eight and raised four fingers instead of starting from five 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." As 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, since before starting the Nth-After task all participants had been able to perform the tree training trials and recite the ordered sequences.

Table 2.

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

Categories 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	Omissions 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. 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.

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 typically developing children. Indeed, children with DCD made almost 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 three children with severe fine motor impairment (Manual Dexterity index ≤ 1st percentile for two of them and at the 9th percentile for the third).

3.3. Biomechanical data.

The four functionality indexes (i.e., *total duration, inter-finger (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, finger-counting 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 2 to 9 fingers, while 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, the group was added as main predictor while participants and items were considered as random effects. Results revealed that neither total duration (SE=.67, *t*(58)=-1.51, *p*=.13, OR=.36), IF transition (SE=-.12, *t*(58)=-1.56, *p*=.12, OR=.88), nor IF variance indexes (SE=.06, *t*(58)=-.92, *p*=.36) were 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 finger-counting 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, the group was added as main predictor while participants and items were considered as random effects. Results revealed that the group significantly predict IF variance (SE=.01, *t*(69)=-54.2, *p*<.001, OR=.94, small effect size) but not total duration (SE=.58, *t*(69)=-.02, *p*=.98, OR=.98), IF transition index (SE=.11, *t*(69)=-.96, *p*=.34, OR=.90) or finger/voice synchronization (SE=.08, *t*(69)=-.01, *p*=.99, OR=.99). This indicated that FC movements in coordination with the verbal number sequence were less regular in children with DCD, compared to 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-accuracy interactions were added to the model respectively as first-, second-, and cross-level predictors. Participants and items were treated as random effects. Neither the group (SE=.06, *t*(686)=.03, *p*=.97, OR=1.00), the item accuracy (SE=.01, *t*(686)=1.48, *p*=.14, OR=1.02) nor the interaction (SE=.03, *t*(686)=1.62, *p*=.11, OR=1.05) predicted the total duration. Furthermore, the IF transition index was predicted by item accuracy (SE=.05, *t*(686)=2.97, *p*=.003, OR=1.15, small effect size) while the group effect (SE=.22, *t*(686)=.60, *p*=.55, OR=1.14) and group-by-item accuracy interaction (SE=.09, *t*(686)=.81, *p*=.42, OR=1.08) were non significant predictors. 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, while group (SE=.79, *t*(686)=.12, *p*=.90, OR=1.10) and 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 affect size) while neither the group (SE=.44, *t*(686)=-1.05, *p*=.29, OR=.63) nor the group-by-item accuracy interaction (SE=.30, *t*(686)=.90,

p=.37, OR=1.31) were significant predictors. Altogether, these findings reflected that FC movements made during failed trials were less regular, less synchronized with the recitation and exhibited longer IF transition speed compared to FC movements executed during successful trials. Crucially, these features were not specific to one of the groups as none of the indexes were predicted either by the group or by 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 (N^{th}-After task) whether the trial was succeeded or failed.

3.4. Bayesian analyses

Given the absence of significant effects in the analysis of biomechanical data, Bayesian paired-sample t-tests were conducted to determine whether or not the absence of significant group difference in the GLMMs were conclusive and support the null hypothesis (H_0: no difference between groups).

In the counting-like finger movement task, the data are equally likely to be observed under the null (H_0) or 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}=.91, BF_{10}=1.10; IF transition: n=14, BF_{01}=.91, BF_{10}=1.10; IF variance: n=14, BF_{01}=.67, BF_{10}=1.49). This indicates a lack of evidence to support either the absence or the presence of significant group differences in functionality indexes when participant have to perform stand-alone counting-like finger movement.

In the finger-counting task, overall, the data were more likely to be observed under the null hypothesis (H_0) compared to 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 time more likely considering the absence of group difference compared to 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 H_1 or H_0 hypothesis with regards to finger movement transition speed and regularity.

Finally, in the Nth-After task, the data provide moderate evidence for the null (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 3 to 7 times more likely under a model with no difference between groups compared to 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 (Nth After).

4. 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 Nth-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 typically developing children. Contrasting with the Nth-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 to the control group, children with DCD were less accurate in the Nth-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, as 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 while manual dexterity did not. Indeed, the Nth-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 child had (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 typically developing 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 Nth-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 almost three times more frequent in children with DCD. They could be related to their weaknesses in WM, an impairment which 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 (Dupont-boime & Thevenot, 2018) showed that 6-year-olds 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 the implementation of FC as a relevant strategy to solve additions would require high level 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 have 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 N^{th}-After task is a dual task situation which not only requires the coordination of recitation and finger movements but also 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 intructions.

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 were anecdotical 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 difference on a significant number of parameters. When FC movements had 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 N^{th}-after task which 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 quite marginal compared to the number of other errors, *n*=11 vs 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 the 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 present results highlights a similar impact of working memory load on execution speed and finger/voice synchronization in children with DCD compared their typically developing peer, at least in the context of the present 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 are 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, high) to examine the developmental trajectory of FC automatization (as attested by lower dual task effect on FC functionality) in children with DCD compared to typically developing children.

To sum up, the present study failed to find functional limitation of FC gestures 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 smaller effect size. The future investigations could contrast FC/ no-FC conditions in arithmetical tasks with various WM load to examine the extent to which FC offers tangible help for these children. Such a comparison would provide insightful evidence for the interplay between 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 present findings are specific to DCD, or whether they would be the consequence of some of the comorbidities in the present 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; P. Wilson et al., 2020) or of mathematical learning disabilities (Pieters, Desoete, Van Waelvelde, et al., 2012), two conditions themselves frequently associated with a WM deficit (De Smedt et al., 2013; Mazzocco et al., 2011). A such, a straight comparison of children with mathematical learning disability in a task similar to the Nth-After task would be particularly interesting as they were found so far 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 present study. Interestingly, the limited number of FC errors were made exclusively by three 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 present 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.

In conclusion, the current findings show that children with DCD are less accurate than typically developing children in a FC task that puts heavy demands on WM. The present results suggest that these difficulties could be more closely related to a limitation of WM resources rather than to dysfunctional FC gestures. 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. 3D motion analysis opens up many new perspectives on understanding the issues relating to embodied numerical cognition. In particular, this technique should make it possible to focus on the functionality of the gestures involved in numerical and arithmetical 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, stacking cubes; for reviews see Barrocas et al., 2020; Neveu et al., 2023). From a functionalist point of view, future works should take a closer focus on fine motor skills, which are more proximal to those used in numerical contexts, in order to gain a better understand their involvement in typical and atypical numerical and arithmetic development.

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