Contribution of finger gnosia and fine motor skills to early numerical and arithmetic abilities: New insights from 3D motion analyses

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Declaration of interest statement

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Abstract:

Finger gnosia and fine motor skills (FMS) are assumed to play a key role in the development of arithmetic abilities, but their contribution to early numerical skills (i.e., enumeration skills and cardinality) has received little attention so far. The purpose of this study was to investigate the predictive value of finger gnosia and FMS to enumeration, cardinal, and arithmetical abilities and how these different dimensions contribute to arithmetic development. Three- to five-year-old preschoolers were asked to perform tasks assessing enumeration, cardinality, and early arithmetic, as well as finger gnosia and FMS. FMS, involving either static or dynamic fine finger movement, were examined using a 3D motion analyses. Using hierarchical regression, FMS were found to be the best predictor of both cardinality and early arithmetic skills, while finger gnosia did not predict the additional variance of arithmetic performance when FMS and age were considered in the regression model. Moreover, neither finger gnosia nor FMS were significant predictors of enumeration. Mediation analyses indicated that knowledge of the cardinal principle fully mediates the relationship between FMS and arithmetic skills, suggesting that FMS contribute to cardinal principle knowledge development, which would be a gateway to more complex arithmetical processing.

Public significance statement:

This study suggests that fine motor skills contribute to the development of cardinality, which would be a gateway to more complex arithmetic processing.

Keywords:

Early numerical skills, cardinality, enumeration, arithmetic, finger gnosia, fine motor skills, 3D motion analyses.

1. Introduction

The preschool and early school years constitute a critical period for children's academic development. In mathematics, early numerical skills learned in this developmental window play a key role in predicting children's later mathematics outcomes (Jordan et al., 2009; Nguyen et al., 2016; Watts et al., 2014), even going so far as to predict their enrolment in higher education (Davis-Kean et al., 2022). Over the past 15 years, there has been increasing interest in the cognitive factors underlying the development of numerical skills.

Early numerical skills gradually develop throughout childhood. Between the age of two and four, children begin to recite the sequence of number words by rote (Fuson et al., 1982; Wynn, 1992) and learn to determine the exact number of objects in a set, establishing a one-to-one correspondence between number words and items to be counted (Gelman & Gallistel, 1978). During preschool years, counting skills improve to achieve increasing flexibility in the recitation of the verbal number sequence as well as a more in-depth understanding of the cardinal meaning of number words. Commonly assessed using the 'Give-a-Number' task (i.e., children asked to give a puppet a specific number of objects; Wynn, 1990, 1992), the acquisition of the cardinal meaning of number words is a long process (i.e., lasting more than a year) during which children move, for one number at a time, through different number-knowledge levels (Le Corre et al., 2006; Le Corre & Carey, 2007; Rousselle & Vossius, 2021; Sarnecka & Gelman, 2004; Wynn, 1990, 1992).

In their developmental model, Krajewski and Schneider (2009) identify recitation, enumeration skills, and cardinal principle knowledge as precursors to the development of arithmetic skills. In this respect, some recent studies have investigated how their acquisition by preschoolers can predict later arithmetic skills. Longitudinal investigations provide evidence that advanced counting (i.e., conceptual elaboration of the verbal number sequence) at age five is a strong predictor of arithmetic skills two years later (Lê & Noël, 2021). Likewise, enumeration abilities (i.e., subitizing and/or counting in dot enumeration tasks) assessed at age five were found to predict fluency in addition tasks five to seven years later (Bartelet et al., 2014; Major et al., 2017). Cardinal principle knowledge (i.e., 'Give-a-Number' task) also appeared to be a strong predictor of arithmetic development since it has been shown that children's understanding of the cardinal value of number words at age four predicts performance in addition four months later (Scalise & Ramani, 2021) as well as the sophistication of arithmetic solving strategies three years later (Chu et al., 2018). Taken together, this evidence suggests that enumeration skills and cardinal principle knowledge play a key role for later arithmetic development.

A growing body of research suggests that the development of mathematical concepts is deeply rooted in children's sensorimotor experiences, a hypothesis that fits into the broader theory of embodied cognition. In the context of mathematical development, this theoretical framework posits that numerical symbols and concepts become meaningful when embedded in bodily experiences (Barsalou, 2008; Moeller et al., 2012; see Andres & Pessenti, 2015, for a review). In this respect, fingers have a privileged status for the development of numerical concepts. They provide an embodied representation of different core numerical properties (cardinality, ordinality, one-to-one correspondence, abstraction; Crollen et al., 2011) which support the internalization of abstract concepts through the multimodal (visual, motor, and proprioceptive) association between numbers and fingers (Butterworth, 1999; Fuson et al., 1982; Lakoff & Nunez, 2000). Concrete and always available, they are the ideal tool for young children to begin learning numbers.

During class activities, preschoolers often use their fingers to solve various types of numerical problems (Gordon et al., 2019; Noël, 2005; Reeve & Humberstone, 2011). As an extension of the developmental model of Krajewski and Schneider (2009), Roesch and Moeller (2015) have clarified how fingers presumably contribute to early numerical and arithmetical acquisitions. Specifically, they assumed that fingers not only help children to visualize and combine quantities in solving arithmetic problems, but also support early numerical development including the acquisition of the verbal number sequence, counting skills, and cardinal concepts. Consistent with their proposal, fingers proved to be a very effective tool in solving problems from the age of five (Baroody, 1987; Dupont-Boime & Thevenot, 2018; Jordan et al., 2008), laying ground for the development of finger-based solving strategies. Furthermore, combining *finger-counting* that provides ordinal finger-based numerical representations (i.e., raising and counting fingers one at a time) with *cardinal number gestures* that provide a cardinal finger-based numerical representation (i.e., using a finger pattern to represent the cardinal of a set)[1] turned out to be more effective than strategies involving finger-counting only (Björklund et al., 2019). Critically, what makes the fingers a powerful tool when solving arithmetic tasks in the early years would depend on children's ability to recognize the meaning of cardinal number gestures, as well as on their knowledge of the part-whole relationships between numbers that are intrinsically embedded in fingers (Kullberg & Björklund, 2020).

While the role of fingers in the development of arithmetic in preschoolers is quite clear, little is known about their possible role in the acquisition of cardinal concepts. As cardinal number gestures provide an iconic representation of numbers (i.e., each raised finger can be mapped to an item of the set), some authors suggest that four-year-old children learn the cardinal meaning of number gestures earlier than number words (Gibson et al., 2019; Gunderson et al., 2015). In a randomized controlled trial, training cardinal principle knowledge through counting and labelling activities in

[1] Also known as finger-montring when cardinal number gestures are used to show numerosities *to other people* using fingers (Crollen et al., 2011; Di Luca & Pesenti, 2008; Fischer et al., 2022).

three-year-old children was found to be more effective when enriched with cardinal number gestures (Orrantia et al., 2022). Conversely, other authors have claimed that children between the ages of two and five are not sensitive to the iconicity of cardinal number gestures (Nicoladis et al., 2018) and consider that this medium provided no advantage in the acquisition of cardinal concepts (Nicoladis et al., 2010). Thus, for now, the contribution of fingers to cardinal understanding is still a matter of debate.

Recent investigations have been conducted to determine which sensorimotor finger skills promote early numerical processing development to gain further insight into the mechanism involved. To date, the sensorimotor finger skills identified as related to numerical development fall into two different categories. The first to be identified is finger gnosia, which refers to the representation of finger positions on one's own hand (Noël, 2005; Strauss & Werner, 1938). This component, usually assessed through tactile stimulation, was found to predict numerical system development (i.e., transcoding, ordinality, and place value in six-year-olds; Penner-Wilger et al., 2007) and arithmetic development in typically developing children between five to twelve years (Newman, 2016; Noël, 2005; Wasner et al., 2016) as well as in children with mathematical learning disabilities (Costa et al., 2011). More recently, the motor component, captured in tasks assessing fine motor skills (i.e., the ability to move fingers differentially) has attracted attention. Fine motor skills (FMS) were found to be directly (Fischer et al., 2022; Gashaj et al., 2019; Penner-Wilger et al., 2007) and indirectly related to number processing through ordinal and cardinal finger-based numerical representations (respectively, finger-counting (Fischer et al., 2018, 2020, 2022; Suggate et al., 2017) and cardinal number gestures (Fischer et al., 2020; Suggate et al., 2017)). A positive influence of FMS training on finger gnosia and arithmetic skills has also been demonstrated in six-year-old children (Asakawa et al., 2019; Gracia-Bafalluy & Noël, 2008; but see Schild et al., 2020, for conflicting results) clarifying the causal mechanisms underpinning this relationship.

In short, a number of publications suggest that finger gnosia and FMS somehow contribute to numerical and arithmetic development. These associations make sense in the functionalist hypothesis, which assumes that sensorimotor finger skills support the development of ordinal (i.e., finger-counting) and cardinal (i.e., cardinal number gesture) finger-based numerical representations, which in turn promote the development of verbal cardinal knowledge and arithmetic processing (Brissiaud, 2005; Butterworth, 1999). Under this assumption, some specific dimension of sensorimotor finger skills should be more determinant to the development of finger-based numerical representation and, by extension, to development of counting, cardinality, and arithmetic. However, the nature of these specific dimensions remains unclear. The vast majority of tasks used to assess FMS in children and adolescents involve object manipulation (e.g., pegboard, threading beads, posting coins, etc.) or drawing (e.g., figure copying), resulting in tasks that are often multi-determined, requiring not only FMS but also visual-spatial or grapho-motor abilities (see Neveu et al., 2023, and Barrocas et al., 2020, for a discussion about the tasks). In this respect, Barrocas et al. (2020) stressed the importance of isolating FMS from visual components to better understand their involvement in numerical development. Only two studies have been conducted in this direction, using finger tapping tasks (Fischer et al., 2022; Penner-Wilger et al., 2007) that have the advantage of involving only selective finger movement (i.e., no visual-spatial or grapho-motor abilities) but with limited demand in terms of fine motor precision. In its current state, such a task remains insufficient to specifically identify the FMS components that bring added value to the understanding of numerical concepts.

The purpose of the present study is to go one step further to understand the relationship between sensorimotor finger skills (i.e., finger gnosia and FMS) and early numerical abilities (i.e., enumeration, cardinal principle knowledge, and arithmetic skills), focusing on FMS that are closely related to the motor processes involved in ordinal (i.e., finger counting) and cardinal (i.e., number gestures) finger-based representations in typically developing young children. Two main categories of FMS were thus considered here: (1) the *static FMS* that enable the positioning of fingers in space to adopt finger configurations (i.e., a key component of cardinal finger gestures), and (2) the *dynamic FMS* that allow the sequential coordination of individual finger movements (i.e., a key component of finger-counting). To overcome the limit of paper-and-pencil measures that provide only dichotomous outcomes (i.e., correct or incorrect positioning), FMS were examined using a three-dimensional (3D) motion technique to provide fine-grained continuous measurement of finger movement quality. 3D motion analysis is a non-invasive method of tracking human movements and is used to measure the position and movement velocities of specific body segments.

The present study addresses two main issues in relation to the functionalist hypothesis: (1) the predictive value of sensorimotor finger skills in enumeration, cardinal, and arithmetical abilities and (2) the mediating role of early numerical skills (enumeration and cardinality) in the possible relation between sensorimotor finger skills and arithmetical development. With regard to the first issue and in line with previous findings (e.g., Noël, 2005; Penner-Wilger et al., 2007), finger gnosia was expected to predict arithmetic skills but its possible contribution cardinal principle knowledge has, to our knowledge, not been examined so far. As findings regarding the contribution of finger gnosia to enumeration skills are contradictory (Long et al., 2016; Malone et al., 2020), no expectation has been advanced here. Moreover, considering their essential role for cardinal and ordinal finger-based solving strategies involved in early arithmetic, *static* and *dynamic FMS* should be significant predictors of arithmetic skills. In addition, as a key component of cardinal number gestures, static FMS specifically were expected to predict verbal cardinal knowledge. By contrast, enumeration skills involve either subitizing for small numerosities or single finger pointing in counting routines for numerosities larger than three. As these processes involve no (complex) finger movement, they have little to do with the finger gnosia and motor processes involved in finger-counting and cardinal finger gestures. As such, *static* or *dynamic FMS* and finger gnosia were not expected to predict enumeration abilities, as assessed in the current experiment. With regard to the second issue, depending on the results of the first set of analysis, the predictive relationship between sensorimotor finger skills and arithmetic will be further explored through mediation analysis to determine whether early numerical abilities could act as mediators in this relationship.

2. Methods

2.1. Participants

Thirty-four typically developing French-speaking three- to five-year-old preschoolers (M=51.9±7.7 months, range=39-63 months, 16 girls) participated in the experiment. Parents were asked to complete an anamnestic questionnaire about their children. They reported no history of learning disabilities, or neurological, developmental, or psychiatric disorders. Socio-economic status of the families, collected with the International Standard Classification of Occupation (ISCO-08; International Labour Organization [ILO], 2008), was predominantly high, with 63.7% of parents reporting working as managers or in an intellectual profession, 33.3% as employees or technicians, and 3% in the agricultural sector.

The research was approved by the local ethics committee. The parents of participants gave written informed consent. Each child was informed of the research and consented to participate.

2.2. Tasks

2.2.1. Early mathematical skills

Four tasks were used to assess early mathematical skills.

Verbal number sequence. Knowledge of the verbal number sequence was assessed in a recitation task in which the child was asked to count aloud as far as possible (until maximum 20). If necessary, the experimenter could initiate the sequence to prompt recitation (one, two…). The task was performed twice to identify the stable and the conventional part of the verbal number sequence defined as the longest part the child could recite correctly twice (Fuson et al., 1982). Participants were requested to solve the task to ensure that their ability to process the cardinal task was not limited by their knowledge of the verbal number sequence.

Enumeration. To assess enumeration skills, children were shown pictures with sets of randomly arranged black dots on a grey background. The child was asked to say *how many dots were present in all of the picture.* If the child gave an incorrect answer without having counted verbally, they were explicitly asked to count and to say how many dots were present. The stimuli consisted of sets of one to eight dots for a total of eight trials (i.e., three numerosities in the subitizing range and five numerosities in the counting range). The items were presented in a pseudo-random order, with consecutive numbers never presented in succession. One point was given for each correct cardinal response (maximum score=8) but the trial was scored 0 if the child recounted or gave an incorrect cardinal response.

Give-a-Number. Cardinal principle knowledge was assessed using the *Give-a-Number* task (Give-N task) (Le Corre & Carey, 2007; Wynn, 1990). A set of fifteen penguin figurines was presented to the child who was asked to place *n* penguins on a cardboard ice floe placed in front of him. The numerosity of the set was given verbally. If the child placed the correct number of penguins on the cardboard, one point was given and a set of *n*+1 was requested on the next trial. In case of failure, no point was given and a set of *n*-1 figurines was requested on the next trial. When the child used counting to determine the numerosity of the set, one counting imprecision error was accepted and a response of *n*±1 was considered as correct. Unlike Wynn (1990), who limited the task to number words up to six, children could be asked to give up to ten items to get a broader view of how they generalize cardinal knowledge to large number words. The task was stopped when the child succeeded twice for the numerosity *n* and failed twice for the numerosity *n*+1. The highest numerosity was considered as the child's cardinal knowledge level (maximum score=10).

Early arithmetic. Early arithmetical skills were examined using the pictorial additive fluency task adapted from Noël (2009). Children were asked to solve as many word problems as possible (e.g., *"In this cage, there are two birds. If another bird enters in the cage, how many will there be in total?"*) in a limited time (150 seconds). For each item, children were presented with a picture of the first operand. Tokens were provided as concrete support to solve the problem, if needed. Items consisted of ten single-digit additions of increasing difficulty (i.e.,1+1, 2+2, 2+1, 3+3, 3+2, 4+3, 4+4, 5+5, 5+4, 6+5). Half of them were doubles, the last one involved a carry. One point was given for each correct answer (maximum score=10). When all problems were solved within the time limit, one bonus point was given for each interval of five seconds saved.

2.2.2. Sensorimotor finger skills

Finger gnosia were assessed using behavioural measures while static and dynamic FMS were assessed using behavioural measures supplemented by 3D motion analysis, which provides fine-grained measurement of FMS.

Finger gnosia. Finger gnosia were tested in a task adapted from Noël (2005). The child was asked to put one hand, palm down, flat on the table with fingers spread out. The hand was occluded with a cardboard screen and, out of the child's view, the experimenter touched the middle phalanx of a single finger. Then, the cardboard was removed and the child was asked to indicate, with the other hand, the finger that had been touched. Five trials were administered for each hand (i.e., each of the fingers was touched once) starting with the child's preferred hand. One point was given for each correct response (maximum score=10).

Static FMS. To investigate the static FMS, the child was asked to reproduce, with their preferred hand, finger configurations shown by the experimenter. Each finger pattern had to be held for at least four seconds to record the position. Of the ten trials administered, six depicted numerical finger configurations (i.e., fingers placed in a standard position to represent numbers; e.g., thumb, index, and middle finger raised up, Figure 1) while the remaining four presented non numerical finger configurations (e.g., touch the thumb with the index while raising the middle, ring, and little fingers, Figure 1). One point was given for each finger configuration correctly reproduced (maximum score=10).

Dynamic FMS. To assess dynamic FMS, the child had to reproduce, with their dominant hand, an ordered sequence of finger movements shown by the experimenter. Before each trial, a blank test was conducted to ensure that the equipment did not interfere with the gesture. Three trials were conducted (Figure 1): (1) raising fingers one at a time, following finger anatomical position starting with the thumb, then index, middle, ring, and finally the little finger, (2) tapping each finger, one at a time, on the table in the order of finger anatomical position starting with the thumb, (3) joining the thumb with each other finger of the hand, one at a time, starting with the index, then the middle, ring, and finally the little finger. To be credited as correct, a sequence must be executed in the correct order. One point was given for each ordered sequence of finger movements correctly reproduced (maximum score=3).

[Figure 1]

2.3. 3D motion acquisitions and processing

Data acquisition. Four units of a Codamotion 3D optoelectronic system (Charnwood Dynamics Ltd, UK) were used to localize, with millimeter accuracy (Schwartz et al., 2015), twelve 3D markers placed on the child's dominant hand (i.e., one on the proximal and distal phalanx of each finger and one on the distal parts of the first and fifth metacarpals). Acquisitions were performed at a frequency of 200 Hz.

Data processing. Static and dynamic FMS indexes, reflecting the child's fine motor development, were calculated. To determine the static FMS index, a 3D reference hand was first estimated from acquisitions conducted with 21 typically developing children in primary school (M=10.79±0.59 years, 13 girls) for the static FMS task. The 3D reference hand was constructed through a three-step superimposition procedure (Figure 2) (Decker et al., 2007). First, all similar 3D finger configurations were superimposed by a translation of their barycentre. Then, the sizes of the children's 3D finger configurations were standardized so that they could be compared. The standardization was performed thanks to an estimation of the hand size using the following equation:

$$Hand\ size = \frac{1}{N}\sum_{i}^{N}\|barycentre - M_i\|$$

Barycentre: 3D position of the barycentre markers placed on the hand
N: population size
M_i: 3D position of the i^{th} marker

Finally, a 3D rotation was performed for each 3D finger configuration using a robust iterative closest point procedure (Cresson et al. 2005; Schwartz, 2009). The reference hand was finally defined as the average position of all superimposed hands. A static FMS index was calculated, for each child, as the average distance of each marker placed on their hand and its counterpart on the reference hand. Accordingly, a smaller index indicated a closer distance to the reference hand, with an index of 0 representing a perfect match between the hand configuration and the reference hand.

[Figure 2]

For each participant, the time intervals between consecutive final finger positions were calculated (e.g., time intervals between consecutive finger/thumb contacts) to determine a dynamic FMS index. By taking into account the order of finger movements in the motor sequence, the possible inversions of fingers during the task were automatically penalized. To report motion regularity, the dynamic FMS index was evaluated for each trial using the following equation:

$$Dynamic\ FMS\ index_{trial} = \left(1 - \frac{t_{max} - t_{min}}{t_{total}}\right) \times\ 100$$

t_{max}: largest time interval between two final finger positions.
t_{min}: smallest time interval between final finger positions
t_{total}: total execution time

Finally, the dynamic FMS index was calculated as the average of the three indexes obtained from the three trials. Higher indexes reflected gestures performed with greater regularity.

2.4. Procedure

The entire protocol required two 30-minute sessions. The first individual session took place at home or school and was dedicated to the assessment of finger gnosia and early numerical abilities. The order of tasks was counterbalanced across participants. At the end of the first session, the experimenter presented the 3D device to the child and placed demonstration markers on their fingers to familiarize them with the materials.

The second 30-minute session was conducted in the motion laboratory of the local university to assess the precision of static and dynamic FMS. After a time of acclimation to the environment, markers were placed on the participant’s preferred hand. The experimenter ensured that all children felt comfortable with the equipment before beginning the session. He stopped whenever the child expressed discomfort. Static and dynamic FMS tasks were administered in a counterbalanced random order, separated by a few minutes’ break.

2.5. Analyses

Results were analysed in two stages using SPSS Statistics software (version 28.0; IBM Corp., 2020). The predictive value of sensorimotor finger skills on early numerical and arithmetical abilities was first examined using partial correlations followed by hierarchical multiple regressions. The chronological age was systematically considered as a covariate. Only the variables significantly correlated with early numerical abilities were selected for regression analyses. As biomecanical data from 3D motion analyses were less subject to observation and interpretation biases and provide more sensitive measure of gesture quality than behavioral measure (i.e., wider score distribution), only biomechanical data were considered for regression. Hierarchical multiple regression analyses were conducted to identify the significant predictors of early numerical abilities. In addition to regression analyses, bias-corrected bootstrap mediation analyses (Preacher & Hayes, 2008) were conducted to examine the pathways underpinning the relationships between sensorimotor skills and early numerical abilities. Analyses were carried out with 5,000 bootstrap samples and 95% confidence intervals (CI). To be included in the mediation analyses, variables investigated had to be reciprocally significant predictors. Effect size magnitudes were described throughout the results section based on Cohen's benchmarks (1988). Correlations (r) of .10, .30, and .50 were considered as small, moderate, and strong, respectively.

3. Results

3.1. Descriptive analyses

Table 1 reports descriptive statistics for sensorimotor, numerical, and arithmetic skills, as well as the distribution of children as a function of their cardinal knowledge level and descriptive information about age, academic level, and possible limitations resulting from their verbal sequence knowledge. The enumeration and static FMS tasks showed high internal consistency (Cronbach alpha=.83 and .85, respectively) while this was low for the finger gnosia task (Cronbach alpha=.46). The proportion of small ‘subset-knowers’ (47%) was quite similar to that of large ‘subset-knowers’ (53%) for the age range considered here. Only 8/34 children reached the highest numerosity (within the limits of this experimental design) and could be considered as cardinal-principle-knowers. A large majority (91.2%) of the children were able to recite the verbal number sequence beyond the limit of their cardinal principle knowledge as assessed in the Give-N task, suggesting that they are not limited in their knowledge of the verbal routine to solve the cardinal task.

[Table 1]

3.2. Correlations and hierarchical multiple regressions

Table 2 reports the Pearson’s correlations between chronological age, early mathematical skills, and sensorimotor finger skills. Early mathematical skills and sensorimotor finger skills correlated significantly with chronological age. Partial correlation controlling for age indicated a moderate to strong significant correlation between static and dynamic FMS indexes and cardinal principle knowledge as well as between finger gnosia and arithmetic skills. However, no significant partial correlation was found between finger gnosia and cardinal principle knowledge, nor between sensorimotor finger skills and enumeration.

[Table 2]

The correlations between static and dynamic FMS indexes and scores were strong, reflecting the convergent validity of biomechanical measurements from 3D motion analyses. No significant correlation was found between finger gnosia and the static and dynamic FMS scores and indexes.

In contrast, the correlation between static and dynamic FMS indexes was strong (r=−.74) even after controlling for chronological age (r=−.57), suggesting that the two measures might not be independent. In preliminary analyses, some evidence of multi-collinearity emerged (i.e., tolerance and Variance Inflation Factor (VIF) scores of 0.3 and 2.6, respectively) likely attributable to this strong correlation, suggesting that these two variables may reflect different measures of the same construct. According to Allison (1999), the presence of multi-collinearity is confirmed when the VIF score is over 2.5 and the tolerance score is below 0.4. In this case, a cautious attitude has been favoured to ensure that the following models were free from multi-collinearity. Therefore, a composite FMS index (cFMS index) was extracted from static and dynamic FMS indexes by applying a principal component analysis (PCA). Results of the PCA confirmed that static and dynamic FMS indexes reflected a single construct, accounting for 87% of the total variance across FMS indexes. A similar amount of variance (.54) was extracted from each of the two indexes. Partial correlation controlling for age showed a significant association between the cFMS index and cardinal principle knowledge (r=.61, p<.001; strong association) and arithmetic skills (r=.48, p=.005; moderate association). In contrast, the cFMS index did not correlate significantly with finger gnosia (r=.17, p=.34) nor with enumeration skills (r=.27, p=.14).

Two hierarchical multiple regressions (Table 3) were conducted to examine the predictive value of sensorimotor finger skills on cardinal principle knowledge and arithmetic skills respectively, beyond the influence of age. Chronological age was entered in stage 1 while finger gnosia and the cFMS index were entered additionally in stage 2. Regarding cardinal principle knowledge development, the complete model explained 63% of the variance. Chronological age explained 40% of the total variance (F(1,32)=21.50, p<.001) while finger gnosia and cFMS index entered in the second stage explained an additional 23% of variance ($F(2,30)=9.09$, $p<.001$). Only the cFMS index came out as a significant individual predictor of cardinal principle knowledge ($p<.001$).

For arithmetic skills, the complete model explained 56% of the variance. Both finger gnosia ($p=.04$) and the cFMS index ($p=.01$) came out as significant predictors of early arithmetic skills. Chronological age explained 34% of the total variance ($F(1,32)=16.13$, $p<.001$) while finger gnosia and cFMS index accounted for an additional 22% of total variance ($F(2,30)=7.54$, $p=.002$). Interestingly, with the stepwise method in stage 2, finger gnosia no longer came out as a significant predictor ($p=.09$). The complete model explained 49% of the total variance. Chronological age explained 39% of variance ($F(1,32)=19.13$, $p<.001$) while cFMS index accounted for an additional 10% of the total variance ($F(2,31)=13.8$, $p<.001$).

[Table 3]

3.3. Mediation analyses

With regard to the second issue, these relationships were further explored using mediation analysis, controlling for chronological age, to examine whether the influence of FMS on arithmetic could be mediated by cardinal principle knowledge development. From a functionalist point of view, the FMS targeted here might support cardinal principle knowledge (through cardinal finger gestures) which could then be a mediator in the relationship between FMS skills and arithmetic. As shown in Figure 3, the relationships between the cFMS index and cardinal principle knowledge (path [a], $\beta=.63$, $p\leq.001$), between cardinal principle knowledge and arithmetic (path [b], $\beta=.61$, $p=.002$) and between the cFMS index and arithmetic (path [c], $\beta=.52$, $p=.01$) were all significant prior to the addition of the mediator. Adding cardinal principle knowledge as a mediator of the relationship between the cFMS index and arithmetic made it no longer significant (path [c'], $\beta=.14$, $p=.48$). The bias-corrected bootstrap CI for indirect path (path [ab]) was entirely above zero (95%, [.41 to 1.79]) confirming that cardinal principle knowledge fully mediated the relationship between the cFMS index and arithmetic, after controlling for chronological age.

4. Discussion

The aim of the present study was to investigate the relationship between sensorimotor finger skills and early mathematical abilities in typically developing young children. To this end, we explored the predictive value of finger gnosia, static and dynamic FMS in enumeration, cardinal principle knowledge, and early arithmetic. Although static and dynamic FMS had to be merged into a single composite index, results showed that both FMS and finger gnosia significantly predicted performance in a simple addition task with pictorial support, but FMS turned out to be a better predictor of early arithmetic skills in this task than finger gnosia. Moreover, FMS were a unique predictor of cardinal principle knowledge, and neither FMS nor finger gnosia were significant predictors of enumeration skills. Finally, mediation analyses showed that cardinal principle knowledge fully mediates the relationship between FMS and arithmetic.

The first objective of this study was to examine the specific contribution of FMS involved in finger-based numerical representations to early numerical and arithmetic skills. Accordingly, specific predictions were made about the possible relationship between static or dynamic FMS and enumeration, cardinal, or arithmetic tasks. Yet, static and dynamic FMS assessed in the current study could not be distinguished in the analyses due to the multi-collinearity between the two predictors. This lack of independence suggests that they refer to very similar motor processes and that the variance related to each variable could not be reliably discriminated. Thus, the present study provided no evidence that static and dynamic FMS tasks measure different constructs in their current state.

A second objective was to assess the predictive relationship between sensorimotor finger skills and arithmetic. Both finger gnosia and cFMS index came out as significant predictors, a result in agreement with previous evidence supporting the relationship between arithmetic skills and finger gnosia (Fischer et al., 2022; Newman, 2016; Noël, 2005; Reeve & Humberstone, 2011; Wasner et al., 2016) or FMS (Asakawa et al., 2019; Gracia-Bafalluy & Noël, 2008) in school-aged children (for a review, see Neveu et al., 2023). However, FMS were found to be the best predictor of early additive skills, and finger gnosia did not account for any additional variance after FMS had been selected in the model. One possible explanation would be to consider that finger gnosia is a pre-requisite to fine finger movements related to finger-based arithmetic solving strategies (i.e., finger-counting and cardinal finger gestures). To be able to move fingers in coordinate sequence (i.e., dynamic FMS, as requested in finger-counting) or to put one's fingers in a particular configuration (i.e., static FMS, as involved in cardinal finger gestures), the child should have a clear and integrated representation of the fingers on their own hand, that is, good finger gnosia. Finger gnosia would no longer be a significant predictor once FMS were taken into account in the stepwise regression model because FMS would have captured a larger part of the shared variance. However, this interpretation seems unlikely as no significant correlation was found between finger gnosia and FMS indexes when age was controlled for. As another explanation, the task used to assess finger gnosia presents limited reliability, suggesting internal consistency problems between items. This might explain the lack of sensitivity of this measure, a problem that has already been reported in other studies that reported a comparable Cronbach alpha (e.g., Cronbach alpha=.55 in Wasner et al., 2016; see Wasner et al., 2016, and Barrocas et al., 2020, for a discussion). Although this is a classic measure, future investigation should examine a more reliable measure of finger gnosia.

A third objective was to examine the predictive relationship between sensorimotor finger skills and verbal cardinal knowledge development. Overall, the composite FMS index came out as a unique and strong predictor of cardinal principle knowledge in young children. By contrast, neither finger gnosia nor FMS predicted enumeration abilities, which put no or less emphasis on complex finger movement. In the debate between authors who claim that fingers support the development of cardinal principle knowledge (Gibson et al., 2019; Gunderson et al., 2015) and those who argue that cardinal finger gestures provide no advantage in the acquisition of cardinal concepts (Nicoladis et al., 2010), these results add to existing evidence highlighting the *specific* contribution of FMS to cardinal principle knowledge. Recently, it has been shown that training verbal cardinal principle knowledge would be more effective when enriched with cardinal finger patterns (Orrantia et al., 2022). In line with these findings, the current results suggest that fingers would be a gateway to access the cardinal meaning of verbal number words (Di Luca & Pesenti, 2008; Krinzinger, 2011). When congruent with counting habits, fingers provide an iconic representation of numerosity that could be recognized as a whole, halfway between symbolic and non-symbolic representations of number magnitude, bridging the gap between them (Andres et al., 2008; Di Luca & Pesenti, 2008, 2011; Gunderson et al., 2015; Krinzinger, 2011). Their dual symbolic and non-symbolic status would support the threefold relationship between cardinal finger gestures, the numerosity conveyed by fingers, and the concomitant uttered number-word (Gibson et al., 2019; Gunderson et al., 2015). Altogether, this evidence strengthens the functionalist hypothesis, which assumes that FMS could support the development of ordinal and cardinal numerical representation, presumably through their contribution to finger-based numerical representations.

Interestingly, mediation analyses conducted here indicate that cardinal principle knowledge mediates the relationship between FMS and arithmetic skills, suggesting that FMS indirectly contribute to early arithmetic skills through cardinal principle knowledge. This finding provides new insights into the functional mechanisms by which FMS promote arithmetic development in young children. In previous work, Pitchford et al. (2016) showed that FMS were related to arithmetic performance in five to six-year-olds in the first year of primary school, but not in four to five-year-olds in the foundation year, suggesting that FMS would only support children's numerical development once they were able to use finger-based solving strategies to calculate. The present results not only suggest that such a relationship exists in young children as young as three to five but also that it is mediated by the contribution of fingers to the acquisition of the cardinal concepts. Thus, FMS would give the child access to understanding the meaning of number words, which lay the foundation for arithmetic skills. The present results are consistent with models depicting how finger-use promotes the formation of cardinal concepts, themselves being a preliminary step to early arithmetic skills (Krajewski & Schneider, 2009; Roesch & Moeller, 2015).

Future investigations should confirm these results by enlarging the sample size, which was limited here, and should be conducted with finger gnosia and FMS tasks of equivalent sensitivity to better understand the triadic relationship between finger gnosia, FMS, and early numerical and arithmetic skills. Furthermore, while thinking about more reliable measures of finger gnosia, it would be interesting to shed light on the nature of the perceptual processes involved in finger gnosia that are useful to numerical processing development. Finger gnosia are assessed through tactile input on the finger skin, yet their contribution to numerical processing could be more proprioceptive than tactile in nature. As a cognitive pre-requisite of finger gestures (Hay et al., 2005), finger proprioceptive representation might provide a more intuitive account of how perceptual components contribute to numerical processing. In future work, specific attention should be paid to the distinction between tactile and proprioceptive representation in order to clarify which of these two perceptual components predicts children's arithmetic development. Moreover, given the relationship between FMS and early numerical skills, implementing FMS training would be useful to examine the causal relationship between FMS and early numerical skill development in preschool-aged children. Previous investigations have found an improvement of arithmetic skills after FMS training in primary school children (Asakawa et al., 2019; Gracia-Bafalluy & Noël, 2008). Similarly, a randomized controlled trial could be conducted to test whether FMS training could improve preschoolers' cardinal principle knowledge and transfer, through cascading effects, to more mature numerical abilities such as early arithmetic skills.

To sum up, this research is the first to use a 3D motion analyses to provide new evidence for the contribution of FMS to numerical and arithmetic skills in young children. Using an innovative fine-motion recording technique, the present work provided fine-grained biomechanical data on finger movements. For future investigations, this 3D motion analyses could be fine-tuned to assess the quality of fine finger gestures in several situations as a function of the task goal (i.e., finger placement on pegboard rods, finger lift amplitude in tapping tasks, etc.). The recording system could also be synchronized with a voice recording device to assess the synchronization of finger movements and verbal production such as finger counting, for instance. Unlike behavioral measures which are often limited to dichotomous measures (i.e., correct or incorrect execution of the gesture), 3D motion analyses provide the advantage of reporting the performance on a continuum so as to account for the entire spectrum of possible performances, thus improving the sensitivity of the measures. On the other hand, as the measurement tool is a stationary system, measurements can only be done within a laboratory, which makes the tool unsuitable for large-scale field assessments. In this study, these first findings are promising and open new avenues for future work.

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Table 1

Descriptive statistics of early mathematic and sensorimotor finger skills and the distribution of children as a function of their cardinal principle knowledge level.

	Mean score (SD)	Range	
		Min.	Max.
Sensorimotor finger skills			
Finger gnosia	8.3 (1.4)	4	10
Static FMS task score	7.3 (2.4)	2	10
Static FMS index	0.3 (0.1)	0.2	0.5
Dynamic FMS task score	1.67 (1.1)	0	3
Dynamic FMS index	44.2 (34.1)	−20.2	94.6
Composite FMS index	0.0 (1)	−2.1	1.3
Early mathematical skills			
Verbal number sequence	11.5 (6.6)	0	20
Enumeration	5.5 (2.1)	0	8
Give-a-Number	5.1 (3.4)	2	10
Early arithmetic	3.1 (2.4)	0	9

Cardinal principle knowledge level	n	Mean age [a] (SD)	Range		Preschool level [b]		Verbal number sequence > GaN [c]
			Min	Max	1	2	
Small SS-knowers	16	47.2 (7.2)	39	59	13	3	14 (87.5%)
One	0	-	-	-	-	-	-
Two	14	46.8 (6.4)	39	59	13	1	12 (85.7%)
Three	2	58.5 (0.7)	58	59		2	2 (100%)
Large SS-knowers	18	54.7 (7.1)	39	63	6	12	17 (94.4%)
Four	4	45.0 (4.9)	39	51	4		3 (75%)
Five	1	48.0			1		1 (100%)

Six	2	59.5 (2.1)	58	61		2	2 (100%)
Seven	0						
Eight	2	55.0 (8.5)	49	61	1	1	2 (100%)
Nine	1	61.0				1	1 (100%)
Max-knowers [a]	8	58.4 (3.5)	53	63		8	8 (100%)
Total	34	51.7 (7.7)	39	63	18	16	31 (91.2%)

Note: GaN= Give-a-Number. SS= subset. FMS= fine motor skills. For each cardinal principle knowledge level, the table reports descriptive information about their age and their academic level.

[a] in months. [b] Level 1 and 2 correspond to the first and the second academic year in preschool. [c] Proportions of children whose knowledge of the verbal number sequence outperformed their cardinal principle knowledge level (based on known data, n=29)

Table 2

Pearson's correlations between chronological age, early numerical abilities, and sensorimotor finger skills.

	1	2	3	4	5	6	7	8	9	10
Control										
1. Age	-									
Early mathematical skills										
2. Enumeration	.49**	-	.37*	.33	.17	.16	.28	−.22	.27	.27
3. Give-a-Number	.63***	.56***	-	.65***	.22	.41*	.59***	−.49**	.58***	.61***
4. Early arithmetic	.58***	.52**	.78***	-	.40*	.26	.38*	−.38*	.46**	.48**
Sensorimotor finger skills										
5. Finger gnosia	.56***	.38*	.48**	.59***	-	.18	.17	−.14	.17	.17
6. Static FMS score	.53***	.38*	.61***	.49**	.42*	-	.60***	−.65***	.64***	.73***
7. Dynamic FMS score	.36*	.41*	.66***	.50**	.31	.66***	-	−.53**	.79***	.75***
8. Static FMS index	−.63***	−.46**	−.69***	−.61***	−.44*	−.76***	−.61***	-	−.57***	−.88***
9. Dynamic FMS index	.60***	.48**	.74***	.65***	.44*	.76***	.81***	−.74***	-	.89***
10. Composite FMS index	.66***	.50**	.77***	.67***	.47**	.81***	.76***	−.93***	.93***	-

Note: Simple correlations are presented below the diagonal and partial correlation controlling for age are presented above. FMS= fine motor skills

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

Table 3

Summary of hierarchical multiple regression analyses predicting cardinal principle knowledge and arithmetic skills by sensorimotor finger skills, controlling for chronological age.

Variables	Cardinal principle knowledge				Arithmetic skills			
	β	R^2	ΔR^2	Partial correlation	β	R^2	ΔR^2	Partial correlation
Stage 1		.40				.34		
Age	.63***				.58***			
Stage 2		.63	.23***			.56	.22**	
Age	.18			.20	.10			.10
Finger gnosia	.08			.12	.32*			.38
CFG index	.61***			.60	.46**			−.46

Note: CFG= composite finger gestures.

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

Figure legends:

Figure 1

Finger configurations and ordered finger movements shown during the static and dynamic finger gestures tasks. FMS= fine motor skills.

Figure 2

Three-step superimposition procedure. Each circle represents one marker on the surface of the hand.

Figure 3

Path coefficients of the mediation model where cardinal principle knowledge mediates the relationship between fine motor skills (FMS) and arithmetic skills.

Note: * $p \leq .05$, ** $p \leq .01$, *** $p \leq .001$.

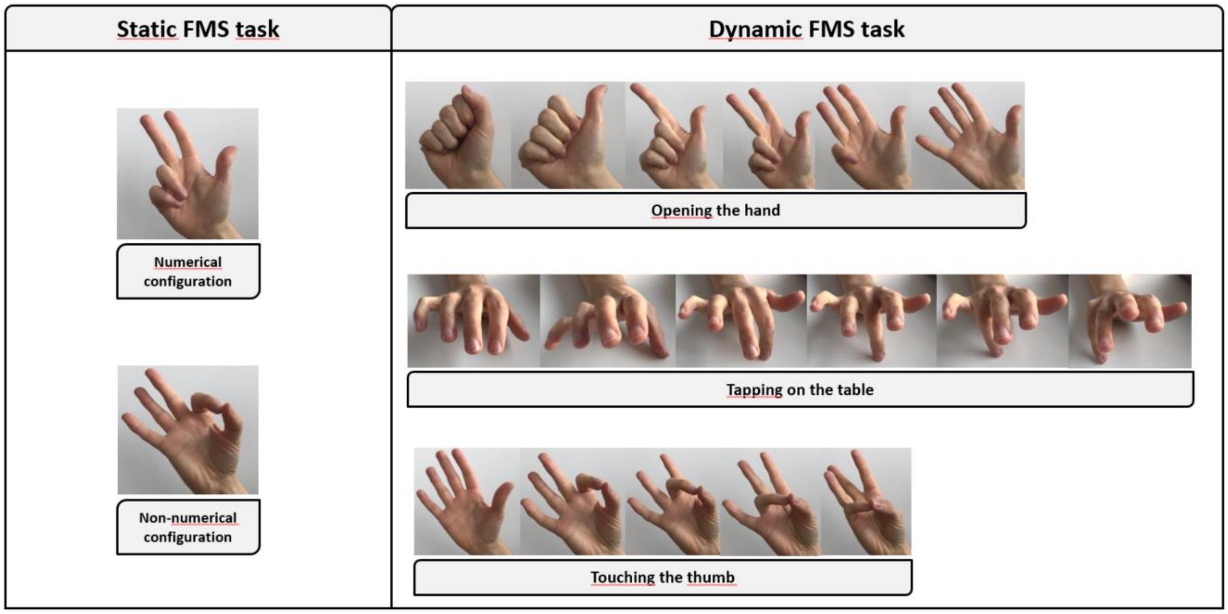

Static FMS task
Dynamic FMS task
Numerical configuration
Non-numerical configuration
Opening the hand
Tapping on the table
Touching the thumb

Figure 1

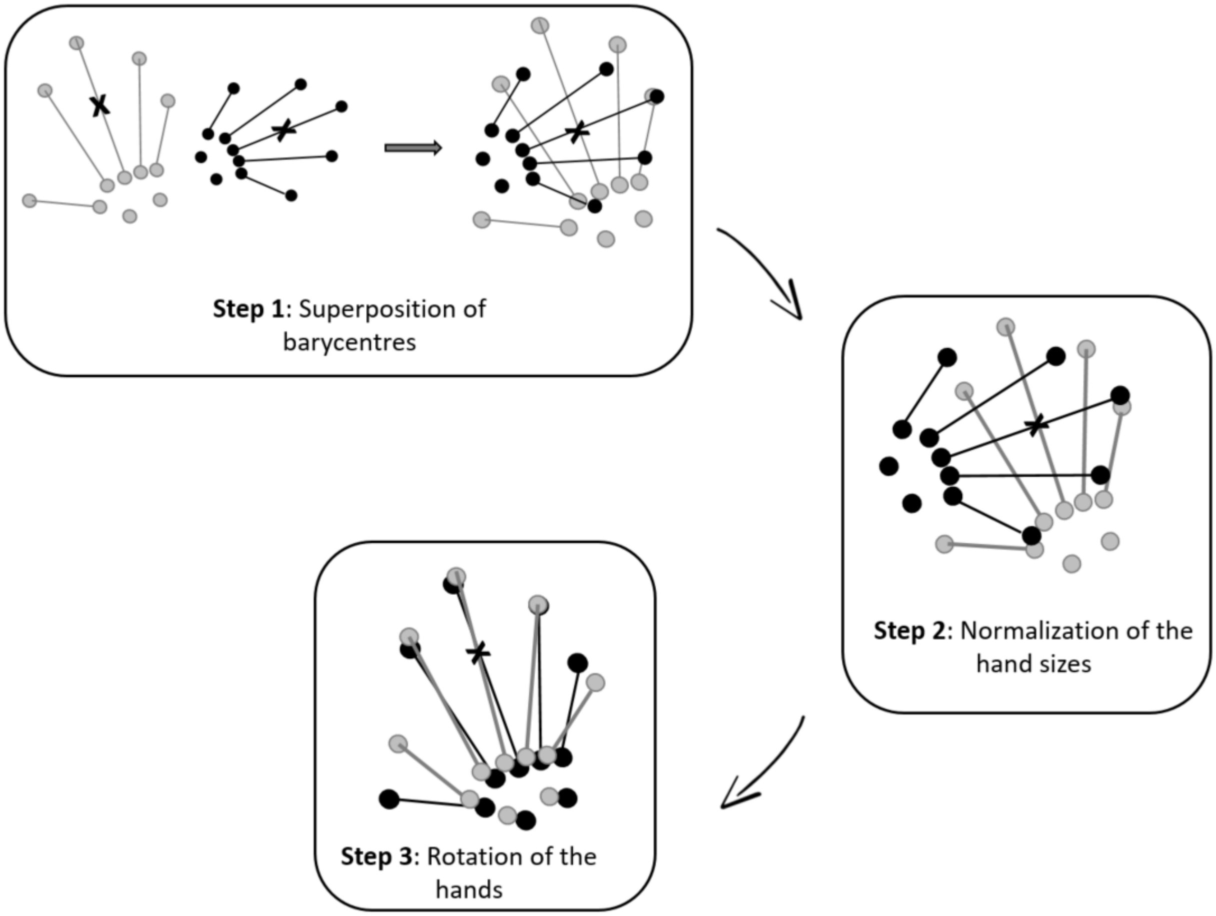
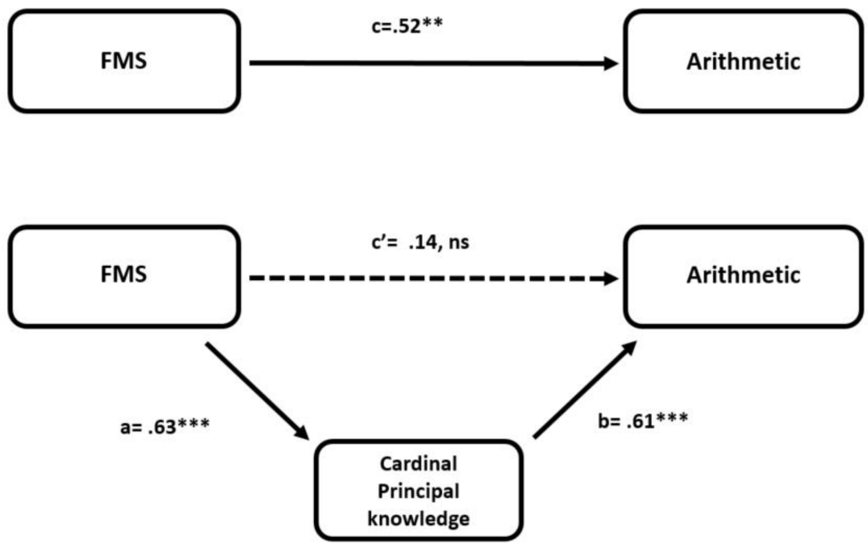

Step 1: Superposition of barycentres
Step 2: Normalization of the hand sizes
Step 3: Rotation of the hands

Figure 2



FMS
c=.52**
Arithmetic
FMS
c'= .14, ns
Arithmetic
a= .63***
b= .61***
Cardinal
Principal
knowledge

Figure 3