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Linking Sensorimotor Skills and Finger Use to Arithmetic Development: A Latent Growth Modeling Approach

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Abstract

Although finger sensorimotor skills, such as finger gnosia and fine motor skills (FMS), are crucial for arithmetic development, the processes underlying this relationship remain poorly understood. This study examined the *functionalist hypothesis* by investigating longitudinal associations between finger sensorimotor skills, finger-based strategies, and arithmetic developmental trajectories. The predictive value of developmental changes in sensorimotor skills on arithmetic development and the possible mediating role of finger use in this relationship were also explored. Seventy-four 6-year-old children were assessed four times between the beginning of Grade 1 and the end of Grade 2. At each assessment time point, participants completed tasks evaluating their general cognitive abilities, arithmetic skills, finger gnosia and FMS. Using latent growth modelling, researchers found that the variance in the intercept of finger gnosia was a key predictor of arithmetic development, even when fluid reasoning was controlled for. Conversely, neither the variance of the FMS intercept nor its slope significantly predicted arithmetic development. Latent growth modelling failed to show that effective finger use during calculation was a predictor of the development of arithmetic skills. The present findings do not provide evidence that the relationship between finger gnosia and arithmetic is kinesthetic in nature in this developmental time window.

Keywords

sensorimotor finger skills, arithmetic development, functionalist hypothesis, finger use

Embodied cognition theories have garnered increasing attention in the context of numerical cognition. These theories postulate that the development of numerical concepts is deeply rooted in children's sensorimotor experiences. In the context of mathematical development, these theories suggest that bodily experiences contribute to the meaning of symbols and numerical concepts (Andres & Pesenti, 2015; Barsalou, 2008; Moeller et al., 2012). In this respect, the fingers are thought to have a privileged status in the development of numerical and arithmetic skills. Although available and easy to manipulate, fingers provide an embodied representation of numerical concepts (i.e., cardinality, ordinality, and one-to-one correspondence) (Crollen et al., 2011; Wasner et al., 2015) and support their internalisation through multimodal associations (i.e., motor and visual) with numbers (Butterworth, 1999; Fuson et al., 1982; Lakoff & Núñez, 2000).

Achieving functional finger use in mathematical tasks requires the ability to rely on sensorimotor skills to control and coordinate fingers. A growing body of research has been conducted to identify sensorimotor finger skills involved in the development of arithmetic processing (for reviews, see Barrocas et al., 2020; Neveu, Geurten, et al., 2023). Two categories of sensorimotor finger skills were examined. Some studies have focused on finger gnosia, which refers to the sensory representation of finger positions in the hand (Fayol et al., 1998; Noël, 2005). Usually assessed through tactile stimulation, finger gnosia has been found to be related to arithmetic skills in children aged between 5 and 10 (Fayol et al., 1998; Neveu, Schwartz, et al., 2023; Newman, 2016; Penner-Wilger et al., 2007). Taking a developmental approach, Noël (2005) has provided evidence that finger gnosia, assessed at the beginning of Grade 1 (Mean age = 6.8 years), was a specific predictor of children's arithmetic development 15 months later.

More recently, motor components, typically assessed through object manipulation tasks that evaluate fine motor skills (FMS) (i.e., the ability to move fingers in various ways), have been considered as an additional source of arithmetic development. Only a handful of studies have targeted arithmetic skills in school-aged children. In 5-year-olds, the FMS was found to explain a unique part of the variance in arithmetic skills in children who were asked to solve arithmetic tasks requiring the addition and subtraction of nonsymbolic quantities (Barnes et al., 2011). Moreover, FMS assessed at Age 4 was shown to specifically predict children's arithmetic development 2 years later (Asakawa & Sugimura, 2014). The positive influence of the FMS training on arithmetic skills has also been demonstrated in 6-year-old children (Asakawa et al., 2019; Gracia-Bafalluy & Noël, 2008; Schild et al., 2020), providing compelling evidence for the causal relationship between the FMS and the arithmetic skills underpinning this relationship.

Taken together, this initial evidence suggests that both finger gnosia and the FMS are particularly important in the development of arithmetic skills. Investigating these sensorimotor finger skills jointly, Asakawa and Sugimura (2022) recently provided evidence that the association between these two components explain a significant proportion of the variance in arithmetic performance among 5-year-olds, without explicitly determining the part explained by each of these two skills. Precisely estimating the contribution of each variable could be decisive in determining whether the acquisition and development of arithmetic skills are more closely linked to finger gnosia or the FMS involved in solving calculations. A closer examination of the processes involved in these relationships could inform our understanding of how sensorimotor finger skills contribute to computational abilities when children begin learning arithmetic. However, this remains unclear.

One explanatory hypothesis for the origin of the association between sensorimotor finger skills and arithmetic posits that these two abilities are linked through a functional relationship (Butterworth, 1999). This hypothesis (known as the *functionalist hypothesis*) assumes that sensorimotor finger skills support the use of finger-based strategies, which in turn promote the development of arithmetic processing. In the early years of schooling (Jordan et al., 2008), fingers helped young children visualize and combine the quantities involved in the calculations (Baroody, 1987; Björklund et al., 2019; Lê et al., 2024; Roesch & Moeller, 2015). They foster the development of early arithmetic skills and enhance young children's chances of mastering addition and subtraction before starting elementary school (Frey et al., 2024; Krenger & Thevenot, 2024; Ollivier et al., 2020; Poletti et al., 2025). When solving complex problems involving multiple-resolution steps, they offer valuable external aid for keeping track of intermediate calculations and freeing up working memory resources for other operations (LeFevre et al., 2005).

Reeve and Humberstone (2011) came closest to testing the f*unctionalist hypothesis* of arithmetic development. Similar to Suggate et al. (2017), who showed that the relationship between the FMS and early numerical skills (counting and enumeration) is mediated by finger use in preschoolers (Age 4), Reeve and Humberstone (2011) examined the triadic relationship between finger gnosis, finger use strategies, and arithmetic skills in kindergarten and first-grade children (Ages 5–7). Their study aimed to determine whether finger gnosia predicts finger use and performance in an additive problem-solving task. The children were divided into four subgroups based on their performance in a finger gnosia task (i.e., finger–hand confusion, finger confusion, good finger gnosia, and high finger gnosia) and into four other subgroups based on finger use frequency and accuracy in a single-digit addition task (i.e., low finger use/low accuracy, low finger use/high accuracy, high finger use/moderate accuracy, and moderate finger use/moderate accuracy). Logistic regression analyses revealed a significant association among finger gnosia, finger use, and calculation performance, which is consistent with Butterworth's (1999) *functionalist hypothesis*. Children with poor finger gnosia were predominantly in the low finger use and poor arithmetic skill groups, whereas children with high finger gnosia were more likely to use their fingers to solve problems. This relationship was age-related, as older children exhibited better finger gnosia, enabling them to rely on their fingers to solve additive problems.

Although pioneering, this work does not provide sufficient evidence to test the *functionalist hypothesis* as it focused exclusively on finger gnosia and explored only the sensory dimension of finger skills, excluding the influence of the FMS on finger use and arithmetic performance. However, converging evidence suggests that the FMS plays a decisive role in the acquisition of finger-based strategies (e.g., Asakawa & Sugimura, 2022; Neveu et al., 2024), which could, in turn, contribute to the development of children's arithmetic skills. Understanding the mechanisms underlying the triadic relationship between sensorimotor finger skills, finger use, and arithmetic skills requires going one step further and contrasting the respective contributions of the FMS and finger gnosia to arithmetic development. Furthermore, Reeve and Humberstone (2011) considered finger use and arithmetic performance together to distinguish different profiles of children in an arithmetic task. However, it is necessary to consider these two variables separately to examine whether finger use supports arithmetic performance in young children.

The objective of this study was therefore to investigate longitudinal associations between finger sensorimotor skills, finger-based strategies, and arithmetic growth, as expected within the functionalist framework. The *functionalist hypothesis* suggests that arithmetic development is supported by the discovery of efficient finger-based strategies, which depend in part on children's ability to recognize the position of their own fingers (i.e., finger gnosia) and, on the other hand, on their ability to move fingers easily and precisely (i.e., FMS). Therefore, the evolution of sensorimotor finger skills should promote increasingly efficient finger use with a positive effect on arithmetic development. As the triadic association between finger sensorimotor skills, finger use, and arithmetic performance was found to be age-related (Reeve & Humberstone, 2011), a longitudinal model was employed to capture developmental changes in these three variables and provide a deeper understanding of their developmental trajectories and predictive factors.

This study examines two main questions. First, we aimed to determine whether the evolution of arithmetic skills could be predicted by developmental changes in sensorimotor finger skills. At different stages of development, finger gnosia and the FMS are specific predictors of arithmetic development (Asakawa & Sugimura, 2014; Noël, 2005). In the present study, latent growth curve analysis was conducted to go one step further and examine how developmental changes in sensorimotor finger skills predict the growth rate in arithmetic development. The mediating role of finger use in the possible relationship between the sensorimotor finger and arithmetic skills was also investigated. Based on Butterworth's (1999) *functionalist hypothesis,* finger use is expected to mediate the relationship between developmental changes in sensorimotor finger skills and arithmetic skills.

Method

Participants

Seventy-four French-speaking children (40 girls; mean age = 6.2 ± 0.3 years at the start of Grade 1, first measurement time) from ten mainstream primary schools took part in this longitudinal study. They taught mathematics according to the official curricula, which neither recommend nor discourage the use of fingers. Parents were asked to complete an anamnestic questionnaire regarding their children. None of the participants reported a history of disability. The socioeconomic status of the families was predominantly high compared to the national statistics.

The participants were assessed at four time points, at the autumn and spring of Grade 1 and 2 (T1, mean age = 6.2 ± 0.3 years; T2, mean age = 6.7 ± 0.3 years; T3, mean age = 7.3 ± 0.3 years; T4, mean age = 7.7 ± 0.3 years; mean interval between two sessions = 5.7 months). The two cohorts of children were enrolled 1 year apart. The first cohort included children (*n* = 36) from September 2020 to May 2022, while the second cohort (*n* = 35) included children from September 2021 to May 2023. Due to the disruptions caused by the COVID-19 pandemic, children in the first cohort were home-schooled in September 2020. However, the analyses indicated no significant differences in academic performance between the first and second cohorts, suggesting that their outcomes were directly comparable. This study was approved by the local ethics committee (reference number: 1819-64).

Measures

Arithmetic

To assess arithmetic skills, the children were asked to solve calculations presented horizontally on a computer screen. No guidance on calculation strategies was provided; therefore, spontaneous finger use could be observed. The stimuli comprised 36 items of increasing difficulty (18 additions and 18 subtractions mixed; Table 1), half of which involved carrying or borrowing.

Item difficulty was determined using a staircase procedure (inspired by Geurten et al., 2021) established through the pre-testing of 30 children enrolled in kindergarten (*n* = 11, mean age = 5.2 ± 0.2 years), in Grade 1 (*n* = 10, mean age = 6.4 ± 0.2 years), or in Grade 2 (*n* = 9, mean age = 7.3 ± 0.2 years). Prior to the pre-test sessions, the 36 items were classified into three levels of difficulty based on the mathematics curricula for children attending school in the French-speaking part of Belgium. Level 1 items consisted of Unit+Unit (U + U) additions without a carry, which were suitable for kindergarten students. Level 2 items include Tens-Units+Units (TU+U) and TU+TU without carry, U-U and TU-U subtractions without borrow, and U+U and TU+U additions with carry. All these items were considered suitable for first graders. Finally, Level 3 items, intended for second graders, consisted of TU+TU additions with carry and TU-U subtractions with borrows. During the pre-test sessions, kindergartners were asked to solve items from Levels 1 and 2, whereas second-graders were asked to solve items from Levels 2 and 3. First graders were divided into two groups: five were asked to solve Levels 1 and 2 items, and the others were asked to solve Levels 2 and 3 items. Level 1 items, which were not presented to second graders, were deemed successful for these children. In contrast, Level 3 items, which were not administered to kindergartners, were considered to have failed for this younger subgroup. The final order of the items was established according to the average success rate of each item obtained during the pre-test sessions.

Table 1

Additive and Subtractive Problems of the Arithmetic Task in Order of Increasing Difficulty

1 + 2 =	12 + 4 =	23 - 4 =	16 - 9 =
3 + 1 =	3 + 8 =	42 - 4 =	48 - 6 =
3 - 1 =	7 + 5 =	31 - 2 =	17 - 8 =
4 - 1 =	14 - 2 =	12 - 5 =	42 - 7 =
6 - 3 =	2 + 23 =	38 - 5 =	23 + 57 =
5 + 3 =	5 + 14 =	13 - 5 =	37 + 29 =
9 - 5 =	26 - 4 =	24 - 9 =	9 + 13 =
4 + 6 =	7 + 16 =	38 + 11 =	46 + 16 =
8 - 4 =	25 + 8 =	12 + 24 =	35 + 23 =

When solving the experimental task, the children were asked to provide their answers orally. The answers and the time intervals between the presentation of the item and the child’s responses were recorded. In addition, the strategies used to solve each problem (i.e., mental calculation or finger use) have been reported. The finger-use accuracy score was calculated as the ratio of the number of items correctly solved using the fingers to the number of items processed using the fingers throughout the arithmetic task. Each correct answer was awarded one point. The test was discontinued after three consecutive errors. The internal consistency of the task was high with a Cronbach’s alpha of 0.89.

Fine Motor Skills

FMS was assessed using four tasks: three subtests from the Movement Assessment Battery (MABC-2, Henderson et al., 2007) measuring visuomotor precision and one task designed specifically for the present study to assess sequential finger movement coordination. This additional task was included alongside the MABC-2 subtests to evaluate finger coordination in a manner comparable to that for counting fingers.

The first visuomotor task was the *Placing Pegs* subtest of the MABC-2, which requires unimanual fine motor skills. In this subtest, the child is asked to place 12 pegs as quickly as possible on a pegboard (i.e., a 12-hole board with four lines of three holes). They were instructed to use one hand and manipulate each peg simultaneously. Both hands were tested sequentially, starting with the dominant hand. The subtest started with a training trial in which the child had to place six pegs, followed by test trials requiring the placement of 12 pegs, with the execution time recorded. Two trials were conducted for each hand, and only the best execution time was recorded. The mean execution time for both hands was used as the score for the first subtest.

The second visuomotor task was the *Threading Lace* subtest of the MABC-2 which requires bimanual motor skills. In this subtest, the child is asked to thread a lace through eight holes drilled into a board as quickly as possible. To do so, he had to insert a lace into the first hole and move it back and forth until the task was completed. The child could choose the hand that guided the lace. The subtest began with a practice trial, in which the child threaded the lace through four holes, followed by test trials that required completing all eight holes, with the execution time recorded. Two trials were required to complete each task. The best time of the two was considered as a measure of the execution time.

The third visuomotor task was the *Drawing Trail* subtest of the MABC-2, a graphomotor task in which participants had to draw a continuous line within a pathway delimited by two equidistant curved lines. Each child was required to comply with the following rules: (1) The drawn line must not cross boundaries. (2) Pen should not be lifted from the sheet. If so, the drawing had to resume where the pen had been lifted. (3) A line was drawn in a single direction. (4) The exercise sheet could not be tilted by >45°. A training trial was presented to the children before they started the subtest. One error was recorded each time one of the four rules was broken. The child repeated the subtest twice, with the best time reported as the measure of execution time.

Finally, a timed finger movement sequence subtest was conducted to assess the sequential coordination of the individual finger movements. The participants had to reproduce as many finger movement sequences as possible in 30 s. In all trials, sequential finger movements involved tapping a table. Four trials were conducted, all involving sequential finger tapping on the table: (1) Single-hand unidirectional sequence, following the successive order of fingers on the hand (i.e., starting with the thumb and ending with the little finger; five taps). The trial was first conducted with the right hand and then with the left hand. (2) Two-hand unidirectional sequence, following the successive order of fingers on the hand (i.e., starting with the left little finger and ending with the right little finger, 10 taps). (3) Two-hand unidirectional sequence, alternating every other finger (i.e., starting with the little finger, middle finger, and thumb of the left hand, followed by the thumb, middle finger, and little finger of the right hand, six taps). (4) Two-hand bidirectional sequence alternating with every other finger. In this trial, the child was required to perform the sequence from the third trial in both forward and backward directions (12 taps).

Before each trial, the child was asked to repeat the movement three times for practice. One point was awarded for each correctly executed finger movement sequence (i.e., when the fingers were mobilised one after the other in the correct order). The average performance of both hands was used as the score for the first trial. The subtest score was the sum of correctly executed finger sequences across the four trials.

An FMS score was extracted from the four task scores by applying a Principal Component Analysis (PCA). The PCA results confirmed that the four subtests reflected a single construct that accounted for 65% of the total variance across the subtests. The factor loading were .32, .31, .30 and .30 respectively, for the Placing Pegs, the Threading Lace, the Drawing Trail and the Timed Finger Movement Sequence subtests.

Finger Gnosia

The child was asked to place one hand palm-down and flat on the table with the fingers spread out. The patient was shown a reference card on which a hand with coloured fingers was drawn. His hand was covered with cardboard, and out of the participant's view, the experimenter touched the middle phalange with one finger. The cardboard was then removed and the child was asked to indicate the colour of the finger touched using the reference card. Ten trials were performed for each hand. The first five trials consisted of one touch, whereas the last five trials consisted of two successive touches. One point was awarded when the child correctly reported touching the finger(s) touched. For two-touch trials, one extra point was awarded when the fingers were identified according to the order in which they were touched. The sum of the points was used as the task score. The highest possible score is 30. The internal consistency of the task was acceptable with a Cronbach's alpha of 0.69.

General Cognitive Abilities

The *Matrix Reasoning* subtest of the WISC-V (Wechsler, 2016) was used to control the effect of fluid reasoning in the statistical analysis. In this task, children were asked to complete a visual matrix by selecting the element that followed the underlying rule governing the patterns from several alternatives. Two practice trials were conducted to ensure comprehension of the instructions. Responses were provided either by pointing to the selected element or stating its number aloud. This subtest comprised 32 items and was discontinued after three consecutive errors. Subtest performance was assessed using standardised scores derived from the total number of correct responses based on the WISC-V normative data.

Procedure

Children were assessed individually in a quiet room within their school. Tasks assessing general cognitive abilities, FMS, finger gnosia and arithmetic were administered at each of the four testing times. Considering a relatively stable measure over time (Schneider et al., 2014), fluid reasoning was assessed only once, at the first measurement time point (Grade 1 – autumn). Each testing session lasted approximately 30 min. The order of the measurements was counterbalanced across children. Half of the participants completed the protocol in the following order: FMS, finger gnosia, arithmetic, and fluid reasoning (when applicable), while the others completed the protocol in reverse.

Analyses

Analyses were conducted in three parts to address the issues addressed in this study. General cognitive abilities were systematically controlled as covariates in the association between sensorimotor and arithmetic abilities. This approach was adopted because the findings showed that general cognitive abilities account for a substantial proportion of the variance in arithmetic performance, thereby reducing the apparent explanatory role of finger gnosia in 6-year-olds (Wasner et al., 2016).

Regarding the first issue, descriptive analyses were conducted. The predictive value of developmental changes in finger gnosia and the FMS for age-related changes in arithmetic skills was then examined using correlations. Given the large number of correlations computed, we use the Benjamini–Hochberg procedure (1995) to control for Type I errors, which lowers the significance threshold from .05 .016. Three latent growth models (LGM) were estimated using Mplus 5.21 software (Muthén & Muthén, 2010). The first LGM was used to analyze the developmental trajectories of the three measures (finger gnosia, FMS, and arithmetic). A second model then examined these trajectories while controlling for fluid reasoning. Each variable had to show significant changes over time to be considered in the LGM with time-varying covariates. If this prerequisite was met, all three variables were entered into the third LGM with time-varying covariates to identify significant longitudinal predictors of arithmetic skill development.

Regarding the second issue, the potential mediating role of the rate of correct finger use was investigated through correlations and subsequently with the LGM. Initially, changes in the rate of correct finger use over time were analysed using a linear LGM, which was a prerequisite for subsequent analyses. This variable was then entered into the LGM with time-varying covariates to examine whether developmental changes in the rate of correct finger use predicted changes in arithmetic skills over time, and whether it could serve as a longitudinal mediator of the relationship between sensorimotor finger skills and arithmetic abilities.

Results

Descriptive Analyses

Table 2 presents the descriptive statistics for general cognitive abilities, finger gnosia, FMS, arithmetic, and finger use across four measurement points. Regarding general cognitive abilities, children obtained an average score of 11.56 at T1 (Table 2). For finger gnosia, the mean score at the first measurement was 20.84 points. Scores increased by 2.3 points between T1 and T4 (Table 2). FMS results indicated that at T1, children had an average score of −0.43[1]. Between T1 and T4, FMS gradually increased by 1.3 points (Table 2).

Table 2

Descriptive Analyses of Fluid Reasoning, Finger Gnosia, FMS, Arithmetic and Finger Use

			Range	
Measure	***N***	**Mean score (*SD*)**	***Min.***	***Max.***
General cognitive abilities				
Grade 1 – autumn	71	11.56 (5.74)	2.0	19.0
Finger-gnosia				
Grade 1 – autumn (T1)	71	20.50 (5.30)	9.0	30.0
Grade 1 – spring (T2)	70	22.00 (4.70)	12.0	30.0
Grade 2 – autumn (T3)	67	21.80 (5.22)	5.0	30.0
Grade 2 – spring (T4)	65	22.80 (5.03)	11.0	30.0
FMS[a]				
Grade 1 – autumn (T1)	70	-0.41 (0.99)	-4.8	1.0
Grade 1 – spring (T2)	69	-0.22 (0.88)	-4.6	0.8
Grade 2 – autumn (T3)	67	0.50 (0.61)	-1.6	1.5
Grade 2 – spring (T4)	65	0.81 (0.61)	-1.0	2.1
Arithmetic				
Grade 1 – autumn (T1)	68	2.96 (3.28)	0.0	17.0
Grade 1 – spring (T2)	68	6.69 (6.10)	1.0	27.0
Grade 2 – autumn (T3)	67	12.50 (6.37)	0.0	31.0
Grade 2 – spring (T4)	64	18.20 (8.78)	1.0	33.0
Finger Use[b]				
Grade 1– autumn (T1)	39	.51 (.37)	0.0	1.0
Grade 1 – spring (T2)	47	.60 (.37)	0.0	1.0
Grade 2 – autumn (T3)	49	.72 (.30)	0.0	1.0
Grade 2 – spring (T4)	44	.75 (.31)	0.0	1.0

[a]FMS score was derived using Principal Component Analysis (PCA), which can yield negative values. [b]Finger use score reflects the rate of correct finger use.

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1) FMS score was derived using Principal Component Analysis (PCA), which can yield negative values.

For arithmetic, the descriptive analyses show that, on average, children correctly solved 2.89 problems at T1. From T1 to T4, arithmetic performance gradually increased by 15.24 points (Table 2). Finally, the trajectory of change of the rate of correct finger use showed that at the first measurement, children solved on average 51% of arithmetic problems correctly when using finger-based strategies. Between T1 and T4, this success rate increased by 24% (Table 2).

Predictive Value of Changes in FMS and Finger Gnosia on Arithmetic Development

Correlations

Table 3 reports Pearson's correlations and partial correlations between finger-gnosia, FMS and arithmetic at the four measurement times (i.e., Autumn and spring and of the Grade 1 (T1 and T2) and of the Grade 2 (T3 and T4)). General cognitive abilities appear to have only a negligible effect on the association between sensorimotor skills and arithmetic abilities. When general cognitive abilities were considered, significant correlations were found between FMS at T1 and finger gnosia at T3 (p = .01) and T4 (p = .004), as well as between FMS at T2 and finger gnosia at T4 (p = .004). There was also a strong correlation between children's arithmetic skills at T3 and T4 and the immediately preceding measurement time (T2 x T3, p < .001; T3 x T4, p < .001). Finger gnosia was moderately correlated with concurrent arithmetic skills at T2 (p < .001), T3 (p < .001) and T4 (p = .003). A significant correlation was reported between finger gnosia at T1 and later arithmetic skills at T4 (p = .004). By contrast, at each time point, FMS showed a weak correlation with concurrent arithmetic skills (from r = .09 to r = .17), none of which were significant. Moreover, arithmetic skills were found to be unrelated to FMS assessed at the previous time point (from r = .11 to r = .21).

Table 3

Pearson's Correlations and Partial Correlations Between Arithmetic, Finger Gnosia, FMS and Finger Use at the Four Measurement Times

Measure	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
1. Arithmetic T1	—	.22	.33**	.08	.05	-.03	.34**	.30*	.09	.18	.16	.04	.27	.10	-.08	.01
2. Arithmetic T2	.22	—	.46***	.18	.33**	.41***	.19	.19	.11	.10	-.09	-.12	.10	.49***	.16	.15
3. Arithmetic T3	.35**	.47***	—	.46***	.38**	.42***	.49***	.45***	.21	.20	.15	.26*	-.08	.20	.39**	-.02
4. Arithmetic T4	.08	.18	.46***	—	.14	.21	.24	.37**	.23	.13	.06	.17	.01	-.02	.13	.40**
5. Finger gnosia T1	.06	.33**	.38**	.13	—	.50***	.37	.28*	.08	.15	.16	.13	.19	-.05	.14	.07
6. Finger gnosia T2	-.03	.41***	.44***	.22	.50***	—	.22	.39**	.16	.29	.16	.11	.11	.25	.12	.31*
7. Finger gnosia T3	.36**	.20	.46***	.23	.38**	.24	—	.66***	.33**	.26	.20	.23	.33	-.06	.23	.10
8. Finger gnosia T4	.31*	.19	.44***	.36**	.28	.39**	.66***	—	.37**	.36**	.25	.20	.35	.13	.22	.34*
9. FMS T1	.11	.11	.20	.23	.07	.17	.32**	.36**	—	.87***	.66***	.42***	.21	-.08	.03	.03
10. FMS T2	.18	.10	.20	.13	.15	.29	.26	.36**	.88***	—	.67***	.37**	.24	-.02	.06	.06
11. FMS T3	.17	-.10	.10	.04	.15	.18	.15	.23	.66***	.69***	—	.78***	.04	-.16	-.05	-.05
12. FMS T4	.06	-.13	.19	.16	.11	.16	.15	.18	.37***	.37**	.74***	—	-.08	-.09	-.06	-.06
13. Finger use T1	.26	.05	.09	-.02	.21	.12	.35	.36	.21	.24	.05	-.08	—	-.16	-.04	-.04
14. Finger use T2	.09	.53***	.28	.04	-.01	.28	.01	.17	-.07	-.02	-.09	.03	-.17	—	.01	.26
15. Finger use T3	-.09	.15	.39**	.12	.13	.12	.21	.22	-.02	-.07	-.18	-.02	-.12	.02	—	-.21
16. Finger use T4	.04	.23	.08	.43**	.12	.36	.19	.37*	.06	.04	-.04	.06	-.20	.23	-.19	—

Note. Pearson's correlations are presented above the diagonal and partial correlations controlling for fluid reasoning are presented below. FMS = Fine motor skills; T = Time.

$^{*}p < .016$ (significance level corrected using the procedure of Benjamini & Hochberg, 1995). $^{**}p < .01$. $^{***}p < .001$.

Trajectory of Change of Finger Gnosia, FMS and Arithmetic

Before conducting the LGM with time-varying covariates, the trajectories of changes in finger gnosia, FMS, and arithmetic were examined using a linear LGM.

Regarding finger gnosia, the children had an average score of 20.84 at the intercept. The average slope was .67. The estimated parameters of the linear LGM for finger gnosia showed that the variance of the intercept (*Estimate* = 14.83, p < .001) and the slope (*Estimate* = 2.26, p = .01) both differed significantly from 0, confirming the presence of inter-individual differences in finger gnosia at T1, as well as age-related changes observed up to the end of Grade 2. Fluid reasoning did not affect the variance of the intercept (*Estimate* = .09, p = .51) or the slope (*Estimate* = .06, p = .71) of finger gnosia. The correlation between the variance of the intercept and the slope of finger gnosia was significant (*Estimate* = −.45, p = .01), even when controlling for general cognitive abilities, indicating that higher initial values of finger gnosia were associated with a slower rate of increase.

At the first measurement point, children had an average FMS score of -.42 points[2]. The mean slope was .39. The estimated parameters of the linear LGM for FMS showed that both the variance of the intercept (*Estimate* = -.42, p < .001) and the slope (*Estimate* = .39, p < .001) differed significantly from 0, confirming the existence of inter-individual differences in FMS at T1 as well as in developmental changes observed up to the end of Grade 2. General cognitive abilities significantly affected the intercept (*Estimate* = .02, p = .04) but not the slope (*Estimate* = .001, p = .77) of the FMS. The correlation between the intercept and the slope of FMS was significant (*Estimate* = −.82, p < .001), even when controlling for general cognitive abilities, indicating that higher initial scores of FMS were associated with a slower rate of increase.

Finally, the children had an arithmetic mean score of 2.89 points at the intercept, while the mean slope was 4.87. The estimated parameters of the linear LGM for arithmetic showed that the variance of the intercept did not statistically differ from 0 (*Estimate* = 5.95, p = .24), suggesting that at T1, there were no notable individual differences in arithmetic skills among the children. Conversely, the slope variance (*Estimate* = 3.90, p = .006) was significantly different from 0, suggesting a heterogeneous developmental trend among children. General cognitive abilities did not significantly affect either the intercept (*Estimate* = -.02, p = .62) or the slope (*Estimate* = .05, p = .15) of arithmetic. The correlation between the intercept and the slope was not significant (*Estimate* = -.24, p = .89), indicating that the children's improvement in arithmetic between Grade 1 and 2 was independent of their skills at T1.

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2) FMS score was derived using Principal Component Analysis (PCA), which can yield negative values.

Latent Growth Model With Time-Varying Covariates

As all three variables of interest showed significant changes over time, two linear LGMs with time-varying covariates were estimated to examine the predictive value of the intercept and slope of finger gnosia (Model 1) and the FMS (Model 2) for age-related changes in arithmetic skills while controlling for general cognitive abilities.

According to the first model, the intercept of finger gnosia was not a significant predictor of the intercept of arithmetic skills (*Estimate* = .15, p = .19). In contrast, the intercept of finger gnosia was a significant predictor of the arithmetic slope (*Estimate* = .43, p < .001). The slope of the finger gnosia latent variable was not significantly associated with arithmetic development (*Estimate* = .03, p = .95). The R-square analysis further indicated that the intercept and slope of finger gnosia accounted for 50% of the development of arithmetic skills between the beginning of Grade 1 and the end of Grade 2 once fluid reasoning was considered, which represents a significantly large explanatory share (p = .02).

A second linear LGM with the FMS as the time-variant covariate was conducted. The intercept of the FMS significantly predicted neither the intercept (*Estimate* = .38, p = .55) nor the slope of arithmetic skills (*Estimate* = .67, p = .35). Likewise, improvements in FMS scores over time did not predict age-related changes in arithmetic skills (*Estimate* = .34, p = .89).

Longitudinal Mediating Effect of the Rate of Correct Finger Use

Correlations

Table 3 reports partial correlations between finger use, finger-gnosia, FMS and arithmetic, at the four measurement time points. General cognitive abilities appears to have only a negligible effect on the association between sensorimotor skills and arithmetic abilities. Children's rates of correct finger use were not related to their abilities at the previous measurement time (from r = -.17 to r = .03). Finger gnosia and the rate of correct finger use negatively correlated at T4 (p = .01). Finger gnosia at T3 and T4 was related to the rate of correct finger use at T1 (T3xT1, p = .04; T4xT1, p = .04). On the other hand, FMS did not correlate with concurrent rates of correct finger use at any specific time point (from r = -.18 to r = .24). Finger use moderately correlated with concurrent arithmetic skills at T2 (p < .001), T3 (p = .006) and T4 (p = .004). Finally, no significant relationships were found between the rate of correct finger use and the subsequent arithmetic performance (from r = .05 to r = .28).

Trajectory of Change of Rate of Correct Finger Use and Latent Growth Models With Time-Variant Covariates

The linear LGM, examining the trajectory of change in the rate of correct finger use, showed that the variance in the slope (*Estimate* = -.009, p = .10) was not significant, indicating that there were no inter-individual differences in the progression of the rate of correct finger use between the beginning of Grade 1 and the end of Grade 2. As the variability in the rate of change in finger use was not significant, it was not relevant to conduct multivariate analyses to examine its predictive value for the development of children's arithmetic skills or its mediating role in the relationship between sensorimotor finger skills and arithmetic development.

Discussion

This study aimed to investigate longitudinal associations between finger sensorimotor skills, finger-based strategies, and arithmetic growth, as expected within the *functionalist* framework (Butterworth, 1999). Primary school children were assessed four times every 6 months between autumn and spring for Grade 1 (T1 and T2) and 2 (T3 and T4). The developmental trajectories of finger gnosia, FMS, arithmetic skills, and age-related changes in the rate of correct finger use were examined. Additionally, the influence of general cognitive abilities was considered to determine whether (1) the improvement in arithmetic skills could be predicted by developmental changes in finger gnosia and FMS, and whether (2) this relationship, if any, would be mediated by the effective use of finger-based strategies.

First, the results showed that arithmetic skills improved between Grades 1 and 2 beyond the influence of general cognitive abilities. Children exhibited heterogeneous developmental trajectories with varying rates of improvement. The lack of correlation between the intercept and slope in the linear LGM indicated that the children’s arithmetic skills at the beginning of Grade 1 did not explain these individual differences. In the first measurement, arithmetic skills were uniformly poor among all children, as the majority (72%) found it difficult to solve more than 2 of the 33 calculations in the given task.

Interestingly, finger gnosia at the beginning of grade one was a strong predictor of arithmetic skill development over and above the contribution of general cognitive abilities. Finger gnosia at the beginning of primary school and its evolution over the four measurement times accounted for 50% of the development of arithmetic skills, when fluid reasoning was taken into account. These findings indicate that finger gnosia is a key predictor in the development of arithmetic skills. This finding aligns with Noël’s (2005) longitudinal investigations, which demonstrated that finger gnosia at the beginning of Grade 1 was a strong predictor of arithmetic skills by the end of Grade 2. They also align with the *functionalist hypothesis* (Butterworth, 1999), which suggests that sensorimotor skills (i.e., finger gnosia and FMS) support the use of finger-based strategies, which in turn promote the development of arithmetic processing. To do this, each finger must be identified as a distinct entity (reflecting good finger gnosia) so that it can be mobilised in an appropriate movement to accompany verbal counting or to enable the child to perform a cardinal finger-based representation (e.g. by raising the thumb, index, and middle fingers to represent 3). However, two findings in the present results are not fully consistent with this hypothesis. First, except for spring in Grade 2, finger gnosia and finger use did not significantly correlate when controlling for general cognitive abilities. Furthermore, no variability in the rate of correct finger use over time was demonstrated between the beginning of Grade 1 and the end of Grade 2, preventing the application of multivariate LGMs. These results align with those of studies (Asakawa & Sugimura, 2022) that demonstrated a lack of correlation between finger gnosia and finger use in 5-year-old children after controlling for age and working memory. Overall, the present findings do not provide sufficient evidence for an association between finger use during calculation and finger gnosia between Grades 1 and 2 nor for the idea that finger gnosia is linked to the development of arithmetic skills through the acquisition of finger-based strategies.

One way of explaining the current results could be that finger gnosia promotes the development of arithmetic skills through cardinal finger-based representations, also known as “cardinal number gestures”. Indeed, strong finger gnosia relies on the ability to create a mental representation of one's hand, enabling the precise identification of each finger and an understanding of their spatial relationships. Because the same skills are required to identify finger patterns, the development of finger gnosia is assumed to contribute to the development of cardinal-number gestures. When consistent with counting habits, canonical number gestures are processed quickly and accurately by children (Lafay et al., 2013; Noël, 2005). These cardinal finger-based representations provide direct access to the semantics of numbers, making them full-fledged numerical symbols (Di Luca & Pesenti, 2008), on par with Arabic numbers.

In in their longitudinal study, Van Rinsveld et al. (2020) found that finger gnosia correlated with the recognition of cardinal number gestures in 5-year-olds. Nevertheless, their hypothesis that finger gnosia could predict the development of symbolic number magnitude processing (i.e., the number line estimation task) through the ability to identify the cardinal meaning of number gestures was ultimately not supported. As finger gnosia reaches maturity by the age of 10 years (Chinello et al., 2013), Van Rinsveld et al. (2020) proposed an alternative developmental sequence to explain the triadic relationship between finger gnosia, cardinal number gestures, and symbolic numerical processing. Their proposal invited a more nuanced reading of Butterworth's (1999) *functionalist hypothesis*, according to which sensorimotor finger skills appear to support the use of finger-based strategies that themselves play a facilitating role in arithmetic processing. This suggests that the repeated use of fingers in mathematical activities during kindergarten facilitates the internalisation of hands and finger patterns. These patterns could later serve as fully functional numerical symbols in primary school, thereby contributing to arithmetic development. From this perspective, the connection between finger gnosia and the cardinal number of gestures emerges and consolidates through practice, representing the outcome rather than the starting point of development. This perspective invites us to enrich the current models that assume that strong finger perceptual abilities are a prerequisite for finger use by suggesting that this relationship may also be bidirectional. This could help explain why, in the present study, FMS assessed at the beginning of primary school significantly related to finger gnosia assessed 1year later. This could also explain why finger use failed to mediate the relationship between finger gnosia and arithmetic development. However, in the present study, limited variability in finger use constrained model estimation and, consequently, limited the empirical evidence bearing on this alternative hypothesis. Moreover, potential confounding factors—such as poorer educational outcomes known to be associated with weaker fine motor skills (Bowler et al., 2024)—were not considered and may provide an alternative explanation for the delayed association observed. As such, the present findings do not allow causal conclusions, and future studies are needed to disentangle the competing hypotheses discussed here.

In the current study, the predictive value of the FMS in arithmetic development was investigated. Unexpectedly, the present results showed that neither the initial value of the FMS nor its evolution over four measurement times was a significant predictor of arithmetic development. This finding was surprising, as it differed from those of Asakawa and Sugimura (2014), who found that FMS at Age 4 strongly predicted arithmetic skills 2 years later. This discrepancy could be explained by the follow-up period. Unlike the children in the present study, Asakawa and Sugimura (2014) worked with 4-year-old preschoolers. During this period, the fingers play an important role in early numerical learning. Indeed, when they did not know the number of words, the preschoolers preferentially used their fingers to communicate quantities (Gunderson et al., 2015). Moreover, finger use facilitates the learning of the cardinal value of new number words (Gibson et al., 2019; Orrantia et al., 2022), probably by creating bridges between quantities and verbal symbols (Andres et al., 2008; Neveu, Schwartz, et al., 2023). To deepen the understanding of the link between the FMS and arithmetic development, future research should focus on children aged 3 to 5 years, an age at which fingers are an essential tool for learning numbers.

Here, the children were older and made little use of their fingers to solve arithmetic tasks. Over the four measurement periods, fingers were used to solve between 16% (Grade 2) and 21% (Grade 1) of the calculations. These rates of finger use were lower than those reported by Poletti et al. (2022), who found that 23% of Swiss second graders still used their fingers to solve an addition task. As early as the first year of primary school, children showed a strong preference for mental calculation strategies. This was probably because the first four items of the arithmetic task involved children simply adding or subtracting 1. Drawing on the concept of successor function, this type of calculation is acquired at a young age, as early as the second year of preschool (Sarnecka & Carey, 2008). Because it is firmly anchored in memory, it does not require first graders to rely on their fingers to solve the problem.

Another explanation is that the instructions given to the children did not explicitly mention the possibility of using their fingers to avoid induction bias. In this context, children's practices largely depend on their own beliefs about which strategies are considered acceptable by adults, as well as beliefs that are themselves shaped by teachers' attitudes toward finger use in mathematical activities. While primary school teachers consider fingers to be a useful calculation aid in the Grade 1 and 2 (Multu et al., 2020; Poletti et al., 2023), this perception may not be universally shared. Thus, French-speaking Belgian teachers might place a greater emphasis on the use of mental calculation strategies from the start of elementary school. In this study, the children may have relied on symbolic representations of numbers to apply these strategies. It is also possible that they drew on finger-based numerical representations previously internalised during preschool years to solve the arithmetic task. This hypothesis, which remains to be verified, could explain why the arithmetic development of Belgian pupils, as observed here, does not seem to rely on the effective use of finger-based strategies that require the ability to move fingers precisely (i.e., FMS).

Another factor that might explain why the FMS failed to become a significant predictor of arithmetic development could stem from the nature of the tasks used for assessing FMS. In this study, the FMS was mainly evaluated through object manipulation tasks with and without a graphomotor component (i.e., placing pegs, threading a shoelace, or tracing a track). These tasks primarily capture visuomotor abilities but focus on bi-digital grasp (i.e., index finger and thumb), which could possibly make them less sensitive to the motor components involved in finger use within numerical contexts. Notably, the coordination task was the only one that explored fine motor skills beyond the digital grasp. Future research should include tasks that capture the full range of finger movements involved in numerical contexts, including both static and dynamic FMS such as those used in cardinal and counting-based number gestures (see Neveu, Schwartz, et al., 2023).

In summary, this study is the first to investigate the triadic relationship among sensorimotor skills, finger use, and arithmetic abilities from a developmental perspective. Finger gnosia at the beginning of primary school predicts the development of arithmetic skills, even when general cognitive abilities are considered. Surprisingly, the results did not show that this relationship is underpinned by finger use. Moreover, age-related changes in the FMS did not predict the development of arithmetic ability. Future research should incorporate other general cognitive markers, such as working memory, to refine our understanding of how finger sensorimotor skills contribute to arithmetic development. Working memory is considered a core component underlying the execution of arithmetic strategies, as it enables temporary storage and manipulation of the numerical information required for successful implementation (Michel et al., 2020; Peng et al., 2016). It also indirectly supports arithmetic, as finger use, identified as a predictor of calculation performance, reduces cognitive load, as well as facilitates the resolution of demanding problems, particularly in children with limited cognitive resources (de Chambrier & Zesiger, 2018; Noël, 2009, 2005; Passolunghi & Cornoldi, 2008; Reeve & Humberstone, 2011). It remains unclear how fingers contribute to the development of arithmetic skills. The findings of this study open new theoretical perspectives for investigating the *functionalist hypothesis* (Butterworth, 1999), challenging traditional developmental models by considering the possibility of bidirectional, rather than strictly unidirectional relationships.

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

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