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Fine motor skills and finger gnosia contribute to preschool children's numerical competencies

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ABSTRACT

Facets of fine motor skills (FMS) and finger gnosia have been reported to predict young children's numerical competencies, possibly by affecting early finger counting experiences. Furthermore, neuronal connections between areas involved in finger motor movement, finger gnosia, and numerical processing have been posited. In this study, FMS and finger gnosia were investigated as predictors for preschool children's performance in numerical tasks. Preschool children ($N = 153$) completed FMS tasks measuring finger agility and finger dexterity as well as a non-motor finger gnosia task. Furthermore, children completed numerical tasks that involved finger use (i.e., finger counting and finger montring), and tasks that did not (i.e., picture-aided calculation and number line estimation). To control for possible confounding influences of domain general skills, we included measures of reasoning and spatial working memory. We found associations between FMS and both finger counting and calculation, but not finger montring. In contrast, finger gnosia was only associated with finger montring, but not finger counting and calculation. Surprisingly, there were no associations between FMS or finger gnosia with number line estimation. Findings highlight that the relationship between finger gnosia, FMS, and numerical skills is specific to task requirements. Possible implications are discussed.

1. Introduction

Numbers are everywhere – on money, on the faces of watches, on phones, and in cooking recipes, rendering number recognition a key competence for functioning in society. However, the road to this understanding can sometimes be rocky, starting early in life and being influenced by many factors. Infants already have a basic capacity to differentiate “more” from “less” (Dehaene, 1997), but it takes much longer for them to acquire number words and link them to concrete magnitudes (Krajewski & Schneider, 2009). One process by which the connection between number words (also referred to as “numerals”, see Sarnecka & Carey, 2008) and concrete magnitudes might be established is by children counting on their own fingers. The finger counting procedure has been specifically linked to children's development of number skills (Fischer et al., 2020; Lafay et al., 2013) and has been argued to influence different levels of numerical development (Roesch & Moeller, 2015).

However, before children can use their fingers to count, they need (1) awareness of their positioning and sensorimotor movement (Noël, 2005; Wasner et al., 2016), and (2) to be able to move them independently from each other to perform the finger counting procedure (Fischer et al., 2018; Suggate et al., 2017). It has therefore been argued that children's finger gnosia (i.e., their awareness of their own fingers) as well as their fine motor skills (FMS) (i.e., the ability to move fingers individually and perform visuomotor tasks with them) contribute to their finger counting skills and, consequently, their numerical development (Barrocas et al., 2020).

There is, however, a lack of studies that systematically and differentially investigate relevant fine motor skills and finger gnosia and their relation to different numerical skills. The goal of this study was therefore to shed light on how FMS and finger gnosia relate to young children's numerical skills. In the following, we therefore present the steps to children's numerical development, followed by current results linking finger gnosia and FMS to this development. We then present hypotheses on links between these skills before describing the current study.

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1.1. Numerical development

The most well-established model of numerical processing is the Triple Code Model by Dehaene and colleagues (Dehaene, 1992; Dehaene et al., 2003; Dehaene & Cohen, 1995). This model posits that numbers are represented in three different codes, namely: (a) a verbal code (i.e., number words and arithmetic facts stored in verbal long term memory), (b) a visual code (i.e., Arabic digits), and (c) a semantic magnitude code (i.e., non-symbolic magnitude understanding and comparison, as well as spatial ordering of magnitudes); the latter of which gives meaning to number words and digits.

Children's acquisition of these three codes is described in the four-step-developmental model of numerical cognition by von Aster and Shalev (von Aster & Shalev, 2007; but see Fritz et al., 2013; Krajewski & Schneider, 2009 for two alternative models of numerical development). These four steps start with the semantic core system of magnitude, which is hypothesized to represent an innate ‘number sense’ (Dehaene, 1997). That is, children can already compare magnitudes in infancy and can soon also recognize the exact number of small sets of objects, a process referred to as ‘subitizing’ (Hannula et al., 2007; Kaufman et al., 1949). Building on this core system, children then acquire the verbal code, consisting of number words, in early childhood (Benoit et al., 2004). They can count verbally and solve simple calculation problems by counting. At the beginning of formal schooling, children are then introduced to the visual code of Arabic digits (Berch et al., 1999; Brysbaert, 1995). They can now solve written calculation problems and discern between even and odd numbers. In the final step, children start spatially representing numbers along what is referred to as a ‘mental number line’ (Dehaene & Cohen, 1995; Restle, 1970). That is, they visualize numbers on a number line that is most often oriented from left to right, and which enables them to approximate calculations thereby informing their arithmetic thinking. This fourth step represents an expansion of the semantic magnitude code, in that the mental number line has been found to be strongly linked to magnitude understanding. Depending on the sources, however, it has been suggested that the spatial ordering of magnitudes starts much earlier and that the mental number line simply becomes increasingly accurate with age (de Hevia & Spelke, 2010; McCrink & Opfer, 2014; Opfer & Thompson, 2006).

1.2. Embodied numerosity

Numerical development has been argued to be founded in, or at least aided by, children's physical experiences. Indeed, bodily interactions with the world might help children acquire understanding of the meaning or magnitude of numbers (Domahs et al., 2010; Lakoff & Núñez, 2000).

The interaction between numerical development and bodily experiences has received ample research interest within the construct of ‘embodied numerosity’ (Domahs et al., 2010; Moeller et al., 2012), which is derived from the more general concept of ‘embodied cognition’ (e.g., Glenberg, 2010; Smith & Gasser, 2005). Specifically, embodied numerosity posits that numerical cognition is tightly interwoven with early physical and sensory experiences that children make when learning about numbers.

The most prominent example of embodied numerosity is finger counting (Domahs et al., 2010; Soylu et al., 2018). Most children count on their fingers when first learning to count, with this phenomenon occurring across cultures and often without formal or explicit instruction (Morrissey et al., 2016; Previtali et al., 2011). Researchers have argued that this embodied experience of finger counting contributes to growing numerical understanding (Moeller et al., 2011). This holds especially true if children manage to move from simply using their fingers as a counting tool to internalizing specific finger patterns as representing a given number (Adriano et al., 2014; Lafay et al., 2013). For example, if children repeatedly count to three on their fingers in a similar fashion (e.g., thumb – ‘one’, index – ‘two’, middle finger – ‘three’), they will eventually no longer need to count these fingers to know that the thumb, index and middle finger are three fingers in total. That is, children internalize finger patterns and thus, transition from ordered counting to a cardinal understanding of magnitudes (Roesch & Moeller, 2015; Wasner et al., 2015).

Within the construct of embodied numerosity, it has been highlighted that brain areas and brain activity overlap between numerical processing and finger motor processes (Andres et al., 2007; Imbo et al., 2011). Insight into how these neural processes are linked comes from clinical studies, imaging research, and perspectives on human history. Patient studies have shown that brain damage around parietal areas (specifically the angular gyrus) can impact both patient's numerical processing skills and finger gnosia (Gerstmann, 1940; see also Rusconi et al., 2005 for a study using repetitive transcranial magnetic stimulation). That is, participants both lose the ability to process numbers and the sensorimotor awareness of their fingers. Further imaging studies support these findings, showing that finger movements and finger gnosia activate similar brain areas to numerical processing (Andres et al., 2007, 2012; Berteletti & Booth, 2015). It has been argued that this link is the result of neuronal redeployment (Anderson, 2007; Penner-Wilger & Anderson, 2013): Brain areas that were long dedicated to one task (i.e., finger movement and finger gnosia) may have been redeployed to also process numerical quantities once humankind started developing the concept of numbers (Fischer et al., 2017; Penner-Wilger & Anderson, 2013). This systematic overlap is thought to be the result of our base-10 number system being built on our ten fingers. Indeed, our fingers are one of the oldest historical counting and calculation instruments (Ifrah, 1998).

1.3. Finger gnosia, fine motor skills, and numerical skills

In light of the above indications that fingers and numerical concepts might be ontologically linked, it would appear warranted to examine finger gnosia and FMS more closely. Finger gnosia is a relatively unidimensional construct, as it mostly relates to the sensorimotor awareness of one's own fingers – a ‘finger sense’ as it were (e.g., Newman, 2016). Although its measurement varies from study to study, the basic premise stays the same. In all finger gnosia tasks, children's view of their hands is occluded and one or more of their fingers are touched by the experimenter. The child then has to identify the fingers that were touched without the aid of visual feedback. However, in some studies the child is asked to give a motor response (e.g., touching the stimulated fingers themselves or pointing at the stimulated fingers on a drawing of two hands), whereas in others they respond verbally (e.g., naming the fingers that were touched) (for an overview see Barrocas et al., 2020).

FMS are often loosely defined as the ability to perform small manual actions requiring eye-hand coordination (Luo et al., 2007). However, in contrast to finger gnosia, FMS are a multi-faceted construct. Two key aspects of FMS that would seem inherent to numerical cognition are manual dexterity and finger agility. Specifically, manual dexterity is often equated to object manipulation skills. As such, it is frequently measured by object-manipulation tasks such as bead threading or coin posting (Fischer et al., 2020; Petermann, 2015). Children's performance is then often scored based on how fast they finish the given task.

Finger agility is considered a more basic skill, which is described as the ability to individually and purposely move one's fingers (Roesch et al., 2021). It is measured, for example, in a tapping task. Children are sat across from an experimenter, who taps one or two fingers on either hand on the tabletop. They are asked to mirror the movement by tapping the corresponding fingers on their own hands without moving any other fingers in the process.

Given the neural overlap between finger gnosia, finger movements, and numerical skills (Andres et al., 2007, 2012; Berteletti & Booth, 2015), we return to the idea that finger gnosia and FMS might be precursors for finger counting and thus, for the development of numerical skills. Finger gnosia has been found to be related to numerical skills in young children, even when controlling for other predictors of numerical development (Newman, 2016; Noël, 2005; Wasner et al., 2016). Training finger gnosia in first grade was also shown to have benefits for children's representations of numbers with fingers, as well as quanitification skills (Gracia-Bafalluy & Noël, 2008). However, other studies found that finger gnosia did not directly contribute to children's early arithmetic skills when more specific skills such as counting are included as predictors (Long et al., 2016).

As outlined, findings are clearer with regard to FMS with studies linking FMS to numerical and mathematical skills (Fischer et al., 2018, 2020; Lewis & Weixler, 2019; Luo et al., 2007; Roebers et al., 2014; Suggate et al., 2017; Van Rooijen et al., 2016). Although most of these studies did not provide theoretical mechanisms for how these associations are formed, research suggests finger counting as the connecting link. In a recent study, Fischer and colleagues (Fischer et al., 2020) posited that FMS are necessary for finger counting and therefore contribute to numerical understanding. They found that the ability to count with fingers and to show numbers with fingers (also called 'finger montring') mediated the link between FMS (specifically object manipulation skills) and numerical skills in three-to-six year old children. These results were in line with previous studies suggesting that FMS are relevant for the development of counting skills and understanding of cardinality (Fischer et al., 2018) and that the link is stronger for finger-based numerical skills compared to non-finger-based numerical skills (Suggate et al., 2017).

However, thus far it is unclear how finger gnosia and FMS interact with each other in their relationship with numerical skills. To our knowledge, only one study has compared the relative contributions of finger gnosia and finger agility for calculation skills (Roesch et al., 2021) and found that both are associated with early calculation. However, whether these results transfer to other FMS measures such as dexterity and from non-finger-based numerical skills to finger-based numerical skills remains an open question. This gap in research was highlighted in a recent review by Barrocas and colleagues (Barrocas et al., 2020), who also noted that the large variability in measures used to assess finger gnosia and FMS made it difficult to compare results.

1.4. The current study

Both FMS and finger gnosia have been reported to contribute to numerical development. However, previous studies investigating these associations have not captured the entire picture. While the study by Roesch et al. (2021) investigated the association between children's early calculation skills and their finger agility and finger gnosia, this study did not include any finger-based numerical skills or measures of dexterity. If the assumed mechanism connecting FMS/finger gnosia with numerical skills is the finger counting procedure, finger counting and finger montring should be included. Furthermore, this study did not control for children's spatial working memory, which has been found to be associated with both FMS and numerical skills (e.g., Cameron et al., 2016; Roebers et al., 2014).

In contrast, the previous study by Fischer and colleagues (Fischer et al., 2020) investigating the association between FMS and numerical skills did include finger counting, finger montring, and spatial working memory tasks. However, in this study, finger gnosia was not included, and calculation was not included as an outcome variable.

The current study therefore aims to address these gaps in previous studies by investigating the relative contributions of FMS and finger gnosia to children's finger-based and non-finger-based numerical skills.

Regarding FMS, it is still unclear which facets of FMS are directly associated with numerical development. For instance, Fischer and colleagues (Fischer et al., 2020) observed that dexterity, but not visuomotor integration as measured by a line-tracing task, was associated with children's numerical and finger counting skills. Likewise, Roesch and colleagues (in preparation) found that finger agility predicted children's mathematical skills, whereas visuomotor integration did not. In this study, we therefore measured both finger agility and dexterity to investigate how they contribute to children's numerical development. Regarding finger gnosia, we chose a non-motor format, so that the employed tasks show little to no overlap in the required underlying skills.

Altogether, we tested preschool children on dexterity, finger agility, finger gnosia, and four numerical tasks: two finger-based numerical tasks (finger counting and finger montring), and two non-finger-based numerical tasks (picture-based calculation and number line estimation). In addition to investigating these associations, we controlled for maturation, reasoning skills, and spatial working memory.

The data reported here are part of a larger study, of which selected variables were previously analyzed in a paper by Papadatou-Pastou and colleagues regarding children's handedness and mathematical learning difficulties (see Papadatou-Pastou et al., 2021, for these analyses).

In accordance with previous studies, we hypothesized that both FMS as well as finger gnosia should be associated with children's numerical skills. Specifically, we expected that (1) FMS and finger gnosia would be correlated with children's finger-based numerical skills and non-finger-based numerical skills; (2) that these associations would remain when controlling for maturation, reasoning skills, and spatial working memory; and (3) that FMS and finger gnosia would be more strongly related to finger-based compared to non-finger based numerical skills.

2. Method

2.1. Participants

The required sample size was calculated a priori using the program G*Power 3.1.9.6 (Faul et al., 2009). We calculated a power analysis for linear multiple regression with a fixed model and R^2 increase. Assuming a medium effect size of $f = 0.15$, an intended statistical power of 0.85, and 6 predictors in the model, the power analysis suggested a necessary sample size of $n = 109$.

Participants were 155 German preschool children attending public kindergartens.[1] Two children had to be excluded from the analysis due to missing data (one child refused to participate, and one child participated only in one of the two testing sessions). The final sample consisted of 153 children (74 girls; age: $M = 5;5$ years, $SD = 8$ months, range: 3;11–6;9 years). According to the parent questionnaires, 27% of children spoke a language other than German at home, and 5% of children were born outside of Germany. Also, 38% of mothers and 39% of fathers reported having completed tertiary education, which is somewhat higher than the national average of around 32% at the time of testing (OECD, 2019).

This study was conducted in accordance with the recommendations of the Ethical Principles of the German Psychological Society (DGP) and the Association of German Professional Psychologists (BDP). Written informed parental consent was obtained and children gave their verbal assent prior to test administration, in accordance with the Declaration of Helsinki.

2.2. Test battery

2.2.1. Finger-based numerical tasks

To assess children's ordinal and cardinal finger-based numerical skills, two types of finger-based tasks were administered. These tasks were self-developed or adapted from previous studies and therefore, the information regarding reliability is provided based on the current sample instead of previous literature. No information on validity was available at the time of writing.

[1] In Germany, children generally attend a non-academic, play-focused kindergarten from ages 3 to 6 years.

2.2.1.1. Finger counting. In the finger counting task, which assessed children's ordinal finger-based number representation, children were asked to count on their fingers to a given number (e.g., "Please count to four on your fingers."). All numbers from 1 to 10 were administered in a pseudo-randomized order: Numbers 1–5 were presented prior to numbers 6–10, as the latter needed to be counted on both hands and switching between one and two hands could have been confusing or too difficult for the younger children in our sample. The experimenter documented the precise order in which the child extended his or her fingers as well as whether the verbal counting sequence was recited correctly, with one number word uttered per extended finger. A trial counted as solved if the child both correctly counted verbally and extended one finger per number word, and the counting resulted in the correct number of extended digits. The specific fingers children used did not play a role in the scoring, so children could for example start counting with their right or left hand as well as with their pinkie finger or thumb. Children could score a maximum of 10 points in this task. Cronbach's alpha for this task was excellent in our sample, $\alpha = 0.91$.

2.2.1.2. Finger montring. In the finger montring task, children's cardinal finger-based number representation was assessed. To this end, children were asked to show a certain number with their fingers (e.g., "Please show me four fingers."). Again, numbers 1–5 were presented prior to numbers 6–10 in a pseudo-randomized order. The experimenter documented which fingers the child extended and whether he or she extended the correct number of fingers, noting whether children extended their fingers simultaneously or consecutively. Because this task was supposed to measure whether children had internalized number magnitudes as finger patterns, a trial only counted as solved if the child extended the fingers simultaneously without counting. Again, it was not relevant to the scoring which fingers children used to display which number. The maximum score was 10 points, and Cronbach's alpha in our sample was good, $\alpha = 0.84$.

2.2.2. Numerical tasks

In order to account for the influence of both FMS as well as finger gnosia on numerical skills in general, we included additional numerical tasks that were not related to finger use.

2.2.2.1. Number line estimation. To test children's spatial-numerical abilities, they were provided with a number line estimation task ranging from 0 to 10 (for a similar task setup see for example Fischer et al., 2011). Children were presented with 10 number lines of which only the endpoints 0 and 10 were marked. A number written above the number line served as the target number, and children were asked to estimate where they thought the number had its place on the number line. Children's absolute estimation error averaged over all 10 trials was used in the analysis. In previous research, reliability for this task was reported to be good to excellent at $\alpha = 0.83$–0.93 (Clarke et al., 2018). In our sample, it was acceptable, $\alpha = 0.70$.

2.2.2.2. Calculation. Children's calculation abilities were tested with a subtest from the TEDI-MATH assessment battery (Kaufmann et al., 2009), specifically with the object calculation subtest. In this test, children are presented with pictures representing an addition or subtraction problem. They are then read the problem (e.g., "How much is 2 balloons plus 3 balloons?") and asked to solve the problem with the help of the picture. Children are allowed to count the objects in this task. The subtest consists of three addition and three subtraction problems, resulting in a maximum sum score of 6. According to the TEDI-MATH test manual, reliability for this subtest lies between $\alpha = 0.52$–0.76 depending on age group and sample and is therefore low to acceptable (Kaufmann et al., 2009). In our sample, reliability was acceptable at $\alpha = 0.73$.

2.2.3. Fine motor skills

The motor skill test battery consisted of measures for children's dexterity and finger agility. This battery consisted of both standardized tasks (i.e., the manual dexterity scale of the Movement-ABC 2; Petermann, 2015), as well as unstandardized measures that were either previously established or developed specifically for the current study.

2.2.3.1. Measures of dexterity. Dexterity was measured with the dexterity subscale from the German version of the Movement Assessment Battery for Children 2 (M-ABC 2; Petermann, 2015), which consists of three tasks.

2.2.3.1.1. Coin posting. Children were asked to insert coins into a slot in a box as quickly as they could. Children from 3 to 4 years old received 6 coins, whereas children aged 5–6 years received 12 coins. Children were encouraged to use their dominant hand for this task, and were given two trials, the faster of which was scored.

2.2.3.1.2. Bead threading. In the bead-threading task, children were instructed to thread square beads onto a string with a pointed end that made the beading easier. Again, children aged 3–4 years received 6 beads, and children aged 5–6 years received 12 beads. The beads were placed in a line in front of them and children were again instructed to complete the task as fast as possible. Out of two trials, the faster was scored.

2.2.3.1.3. Drawing trail. In this task, children were presented with a print-out of a trail. They were instructed to help a biker depicted at the beginning of the trail to reach his house, which was depicted at the end of the trail. Using a red marker, the children had to draw the path for the biker within the boundaries of the trail, preferably without drawing outside the given lines. This procedure was first demonstrated by the experimenter, after which children performed the task twice. Here, children were instructed to work as accurately as possible. The score in this task was the number of errors children made on the more accurate of the two trials.

Reliability for this subscale was reported to be low at $\alpha = 0.51$, but its internal validity was reported high with ICC = 0.82 (Ellinoudis et al., 2011). In our sample, Cronbach's alpha based on raw scores was higher but still questionable, $\alpha = 0.69$. Raw scores for each task were converted to standard scores (range 1–19) based on the age norms given in the Movement-ABC 2 manual. The score used in the analysis was the mean of these three standard scores.

2.2.3.2. Finger agility. We chose a finger agility task previously used by Roesch et al. (2021). In this task, finger agility was assessed as the ability to separately move individual fingers. Children sat opposite the experimenter and placed both hands on a table with their palms open and down. The experimenter similarly placed his hands, mirroring the child's. The experimenter then tapped either one or two fingers on the table and asked the child to lift the same fingers and tap them on the table repeatedly. Children received a point if they managed to imitate the experimenter's movement, tapping the target finger or fingers while all other fingers remained on the table. There were ten items with one target finger and six items with two target fingers, resulting in a maximum of 16 points. In our sample, the internal consistency was good with $\alpha = 0.84$.

2.2.4. Finger gnosia

The non-motor finger gnosia task was based on previous studies (e.g., Wasner et al., 2016) and besides requiring minimal FMS, was also designed to require as little cognitive effort as possible. Sitting opposite the experimenter, children put both their hands through a slot in a box that had its backside removed. This way, children could not see their own hands, but the experimenter could. Next to the box, the experimenter placed an image of two hands laid out in the same pattern as the children's. The experimenter then tapped one of the child's fingers and pointed to one of the fingers on the hand image and asked whether these were the same fingers. Children responded either "yes" or "no". The task consisted of seven items, with corrections being allowed on the first one. On four items, the finger was the same, and on three items, it was not. Among the three items where the finger was not the same, the other finger was once on the same hand (right ring finger and index finger), once on the other hand but both fingers were index fingers, and once on the other hand and also a different finger (left ring finger and right index finger). The sum of correctly solved items (maximum of 7) was used in the analysis. Wasner et al. (2016) previously reported weak reliability for this task, α = 0.55. In our sample, reliability was even worse, α = 0.39.

2.2.5. Control measures

To control for children's reasoning skills, we administered the conceptual thinking subtest from an intelligence test battery (Kaufman-ABC-II, Kaufman & Kaufman, 2015) as well as a spatial working memory test (Corsi block-tapping task, adapted from Kessels et al., 2008; Kessels et al., 2000).

2.2.5.1. Reasoning. The conceptual thinking subtest measures a child's ability to reason about classifications of things and objects in a nonverbal format, and is part of the problem-solving portion of the Kaufman-ABC-II. In the conceptual thinking subtest, children are presented with 4 or 5 pictures and have to decide which one of the pictures does not fit with the set (e.g., three red umbrellas and one yellow umbrella). Again, children give their response by pointing at the chosen picture and are awarded one point per correct response. In total, the subtest consists of 28 items, but testing stops when a child answers 4 out of 5 consecutive items incorrectly. As for verbal knowledge, a sum score was entered as a covariate in the analysis. According to the test manual, this subtest has good reliability, α = 0.83 (Kaufman & Kaufman, 2015), which was very similar to that in our sample, α = 0.82.

2.2.5.2. Spatial working memory. Children's spatial working memory was assessed via a backward Corsi block-tapping task, in which children had to memorize and replicate a visually presented sequence in a reverse order. The task was conducted using a wooden board with 9 wooden cubes (3 cm × 3 cm × 3 cm) glued onto it in a non-geometrical pattern (replicated after the layout presented in Kessels et al., 2000). First, the experimenter tapped the cubes in a certain order at a speed of approximately one cube per second. The child was instructed to wait until after the experimenter was finished, and then tap the cubes in the same reversed order. Two items were presented per span length, with difficulty starting at two blocks and increasing up to seven blocks. If the child successfully replicated at least one of the two items of a given length, testing continued with length increasing by one. As soon as two items of the same length were replicated incorrectly, testing was stopped. The longest successfully replicated span – not the number of correctly remembered items – was used in the analysis as the child's backward spatial working memory span. A previous study investigating the reliability of this task found that internal consistency was acceptable for the number of solved trials in the backward Corsi task, α = 0.78 (de Paula et al., 2016). In our sample, internal consistency was good, α = 0.80.

2.2.6. Demographic variables

Prior to the study, parents filled out a questionnaire on demographic information and their child's home learning environment (which will not be reported here). Parents provided demographic information regarding the child's country of birth, languages spoken at home, and parents' highest educational achievement (0 = no secondary school qualification to 5 = university degree).

2.3. Procedure

Parents completed the questionnaire at home and returned it together with written consent to the kindergarten staff. Children were then tested individually in their respective kindergartens across two sessions by undergraduate thesis students and the first author. The tasks were presented in the same order to each child, and each of the two sessions took approximately 20–30 min per child.

2.4. Analytical approach

We first correlated measures of FMS and finger gnosia with all numerical tasks while controlling for age, spatial working memory and reasoning. Second, we calculated hierarchical linear regression models to assess whether FMS and/or finger gnosia explained unique variance in any of the four numerical tasks beyond the variance explained by the control variables.

3. Results

3.1. Data preparation and descriptive statistics

Out of the 153 participants, 147 spontaneously wrote and drew with their right hand, five with their left hand, and one child switched their writing hand between tasks. Because the six non-right-handed children did not differ from the right-handed children in their fine motor or numerical task performance, data from all children were analyzed together.

Descriptive statistics for all measures are displayed in Table 1. Note that Skewness and Kurtosis are high for finger counting and finger montring, indicating ceiling effects for both tasks. Except for age in months, none of the variables were normally distributed as confirmed by Kolmogorov-Smirnov tests of normal distribution.

3.2. Correlations

Because most variables were not normally distributed, both raw and partial correlations were calculated as Spearman correlations. To calculate the partial Spearman correlations, a matrix was created from the Spearman correlations and used to calculate partial correlations (for a description of this procedure see IBM Support, 2020).

As can be seen in Table 2, most variables were correlated prior to partialling out the control variables. Only three correlations were not significant, and two of these were interestingly the correlations between number line estimation and both finger agility and dexterity.

Table 1
Descriptive statistics.

	M	*SD*	Min.	Max.	Skew	Kurtosis
Age in months	65.22	8.70	47.00	81.00	−0.17	−0.80
Fine motor skill tasks						
Finger agility (sum correct)	10.96	3.62	2.00	16.00	−0.48	−0.55
Dexterity (mean standard score)	9.80	2.11	2.00	13.67	−0.61	0.38
Finger gnosia (sum correct)	4.86	1.38	1.00	8.00	−0.21	−0.27
Numerical tasks						
Finger counting (sum correct)	8.95	2.25	0.00	10.00	−2.46	5.57
Finger montring (sum correct)	8.33	2.26	0.00	10.00	−1.59	2.13
Calculation (sum correct)	2.79	1.85	0.00	6.00	0.20	−0.91
Number line estimation (percent estimation error)	0.21	0.09	0.04	0.53	0.99	1.56
Control variables						
Spatial working memory (max span)	3.08	1.66	0.00	6.00	−0.20	−0.45
Reasoning skills (sum correct)	13.29	4.10	1.00	21.00	−0.69	0.35

Table 2
Spearman correlations between all variables.

	1	2	3	4	5	6	7	8	9
FMS									
1 Finger agility	–								
2 Dexterity	0.165*	–							
Finger gnosia									
3 Finger gnosia	0.195*	0.202*	–						
Numerical tasks									
4 Finger counting	0.301**	0.214**	0.310**	–					
5 Finger montring	0.214**	0.224**	0.326**	0.616**	–				
6 Calculation	0.313**	0.244**	0.326**	0.358**	0.455**	–			
7 Number line estimation	−0.143	−0.127	−0.189*	−0.323**	−0.493**	−0.490**	–		
Control variables									
8 Spatial working memory	0.218**	0.194*	0.309**	0.388**	0.452**	0.561**	−0.466**	–	
9 Reasoning skills	0.269**	0.214**	0.149	0.365**	0.444**	0.323**	−0.299**	0.286**	–
10 Age in months	0.232**	0.131	0.328**	0.433**	0.520**	0.495**	−0.388**	0.540**	0.329**

* $p < .05$.
** $p < .01$.

Furthermore, the correlation between age and dexterity was not significant, but this was due to dexterity being the one variable which was calculated by using age-normed standard scores.

More interestingly, when controlling for age, reasoning, and spatial working memory, the correlation results changed substantially (see Table 3). Finger agility, dexterity, and finger gnosia were no longer significantly correlated with each other. Finger agility correlated with finger counting (ρ = 0.172) and calculation (ρ = 0.183), but not with finger montring or number line estimation. Dexterity correlated with no other variables and was therefore excluded from the following regression analyses. Finger gnosia correlated with finger counting (ρ = 0.169) and finger montring (ρ = 0.161), but not calculation or number line estimation.

Among the numerical tasks, finger counting and finger montring were moderately correlated (ρ = 0.442), and number line estimation correlated with both finger montring (ρ = −0.284) and calculation (ρ = −0.259). Note that the correlations with number line estimation were negative because the dependent variable in this task is the estimation error, with smaller values indicating better performance.

3.3. Hierarchical regressions

Prior to conducting the hierarchical regressions, all variables were z-standardized to generate standardized regression weights. We entered the predictors in two steps, beginning with the control variables spatial working memory, reasoning, and age in months. We then entered finger agility and finger gnosia in the second step. With this method, we could assess whether finger agility and finger gnosia added any additional variance to the models.

Because a high correlation between predictors in a regression model can influence the reliability of estimates (Alin, 2010), we tested for multicollinearity by calculating the variance inflation factor (VIF). According to conventions, individual VIF values of 10 and above indicate linear dependency, as does a mean VIF that is substantially larger than 1 (Alin, 2010). In our final regression models, individual VIF values ranged between 1.122 and 1.519, with a mean VIF of 1.318. Therefore, we inferred that there was no substantial multicollinearity between the predictors in our models.

3.3.1. Regression results for finger counting and finger montring

We expected the contributions of FMS and finger gnosia to be strongest for finger-based tasks. For finger counting, the control variables explained a significant amount of variance (26.3%), which was reflected in the significant regression weights of all included variables (see Table 4). When adding finger agility and finger gnosia in the second step, the explained variance increased significantly by 4.3%. Only finger agility was a significant predictor, whereas finger gnosia was not.

In the model for finger montring, an entire 38.4% of variance was explained in the first step with the control variables. The addition of finger agility and finger gnosia in the second step again significantly increased the explained variance (2.8%), with finger gnosia being a significant predictor, but with finger agility not contributing significantly to the model.

3.3.2. Regression results for calculation and number line estimation

We then calculated hierarchical regressions for the two non-finger-based measures calculation and number line estimation with the same two steps (see Table 5). For calculation, control variables explained 36.0% of variance. However, while working memory and age were significant predictors, reasoning was not. In the second step, the inclusion of finger agility and finger gnosia significantly increased the explained variance by 3.9%. Both of these predictors contributed significantly to the model.

In the model for number line estimation, the first step explained

Table 3
Partial Spearman correlations controlling for age in months, reasoning, and spatial working memory.

	1	2	3	4	5	6
FMS						
1 Finger agility	–					
2 Dexterity	0.095	–				
Finger gnosia						
3 Finger gnosia	0.111	0.147	–			
Numerical skills						
4 Finger counting	0.172*	0.115	0.169*	–		
5 Finger montring	0.028	0.110	0.161*	0.442**	–	
6 Calculation	0.183*	0.142	0.146	0.079	0.152	–
7 Number line estimation	0.009	−0.010	−0.013	−0.094	−0.284**	−0.259**

* $p < .05$.
** $p < .01$.

Table 4
Hierarchical linear regressions for finger counting and finger montring.

	Finger counting				Finger montring			
Variables	β	SE β	R^2	$\triangle R^2$	β	SE β	R^2	$\triangle R^2$
Step 1			0.263**	0.263**			0.384**	0.384**
Spatial working memory	0.175*	0.084			0.198*	0.077		
Reasoning skills	0.272**	0.076			0.305**	0.070		
Age	0.217*	0.084			0.297**	0.077		
Step 2			0.306**	0.043*			0.411**	0.028*
Spatial working memory	0.145	0.083			0.172*	0.077		
Reasoning skills	0.239**	0.076			0.291**	0.07		
Age	0.158+	0.085			0.245**	0.078		
Finger agility	0.160*	0.073			0.058	0.067		
Finger gnosia	0.135	0.075			0.162*	0.069		

+ $p < .07$.
* $p < .05$.
** $p < .01$.

Table 5
Hierarchical linear regressions for calculation and number line estimation.

	Calculation				Number line estimation			
Variables	β	SE β	R^2	$\triangle R^2$	β	SE β	R^2	$\triangle R^2$
Step 1			0.360**	0.360**			0.244**	0.244**
Spatial working memory	0.403**	0.079			−0.275**	0.085		
Reasoning skills	0.069	0.071			−0.189*	0.077		
Age	0.244**	0.078			−0.167+	0.085		
Step 2			0.399**	0.039*			0.245**	0.001
Spatial working memory	0.373**	0.077			−0.275**	0.087		
Reasoning skills	0.040	0.071			−0.194*	0.079		
Age	0.186*	0.079			−0.168+	0.088		
Finger agility	0.142*	0.068			0.029	0.076		
Finger gnosia	0.140*	0.069			−0.011	0.078		

+ $p < .07$.
* $p < .05$.
** $p < .01$.

significant variance (24.4%), with working memory and reasoning, but not age, being significant predictors. As expected based on the correlation results, the inclusion of finger agility and finger gnosia in step two did not add significantly to the model, and neither predictor was significant.

4. Discussion

In this study, we set out to investigate the relationship between FMS and finger gnosia with different numerical skills in early childhood. In contrast to previous studies on this topic (Fischer et al., 2020; Roesch et al., 2021), we included both finger-based and non-finger-based numerical tasks and measured two facets of FMS (finger agility and dexterity). Generally, we found that both FMS and finger gnosia contributed to numerical skills, but that their contribution depended on which FMS and which numerical skill were measured. Our results were mostly in line with our expectations based on previous research (e.g., Fischer et al., 2018, 2020; Lewis & Weixler, 2019; Luo et al., 2007; Newman, 2016; Roebers et al., 2014; Suggate et al., 2017; Wasner et al., 2016) but went against our expectations regarding the effects of dexterity and the associations with children's number line estimation skills.

4.1. Associations with finger-based numerical skills

As expected, we found that both finger-based numerical skills, namely finger counting and finger montring, were associated with finger agility or finger gnosia even when controlling for children's age, spatial working memory, and reasoning skills. Children's finger counting skills were associated with finger agility, but not finger gnosia. In contrast, children's finger montring skills were better explained by finger gnosia than finger agility.

To interpret these differential results, a functionalist perspective might shed some light on our findings. When finger counting, children in Western cultures mostly count linearly (Lindemann et al., 2011). That is, they start with their thumb and then extend one finger at a time until they reach the number they want to count to. Considering the motor demands of this task, it requires children to extend one finger after the other individually, by virtue of finger agility. In this case, it might not be necessary for them to be sensorily aware of their fingers, thus rendering finger gnosia as not a necessary prerequisite for success. However, considering finger montring (i.e., the skill to show a number simultaneously with one's fingers), the demands of the task might be different. When children are asked to show a number, this of course requires motor skills. However, when simultaneously extending, for example seven fingers, children need to be sensorily aware of which fingers they are moving. Although visual control can help them correct the result, finger sense or finger gnosia should be the more important skill required in performing this task. This might explain why finger agility was correlated with finger montring but was not a significant predictor in a model that also included finger gnosia. It is also worth noting that children performed almost at ceiling in finger montring, indicating an automated recall of finger number patterns. Thereby, the children in our study might have already transitioned to a cardinal representation of finger number patters and might rely more on finger gnosia than FMS for the task.

Unexpectedly, dexterity was not significantly correlated with either finger counting or finger montring after spatial working memory, reasoning skills, and age were controlled for. Previous studies by Fischer et al. (2020) have shown that this association does not seem to hold up when control variables are taken into account. Perhaps dexterity, operationalized as object manipulation (such as the bead threading and coin posting tasks we used from the M-ABC-2; Petermann, 2015), is less relevant for finger counting and finger montring performance. Instead, finger agility and finger gnosia might be the precursors that are functionally necessary for performing those tasks.

4.2. Associations with non-finger-based numerical skills

For the two non-finger-based tasks, the results for the calculation task were mostly in line with our expectations. We had expected that both finger agility and finger gnosia would be associated with children's calculation skills based on the previous study by Roesch and colleagues (Roesch et al., 2021), but had also expected that dexterity might play a significant part. One reason for this result might have been that, other than Roesch and colleagues, we also included spatial working memory in our test battery. By controlling for spatial working memory, which was by far the strongest predictor in this model, we might have eliminated the effect of dexterity on calculation, as it could have been mediated by spatial working memory.

Contrary to our expectations, we observed that neither finger agility nor finger gnosia explained significant variance in children's number line estimation skills. Note that this task was conducted in a paper-pencil format, which we would have expected to be associated with FMS due to the visuomotor precision required to place their estimate on the number line with the pencil. This expectation was supported by previous reports of associations between visuomotor and visuospatial skills (Simms et al., 2016), and also by findings that number line representations are associated with finger counting habits (Fischer, 2008). An association between FMS and number line estimation could therefore exist through the process of finger counting skills. However, spatial working memory was again a strong predictor for number line estimation skills. It is therefore possible that children relied on their visuospatial working memory skills for solving this task, rather than visuomotor skills. Note that reasoning skills were also a significant predictor for this task. This could speak to the cognitive demands of the number line estimation task, which has previously been assumed to be solved by many participants via proportion-judgment strategies (Barth & Paladino, 2011). Specifically, participants often use a central reference point in the middle of the line (e.g., to estimate the position of the number 50 on a line ranging from 0 to 100) to facilitate their estimates. Such a visuospatial strategy requires both spatial working memory to remember the position as well as reasoning skills to develop the strategy in the first place.

4.3. Limitations

The current study presents interesting findings but is not without its limitations. For one, although all non-standardized tasks used in our study were adapted from previous research, further development might be necessary. Specifically, the finger counting and finger montring tasks appeared particularly easy for the children in our sample, which resulted in ceiling effects. To avoid this, more items could be included and response speed recorded.

The design of our study was also correlational, thus not allowing us to draw causal inferences about the direction in which FMS, finger gnosia, and numerical skills are associated. Longitudinal studies could shed more light on the directionality and possible reciprocity of this relationship. Particularly, it would be of interest to both start at an earlier age when children are not yet as proficient at finger counting, and to extend the measurements into the early school years to assess long-term influences of various aspects of FMS and finger gnosia.

4.4. Practical implications

Early childhood educators are often aware of how important children's numerical skills and FMS are for their successful transition to school. However, the consistent findings that FMS, finger gnosia, and numerical skills are associated should be considered more ubiquitously. Many kindergarten mathematics curricula are play-based, but do not capitalize on the impact finger training can have on mathematical development. Specifically, a conscious integration of fine motor aspects into these curricula could further increase their effectiveness. This is also highlighted in intervention studies, which show benefits of incorporating embodiment into numerical training in general (Fischer et al., 2011, 2015; Link et al., 2013) and potential benefits of finger training in particular (Gracia-Bafalluy & Noël, 2008; Jay & Betenson, 2017).

Additionally, despite critical voices in education speaking out against the use of finger counting in mathematics (for a critical discussion see Moeller et al., 2011), our results suggest that fostering children's early counting skills by encouraging finger use could be beneficial for their later numerical development, and might concurrently train their FMS as well as relieve their working memory (Beller & Bender, 2011; Fischer et al., 2020). Moreover, early finger counting could pave the way for the transition towards a cardinal understanding of numbers (Moeller et al., 2011).

5. Conclusion

The current study adds to the growing body of work showing that FMS and finger gnosia contribute to early numerical development. We were also able to further differentiate the picture by separately examining two relevant aspects of FMS (dexterity and finger agility) in addition to finger gnosia – as well as their relationships to numerical skills for which finger counting is important to varying degrees. Future work should continue to study how these skills emerge and relate to each other at different stages of numerical development. Longitudinal studies are essential for this. Further, this work should ultimately move to test causal mechanisms, most likely through experiments and intervention studies.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. No external funding was received for this study.

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