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Date: 2023-04-01T00:00:00+00:00

Abstract

Existing research on the relationship between children's fine motor skills and mathematical abilities has yielded inconsistent findings. To clarify the overall association strength and its influencing factors, this study employed meta-analysis to synthesize relevant research from domestic and international sources. Through literature search and screening, a total of 34 studies comprising 42 effect sizes were included, with a total sample size of 78,527 individuals. Publication bias tests revealed no evidence of publication bias in the included meta-analytic literature; heterogeneity tests indicated that a random-effects model was appropriate. The results demonstrated a moderate positive correlation between fine motor skills and mathematical abilities ($r = 0.27$, 95% CI [0.23, 0.32]). The relationship was moderated by cultural background and measurement tools for fine motor skills, but not by children's age or gender. These findings suggest that educators should prioritize the development of fundamental motor skills in early childhood, implement effective fine motor skill training methods, enhance children's fine motor proficiency, and thereby facilitate the development of their mathematical abilities.

Full Text

The Relationship Between Children's Fine Motor Skills and Mathematical Ability: A Meta-Analysis

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Abstract: The relationship between children's fine motor skills and mathematical ability has been inconsistent in existing research. To clarify the overall strength of association and its influencing factors, this study employed meta-analysis to integrate relevant domestic and international studies. Through literature search and screening, a total of 34 papers with 42 effect sizes were included, with a total sample size of 78,527 individuals. Publication bias tests showed no publication bias in the literature included in this meta-analysis; heterogeneity tests indicated that the random effects model was appropriate. Results showed that fine motor skills were moderately positively correlated with mathematical ability (r = 0.27, 95%CI = [0.23,0.32]); the relationship was moderated by cultural background and measurement instruments for fine motor skills, but not by children's age or gender. These results suggest that educators need to pay attention to the development of basic motor skills in early childhood, adopt effective training methods for fine motor skills, improve children's fine motor proficiency, and thereby promote the development of their mathematical ability.

Keywords: fine motor skills, mathematical ability, embodied cognition, meta-analysis
Classification: B844

1.1 The Concept and Measurement of Fine Motor Skills

Fine Motor Skills (FMS) refer to the ability to develop and use the small muscle groups of the hands, forearms, upper arms, and shoulders to complete various operational activities (Ning Ke et al., 2020). To date, there is no unified conclusion regarding the structural classification of fine motor skills. Existing research has classified the structure of fine motor skills into three types, all of which include two core components: life skills and writing skills (Table 1). Life skills primarily refer to activities such as dressing, buttoning, and tying shoelaces. These skills not only help children develop good living habits but also promote the development of cognitive abilities in corresponding areas of the cerebral cortex (Qu Fang-bing et al., 2012). Writing skills are mainly divided into two forms: tracing (tracing visible graphics, letters, and numbers through transparent paper placed over the original) and copying (copying letters, numbers, and geometric shapes on a new sheet of paper), both involving synchronous hand-eye movement and visual stimulus processing. Both life skills and writing skills require connecting finger movements with what the eyes see. The difference lies in that life skills focus on controlling finger movements without emphasizing the integration of visual information, whereas writing skills rely more heavily on visual input, with a focus on integrating visual information for output through writing actions (Oberer et al., 2018). Evidently, writing skills are crucial for children's academic development. Research has found that preschool children's writing skills better predict second-grade mathematics and reading achievement than life skills (Dinehart & Manfra, 2013). Even after controlling for covariates such as gender, socioeconomic status, and IQ, writing skills still significantly predict mathematical ability (Carlson et al., 2013). However, most studies have not separated writing skills from life skills in fine motor skills, instead examining them as a whole in relation to mathematical ability. Therefore, this study does not distinguish between the core components of fine motor skills but treats them as an integrated whole to determine their association with mathematical ability.

A variety of measurement tools exist for fine motor skills. For example, the Learning Accomplishment Profile-Diagnostic (LAP-D), Bruninks-Oseretsky Test of Motor Proficiency (BOT-2), Beery Visual Motor Integration (Beery VMI), Movement Assessment Battery for Children (2nd ed.) (MABC-2), Early Screening Inventory-Revised (ESI-R), and East Asia-Pacific Early Child Development Scales (EAP-ECDS) are all standardized measurement tools with good reliability and validity that are widely used (Table 2). Due to inconsistent structural classifications of fine motor skills, the examination focus varies across studies. However, most measurement tasks include the two core components of writing skills and life skills or one of these components. Other self-compiled task tools are based on coordination and control of hand fine motor movements, examining movements of small muscles such as hands and fingers, making their inclusion in the meta-analysis feasible.

1.2 The Connotation and Measurement of Mathematical Ability

Mathematical ability is a multi-dimensional, multi-level structural system. Swedish psychologist Werdelin posited that mathematical ability is the capacity to understand the nature of mathematical problems, symbols, methods, and proofs; to learn them, retain them in memory, and reproduce them; to combine them with other problems, symbols, methods, and proofs; and to apply them in solving mathematical problems (Yu Ping, 2004). Most American scholars believe that children's mathematical ability includes problem-solving ability, logical reasoning ability, mathematical communication ability, mathematical connection ability, and mathematical representation ability (National Council of Teachers of Mathematics, 2014). German scholars contend that children's mathematical ability comprises problem-solving ability, connection ability, mathematical argumentation ability, mathematical modeling ability, and mathematical description ability (Du Wen-ping, 2014). Chinese researchers define mathematical ability as the individual psychological characteristics for smoothly and effectively completing mathematical activities (Hu Zhong-feng, 2001), consisting of three thinking abilities (mathematical operation ability, logical thinking ability, and spatial imagination ability) and five mathematical thinking qualities (depth, flexibility, originality, criticality, and agility of thinking) (Lin Chong-de, 2003). Although scholars from different countries hold divergent views on the structure of mathematical ability, overall, the various components of mathematical ability are interdependent and mutually constraining, collectively forming a dynamic, multi-level, multi-dimensional three-dimensional network structure (Sun Yi-ze, 2003). In summary, this study defines mathematical ability as the individual psychological characteristics for smoothly and effectively completing mathematical activities—that is, the psychological capacity formed and developed through activities of learning, researching, discovering mathematical knowledge, and applying mathematical knowledge to solve mathematical problems, specifically manifested as scores on various mathematical ability measurement instruments and tasks.

Many measurement tools exist for children's mathematical ability, among which the most widely used are the Woodcock-Johnson III Tests of Achievement and the Wechsler Individual Achievement Test. The Woodcock-Johnson has reliability coefficients between 0.76 and 0.99 (Mather, 2001); the Wechsler Individual Achievement Test has reliability coefficients of 0.92 to 0.99 (Wechsler, 2005). These two standardized measurements mainly involve arithmetic, mathematical operations, and problem-solving. Additionally, some studies have measurement tools specifically for preschool children's mathematical ability or self-compiled mathematical tasks, mainly involving counting, number comparison, number estimation, and simple addition and subtraction operations. For example, the Test of Early Mathematics Ability (TEMA) developed by Ginsburg and Baroody (2003) has received relatively wide acclaim. This scale is suitable for assessing early mathematical ability in children aged 3 to 8 years 11 months, with test-retest reliability of 0.85 and internal consistency of 0.94 (Kang Dan, 2014). The Early Numeracy Test (ENT) developed by Dutch scholars Van de Rijt et al. (1998) can be used to assess basic mathematical ability in children aged 4 years 7 months to 7 years 6 months, with internal consistency of 0.9 (Aunola et al., 2004). Measurement of school-age children's mathematical ability is mainly examined in national standardized academic tests (such as California Standardized Academic Test, Stanford and Heidelberg tests), primarily involving quantity comparison, addition and subtraction operations, and problem-solving.

1.3 The Relationship Between Fine Motor Skills and Mathematical Ability

Research on the relationship between fine motor skills and mathematical ability has generated some controversy. Integrating previous studies reveals three main viewpoints: The first viewpoint holds that the two are positively correlated, and that fine motor skills are an important predictor of children's mathematical ability. Numerous studies have shown that fine motor skills are positively correlated with literacy and mathematics achievement (Cameron et al., 2012; Roebers et al., 2014). After controlling for other background variables (such as gender, age, and socioeconomic status), preschool children's fine motor skills are not only correlated with mathematical ability but also strongly predict first-grade mathematics achievement (Roebers et al., 2014; Cameron et al., 2016). Children with strong writing skills progress faster in learning numbers, letters, and complex learning tasks than those with poor writing skills (Cameron et al., 2012). Some researchers have also intervened in preschool children's fine motor skills, with results showing significant improvements in mathematical ability in the intervention group (Gracia-Bafalluy & Noël, 2008). Furthermore, mathematical ability can also influence fine motor skills; early mathematical learning in children can enhance their fine motor abilities, as children's fine motor skills develop correspondingly alongside mathematical competencies such as place value, number composition, manipulatives and concrete representations, and number sense (Klupp et al., 2021). Children with weaker mathematical ability development also show weaker fine motor development (Asakawa et al., 2019). The second viewpoint posits that the correlation between fine motor skills and mathematical ability is not significant. Related cross-sectional and longitudinal studies have both indicated non-significant correlations between fine motor skills and mathematical ability (Haapala et al., 2014; Van Niekerk et al., 2015). The third viewpoint suggests that the correlation between fine motor skills and mathematical ability is not robust, with the relationship showing different directional correlations across different age groups. Empirical studies have found that when individuals are in the preschool period, fine motor skills can positively predict mathematical ability (Roebers et al., 2014; Cameron et al., 2016); however, when individuals are school-aged, fine motor skills are negatively correlated with mathematical ability (Li Bei-lei et al., 2003; Morales et al., 2011; Malone et al., 2022).

Currently, three main theories attempt to explain the mechanism underlying this relationship. The Embodied Cognition View posits that, beyond the brain, the body plays an important role in cognitive processes (Wang Cui-yan, Zhang Kai, 2014). Bodily development can be regarded to some extent as the degree of cognitive development, with cognition depending on individuals' perceptual and motor systems (Qu Fang-bing et al., 2012). Fine hand movements play a crucial role in infants' and young children's understanding of various attributes and relationships of things, as well as in the development of perceptual integrity and concrete thinking abilities (Qu Fang-bing et al., 2012). In early childhood, children can form numerical representations through fine finger movements. When counting and calculating, young children rely on external finger representations, mainly manifested as children using their hands to move, manipulate, or touch objects being counted during the counting process, and gradually disengaging from touching objects and using fingers (Huang Jin, Tian Fang, 2015). This change occurs because children internalize finger operation patterns into representational operation patterns. Evidently, finger movements 介入 mathematical cognition, can connect with numbers, present concrete expressions of quantity, and better help children understand numbers. Brain imaging research further confirms this view, showing that brain regions activated by children's finger movements and finger cognitive activities are similar to those involved in number processing (Berteletti & Booth, 2015).

Australian cognitive psychologist John Sweller (1988) proposed Cognitive Load Theory, which primarily refers to controlling memory load during complex teaching processes to minimize cognitive load that hinders learning (Zhou Pan-pan, Yuan Hai-quan, 2021). When counting, young children need to rely on finger movements to coordinate hand and mouth. When children use hand movements to count points, by visually and kinesthetically tracking objects already counted, they can reduce the burden on their working memory, and the released working memory resources can better complete counting tasks (Kirsh & Maglio, 1994).

The 'automation explanation' provided by Schmidt et al. (2017) for the relationship between fine motor skills and academic achievement further substantiates the validity of Cognitive Load Theory. They argue that an indirect causal relationship may exist between children's fine motor skill development and academic achievement, mediated by executive functions (Malone et al., 2022). According to this view, if the fine motor skills required for children to complete basic classroom tasks become automated through practice (such as writing), then their attention and other executive function skills can focus on more complex conceptual and academic skill development (such as arithmetic) (Cameron et al., 2016; Kim et al., 2018). That is, regarding mathematics learning, as fine motor skills gradually become proficient and automated, children's general cognitive abilities are no longer concentrated on fine motor skills but are allocated to more complex mathematical learning tasks, thereby helping to improve mathematics academic achievement.

The Redeployment View, from a neuropsychological perspective, emphasizes the role between finger movements and mathematics. Also known as the 'Massive Redeployment Hypothesis (MRH),' this view suggests that evidence indicates a normal brain region contributes to many cross-domain cognitive uses, performing the same work across these uses (Anderson, 2010). Researchers have found that when individuals count, brain hand motor circuits are activated (Andres et al., 2007); when individuals process numbers, areas around the motor cortex are also activated (Tschentscher et al., 2012). The two share some neural resources, with certain regions involved in finger representation participating in quantity representation through evolutionary mechanisms, or these regions being 'redeployed' to support numerical cognition. Therefore, these regions can be used for both finger representation and quantity representation.

In summary, Embodied Cognition Theory, Cognitive Load Theory, and the Redeployment View all explain the relationship mechanism between fine motor skills and mathematical ability to some extent, but each has certain limitations. Embodied Cognition Theory challenges the basic common sense that 'the brain is the organ of the mind,' the explanation of Cognitive Load Theory may primarily apply to primary and secondary school student populations, and the Redeployment View's claim about overlapping neural networks between finger activities and numerical processing needs more support from relevant cognitive neuroscience studies (Wang Cui-yan, Zhang Kai, 2014). Considering the controversies among these three viewpoints and the limitations of relevant theoretical explanations for the relationship mechanism, this study conducts in-depth analysis and discussion from a meta-analytic perspective. Based on the first viewpoint (positive correlation between the two) being confirmed by numerous studies, we propose Research Hypothesis 1: Fine motor skills are positively correlated with mathematical ability.

1.4 Moderating Variables in the Relationship Between Fine Motor Skills and Mathematical Ability

Children's age may influence the relationship between fine motor skills and mathematical ability. Fine motor skills are the foundation of children's life and learning, typically developing during childhood, but with developmental stages and imbalances. Individuals' fine motor skills begin with unconditional reflexes in infancy and develop rapidly during the preschool period. Research indicates that the preschool period is a critical period for fine motor development because preschool children at this stage continuously attempt drawing, writing, and grasping, with the most rapid development occurring during this time (Dong Qi, Tao Sha, 2004). Preschool children's fine motor skills gradually enrich with increased experience (such as drawing, crafts, playing with sand and water, manipulative activities, and other play activities), generally stabilizing only upon entering school age (Dinehart & Manfra, 2013). Therefore, the developmental level of fine motor skills at different age stages may affect mathematics learning. Additionally, a cross-sectional study of children aged 4-11 showed that the correlation between motor skills and cognition was moderated by different age groups, with school-age children (age 7) showing the weakest correlation between motor skills and cognition (Davis et al., 2011). Thus, this study divides participants into preschool and school-age children, and based on the above, proposes Research Hypothesis 2: Children's age can moderate the relationship between fine motor skills and mathematical ability.

Gender may influence the relationship between fine motor skills and mathematical ability. Gender Schema Theory posits that schemas are formed through individual-environment interactions, and once formed, individuals are expected to behave in ways consistent with traditional gender roles (Xing Qiang, 2002). Research shows that societal expectations for girls are generally 'quiet, liking fine motor movements of small hand muscles,' whereas for boys they are 'active, liking gross motor movements of large body muscles' (Dong Qi, Tao Sha, 2004). Due to the existence of gender stereotyping, children are required to learn the gender schema content of their society, thereby possessing traits associated with their own gender schema (Feng Ming, Ye Ze-chuan, 1996). According to this theoretical perspective, girls may have more opportunities to practice fine motor skills consistent with gender schemas, and girls' fine motor skills may develop better than boys'. Additionally, some studies indicate that girls have lower tactile thresholds than boys and are better at completing fine motor tasks (Fang Ying, 2017), and girls prefer to take on roles such as 'mother' and 'older sister' in role-play games, thus having more training opportunities for fine motor skills (Wu Wei-dong, 2011). Therefore, girls can utilize gender advantages to better develop fine motor skills to support counting and simple operations, whereas boys do not have this advantage. In summary, this study proposes Hypothesis 3: Children's gender can moderate the relationship between fine motor skills and mathematical ability.

Cultural background may influence the relationship between fine motor skills and mathematical ability. Education is an important phenomenon in human society, coexisting with human development throughout history. During the long historical development process, different geographical locations and cultural backgrounds have created different education systems. Cultural Dimension Theory constructs a framework for measuring cultural differences among countries, with these dimensions collectively depicting how deep-rooted social culture influences its members' values, the most typical being the dimension of 'Long-Term Versus Short-Term Orientation.' Long-term oriented cultures focus on the future, while short-term oriented cultures value the present (Wei Linhua, 2012). Research indicates that Eastern countries are primarily long-term oriented, while Western countries are mainly short-term oriented (Zhao Zhiyin, 2022). In Eastern countries dominated by long-term orientation, emphasis is placed on children's academic achievement, with substantial time and money invested in having children participate in various specialty training classes (such as drawing, art, and calculation classes) to cultivate children who meet future talent standards, thereby avoiding future uncertainties (Liu Jun-hong, Xu Wenli, 2020). Compared to the West, children in Eastern cultural backgrounds may spend more time training fine motor skills (drawing and art classes) and improving mathematics academic achievement (calculation classes). Therefore, in Eastern cultural contexts, children can utilize this opportunity or advantage to better develop fine motor skills or mathematical ability, thereby strengthening the correlation between the two. Additionally, chopstick use skill is a culturally characteristic and typical fine motor skill in Eastern countries (Dong Qi, Tao Sha, 2004), with children using daily mealtime to practice using chopsticks, fully exercising fine motor skills, which can support children's mathematical ability development to some extent. In summary, this study proposes Hypothesis 4: Cultural background can moderate the relationship between fine motor skills and mathematical ability.

The type of fine motor skills measurement instrument may influence the relationship between fine motor skills and mathematical ability. As previously mentioned, the structural classification of fine motor skills is not unified, and the core components (life skills and writing skills) have not been separated from the whole, which also leads to diversification of measurement tools. Different measurement tools vary in structural classification, measurement items and difficulty levels, scoring methods, etc., which may affect the degree of association between fine motor skills and mathematical ability. Some researchers believe that different measurement tools affect the strength of the relationship between two variables (Ding Feng-qin, Lu Zhao-hui, 2016; Eisenberg & Miller, 1987). Therefore, this study proposes Hypothesis 5: Different fine motor skills measurement instruments can moderate the relationship between fine motor skills and mathematical ability.

2.1 Literature Search

A comprehensive search for studies on the relationship between fine motor skills and mathematical ability was conducted, retrieving literature from three Chinese databases (CNKI, Wanfang, and VIP) and three English databases (Web of Science, SCI, and Google Scholar). In the Chinese literature search, search terms for fine motor skills included 'fine motor skills' or 'finger dexterity' or 'motor skills' or 'visual-spatial integration' or 'visual-motor coordination.' Search terms for mathematical ability included 'mathematical ability' or 'calculation skills' or 'counting ability' or 'arithmetic skills' or 'numerical skills' or 'finger-counting' or 'embodied numerosity' or 'math achievement' or 'school achievement.' In the English literature search, search terms for fine motor skills included 'fine motor skills' or 'finger dexterity' or 'motor skills' or 'visual-spatial integration' or 'visual-motor coordination.' Search terms for mathematical ability included 'mathematical ability' or 'calculation skills' or 'counting ability' or 'arithmetic skills' or 'numerical skills' or 'finger-counting' or 'embodied numerosity' or 'math achievement' or 'school achievement.' For literature that was located but whose full text could not be obtained, other avenues were pursued. The literature screening flowchart is shown in Figure 1 [Figure 1: see original paper].

2.2 Inclusion and Exclusion Criteria

For the retrieved relevant studies, screening was conducted according to the following criteria to determine inclusion in the meta-analysis: (1) Must be empirical studies measuring the relationship between fine motor skills and mathematical ability, excluding purely theoretical and literature review articles; (2) Must describe the measurement instruments for fine motor skills and mathematical ability; (3) Must report at least one correlation coefficient between a core component of fine motor skills (life skills or writing skills) and mathematical ability, or other indicators that can be converted into effect sizes; (4) Study participants must be from normal populations, with studies on special populations excluded; (5) For duplicate publications, only one was retained; (6) Literature must report in detail the r value between fine motor skills and mathematical ability, or F values, t values, 2 values, or regression coefficients β that can be converted into r values. Ultimately, 34 papers meeting the above criteria were obtained, comprising 42 independent effect sizes.

2.3 Literature Coding

After screening according to the above criteria, the literature ultimately included in the meta-analysis was coded as follows: (1) Basic literature information (author name, publication date); (2) Total sample size; (3) Participant age; (4) Gender ratio; (5) Cultural background; (6) Fine motor skills measurement instrument; (7) Correlation coefficient. Specific information is shown in Table 3 .

The following principles were followed during coding: (1) One effect size was obtained for each independent sample in the original literature. If there were multiple independent samples, they were coded separately. (2) If correlation coefficients for various structures of fine motor skills or correlation coefficients for multiple tasks measuring fine motor skills were reported, the mean was calculated based on the correlation coefficients of each structure or multiple tasks (Wang Hai-hua et al., 2022; Yeniad et al., 2013). (3) For longitudinal studies, coding was based on the first measurement results (Zhang Ya-li et al., 2021).

The coding for this meta-analysis was completed by two coders, with inter-coder consistency of 92%, indicating that the literature coding in this study was relatively effective and accurate. Additionally, studies with disagreements between the two coders were discussed together until consensus was reached. Finally, 34 papers were included in the meta-analysis, totaling 42 independent effect sizes (Table 3).

2.4.1 Effect Size Calculation

This study used CMA 3.0 (Comprehensive Meta-Analysis 3.0) for data processing and analysis. This study adopted correlation coefficients as effect sizes to explore the relationship between fine motor skills and mathematical ability. Generally, $r \leq 0.1$ is considered a small effect size, $r = 0.25$ a medium effect size, and $r \geq 0.4$ a large effect size (Cohen, 1988).

Data analysis mainly included heterogeneity tests, publication bias tests, main effect tests, and moderator effect tests for the meta-analysis. Since moderators were categorical variables, subgroup analysis was employed. When conducting subgroup analysis, to ensure that studies under each level of the moderator could represent that level, each level should have no fewer than 3 effect sizes (Zhang Ya-li et al., 2021).

This study selected correlation coefficient r as the effect size. Some studies did not directly report the correlation coefficient between fine motor skills and mathematical ability but instead reported F values, t values, 2 values, or regression coefficient β values. This study used relevant formulas from Borenstein et al. (2010) to convert them into r values. The specific conversion formulas are: r = [F/(F + df)]1/2, df = n1 + n2 − 2; r = [t2/(t2 + df)]1/2, df = n1 + n2 − 2; r = [2/(2 + N)]1/2; $r = 0.98\beta + 0.05$ ($\beta \geq 0$), $r = 0.98\beta$ ($\beta < 0$). The r values were then converted to Fisher's Z values for data analysis (Borenstein et al., 2010).

2.4.2 Model Selection

Currently, meta-analysis mainly includes fixed-effect models and random-effects models (Zhang Ya-li et al., 2019). Fixed-effect models assume that the true effect size is the same across all studies, with differences between study results caused by random error; random-effects models posit that true effect sizes can differ across studies, being influenced not only by random error but also by differences in study populations and measurement instruments (Borenstein et al., 2010). Through literature review, this study found that the relationship between fine motor skills and mathematical ability may be influenced by factors such as children's age, gender, cultural background, and fine motor skills measurement instruments. Therefore, selecting the random-effects model is more scientific and reasonable for this study.

2.4.3 Publication Bias

Publication bias means that published research literature cannot systematically and comprehensively represent the total body of completed research in the field (Sun Teng-wei et al., 2021). Publication bias affects the reliability of meta-analysis; therefore, this study uses funnel plots, Classic Fail-safe N, and Egger's regression coefficient to assess publication bias.

3.1 Heterogeneity Test

This meta-analysis included 34 papers with 42 independent effect sizes. Among them, 33 were English papers and 1 was Chinese paper. Specific information about the literature is shown in Table 3. This study used the random-effects model and employed CMA 3.0 software for heterogeneity testing. Table 4 shows that the Q value was 1416.72 ($p < 0.001$), indicating that the effect sizes in this study exhibited heterogeneity. The I-squared value was 97.11, indicating that 97.11% of the total variation was due to true differences in effect values (Borenstein et al., 2010). The Tau-squared value was 0.023, indicating that 2.3% of the between-study variation could be used to calculate weights.

3.2 Publication Bias Test

Referring to previous research, this study selected funnel plots, Classic Fail-safe N, and Egger's regression coefficient to assess publication bias. The funnel plot (Figure 2 [Figure 2: see original paper]) shows that studies were basically concentrated at the top of the funnel, with fewer studies at the bottom. Studies were evenly distributed on both sides of the funnel, showing basically symmetrical distribution, indicating a low possibility of publication bias in the meta-analysis.

Since funnel plot judgment involves some subjectivity, Classic Fail-safe N and Egger's regression coefficient were used to test publication bias. This study calculated the Fail-safe N to quantitatively estimate publication bias level at $p = 0.05$. Referring to Rothstein et al. (2006), 5K+10 (where K represents the number of studies) was used as the critical value for judgment (Rothstein et al., 2006; Wang Hai-hua et al., 2022). Results showed that the Fail-safe N was greater than the critical value (Table 4), indicating no publication bias in this meta-analysis.

Egger's regression coefficient results showed an Intercept of -1.37 (CI = -3.72 to 0.99, $p > 0.05$), with a non-significant p value, indicating no publication bias.

3.3 Main Effect Test

This meta-analysis included 34 studies and 42 independent effect sizes, totaling 78,527 participants. This study conducted random-effects model analysis through CMA 3.0, with results showing a correlation coefficient of 0.273 between fine motor skills and mathematical ability (CI = 0.23 to 0.32, Z = 10.74, $p < 0.001$), indicating a moderately strong positive correlation between fine motor skills and mathematical ability. Specific results are shown in Table 4.

3.4 Moderator Analysis

This study examined the moderating effects of children's age, gender, cultural background, and fine motor skills measurement instruments on the relationship, with specific results shown in Table 5 . Moderator effect results indicated that: (1) Children's age did not significantly moderate the relationship between fine motor skills and mathematical ability, with non-significant subgroup analysis results. (2) Gender did not significantly moderate the relationship between fine motor skills and mathematical ability. Meta-regression analysis showed that the regression coefficient of male proportion on effect values was not significant (b = 0.45, 95%CI [-2.21, 3.11]). (3) Cultural background significantly moderated the relationship between fine motor skills and mathematical ability, with subgroup analysis results showing higher correlation coefficients between fine motor skills and mathematical ability for children in Eastern cultural backgrounds. (4) Fine motor skills measurement instruments significantly moderated the relationship between fine motor skills and mathematical ability, with subgroup analysis results showing that correlations measured using Beery VMI were the highest, while those measured using MABC-2 were the lowest.

4.1 The Relationship Between Fine Motor Skills and Mathematical Ability

This study conducted a meta-analysis of empirical research on the relationship between fine motor skills and mathematical ability from the past 30 years domestically and internationally, including 34 studies, 42 independent effect sizes, and 78,527 participants. Meta-analysis results showed a significant positive correlation between fine motor skills and mathematical ability ($r = 0.273$, $p < 0.001$), indicating a close connection between fine motor skills and mathematical ability, supporting Hypothesis 1. This result is consistent with previous research (Pitchford et al., 2016; Suggate et al., 2017; Oberer et al., 2018), supporting the viewpoints of Embodied Cognition Theory and Cognitive Load Theory, and not supporting research findings of non-significant or negative correlations (Haapala et al., 2014; Van Niekerk et al., 2015; Morales et al., 2011; Malone et al., 2022).

This study supports the viewpoint of Embodied Cognition Theory (Lakoff & Núñez, 2000), demonstrating a positive correlation between fine motor skills and mathematical ability. This research finding enhances the explanatory power of this theory for the relationship between fine motor skills and mathematical ability. Specifically, on the one hand, children with higher fine motor proficiency can often develop the ability to represent quantities through finger movements, such as children extending their thumb and index finger to represent two apples, two stickers, or any other collection containing two objects, while also being able to represent the quantity '2' without relying on concrete objects (Gao Jian, 2010). Finger quantity representation helps children assimilate the fixed-order principle and master the one-to-one correspondence principle (Gao Jian, 2010; Hu Yan-rong et al., 2014), which are necessary stages for mastering number concepts and arithmetic operations. On the other hand, because children with higher fine motor proficiency can use their fingers more skillfully and flexibly, they may use finger counting more frequently. They utilize fingers as a 'natural calculating tool' to establish connections between counting and objects, thereby mastering the basic principles of counting and promoting mathematical ability development. Therefore, children with higher fine motor development levels will more actively use fingers to learn mathematics, engage in finger quantity representation or finger counting, and gain mathematical wisdom from their fingertips.

This study also supports the viewpoint of Cognitive Load Theory (Kirsh & Maglio, 1994). This study found that the association between fine motor skills and mathematical ability was lower for school-age children than for preschool children because, by school age, children's patterns of using fingers for quantity representation have become internalized and automated, reducing dependence on concrete movements. The automation of fine motor skills helps children release some executive function resources to focus on more complex mathematical learning tasks (Cameron et al., 2015; Kim et al., 2018). For example, children entering primary school who have already learned to write will focus more attention on more complex mathematics learning such as arithmetic and reasoning. It can be said that the degree of automaticity children achieve in writing-related tasks may determine the amount of cognitive capacity they can devote to other learning goals (Medwell et al., 2007). Conversely, children who have difficulty picking up a pencil and must pay attention to specific movements while writing or have uncoordinated movements will not make rapid progress in cognitive tasks (Cameron et al., 2012). Children with strong tracing or copying (graphics) abilities can learn mathematics and complete basic classroom tasks faster than those with weak tracing or copying abilities (Cameron et al., 2012). In summary, these results indicate that children with higher fine motor skill development levels objectively possess advantages in mathematics learning and development. Simultaneously, this provides new ideas and evidence for diagnosing and intervening with children with mathematics learning difficulties.

4.2.1 Age

Meta-analysis results indicated that children's age did not significantly moderate the relationship between fine motor skills and mathematical ability, failing to support Hypothesis 2. This suggests that the relationship does not change with age. The possible reason is that motor skills and cognitive skills have a similar developmental timeline, accelerating between ages 5 and 10 (Anderson et al., 2001). The school-age children included in this study were all under age 10, with only a few studies including school-age children over 10. Although research shows that school-age children no longer rely on fine motor skills to solve mathematical problems but instead begin to learn mental arithmetic strategies, verbal strategies, or schematic strategies to solve mathematical problems (Chan et al., 2021), the reduced finger use shown by children during this period does not necessarily mean motor degeneration, as both motor and mathematical development show accelerated trends. Therefore, the association between fine motor skills and mathematical ability does not differ significantly due to age.

4.2.2 Gender

Meta-analysis results indicated that gender did not significantly moderate the relationship between fine motor skills and mathematical ability, failing to support Hypothesis 3. This may suggest that the relationship between fine motor skills and mathematical ability has cross-gender stability—that is, high-level fine motor skills accompanied by high-level mathematical ability universally exist across different gender groups. The meta-analysis results do not support the gender schema viewpoint. With the development of the times, modern education advocates androgynous education, where individuals retain their own gender's excellent and distinctive traits while absorbing excellent gender traits from the opposite sex to perfect their own personality traits (Zhang Han, 2010). A study on gender differences in preschoolers' area play showed that boys not only prefer traditionally male play areas (such as construction zones) but also like female play areas (such as dollhouses) (Chen Yue-juan, 2017). Additionally, research shows that girls also like construction zones (Varma, 1980; Chen Yue-juan, 2017). Evidently, both boys and girls have ample opportunities to develop fine motor skills, which to some extent can compensate for boys' innate disadvantage in tactile thresholds compared to girls. Therefore, the association between fine motor skills and mathematical ability does not differ significantly due to gender.

4.2.3 Cultural Background

Meta-analysis results indicated that cultural background could moderate the relationship between fine motor skills and mathematical ability, supporting Hypothesis 4, with higher effect sizes for fine motor skills and mathematical ability among children in Eastern cultural backgrounds. First, this result supports the 'long-term versus short-term orientation' viewpoint in Cultural Dimension Theory. For example, Huang He-qing (2003), through cross-cultural comparison of Chinese and American family education, found that compared to American family education (Western cultural background), Chinese family education (Eastern cultural background) places greater emphasis on intellectual and aesthetic education, mainly reflected in two important stages: preschool and school age.

During the preschool period, Chinese parents are more inclined to teach children knowledge and skills, such as purchasing various intellectual and interesting reading materials for children and training them in reading aloud, writing, and calculation skills; during school age, Chinese family education shows a tendency toward schoolization, with parents supervising children's learning, ensuring timely homework completion, implementing extensive practice, and coping with examinations. Additionally, whether in preschool or school age, Chinese parents demonstrate spending substantial money on training classes for children, such as drawing and piano classes (Huang He-qing, 2003). One characteristic of education in Eastern cultural backgrounds oriented toward long-term orientation is 'greater emphasis on long-term effort, actively changing oneself to adapt to social changes' (Kang Jian-qiu, Yu Na, 2021); thus, parents may focus more on preparing children for future life, making children more pragmatic and hardworking to better face and meet various difficulties and challenges in future life. This 'busyness' provides children with more opportunities for fine motor skills training. Second, chopsticks are the main eating utensils for many East and Southeast Asians, and chopstick grasping skills can fully exercise hand fine motor skills. Research shows that Asian children's hand dexterity is higher than that of European and American children, possibly attributable to differences in hand manipulation practice activities in Asian cultural living environments affecting children's fine motor development levels (Wei Zhuang et al., 2022). Chopstick use, as a necessary process in mealtime in Eastern countries, is a powerful tool for developing children's fine motor skills and can better support children's mathematics learning. Third, research shows that cultural differences affect not only Eastern and Western students' mathematics learning but also mathematics achievement (Zhou Shi-min, Wang Jun, 2014). Specifically, Eastern culture advocates diligent learning, while Western culture advocates joyful learning; children in Eastern cultural backgrounds study more diligently and have better mathematics achievement (Zhu & Leung, 2011). Because children may need to rely on fine motor movements such as fingers when learning numbers, quantity relationships, arrangements, and operations, this means that in Eastern cultural backgrounds, as children work hard to learn mathematics, not only does their mathematical ability improve, but their fine motor skills also develop more fully. Therefore, cultural background can moderate the relationship between fine motor skills and mathematical ability.

4.2.4 Measurement Instruments

Meta-analysis results indicated that fine motor skills measurement instruments could moderate the relationship between fine motor skills and mathematical ability, supporting Hypothesis 5. This moderating effect may be related to the non-unified structure of fine motor skills and the failure to distinguish the two core components. The literature included in this meta-analysis showed differences in the structural classification of fine motor skills. For example, Dinehart and Manfra (2013) divided fine motor skills into fine motor manipulation and fine motor writing; Pitchford et al. (2016) divided fine motor skills into fine motor integration and fine motor precision; Carlson et al. (2013) and Sortor et al. (2003) divided fine motor skills into visual-spatial integration and visual-motor coordination. These different structural classifications also led to differences in examination focus and measurement. Although these different structural classifications all included the two core components of life skills and writing skills or one of them, some studies only reported overall correlation coefficients when examining both core components (Gashaj et al., 2019; Michel et al., 2020), which may have invisibly affected the relationship between fine motor skills and mathematical ability. Notably, Martzog et al. (2019) argue that life skills and writing skills are important components of fine motor skills, but finger speed is also an indispensable component of fine motor skills. Therefore, what affects mathematical ability should be the joint action of multiple components of fine motor skills. However, the studies included in this meta-analysis had deficiencies or mutual fusion regarding fine motor skill components, which to some extent may have affected the selection and use of measurement instruments, thereby producing moderating effects.

Study results found that the correlation coefficient measured using the MABC-2 scale was the lowest, possibly because the items designed in this scale are relatively broad, including not only a battery of motor tests (such as fine motor, gross motor, and balance) but also subjective rating scales. Although this scale has been widely used worldwide and its various validities are relatively good (Wu Sheng-kou, Jiang Gui-ping, 2014), the comprehensiveness, quality, and rigor of these reliability and validity studies are variable (Brown & Lalor, 2009). For example, subjective rating scales have reported neither reliability information such as internal consistency and test-retest reliability nor structural validity (Brown & Lalor, 2009). The original purpose of this scale was to identify and describe motor performance impairments in children aged 3-17 (Brown & Lalor, 2009), focusing on identifying children with motor skill disorders, such as Attention Deficit Hyperactivity Disorder (ADHD) (Harvey & Reid, 2003), Autism Spectrum Disorder (ASD) (Green et al., 2002), language disorders (Hill, 2001), and cognitive impairments or learning difficulties (Jongmans et al., 2003). The MABC-2 scale may be more suitable for screening children with motor performance impairments, while showing lower effect values for measuring fine motor skills in normal children, which also suggests that future research using this tool needs to be cautious.

The Beery VMI measured the highest correlation coefficient between fine motor skills and mathematical ability. This scale measures participants' visual-spatial integration and visual-motor coordination, requiring participants to effectively integrate visual and kinesthetic information when completing these tasks (Zhang Chong-yang, 2021). The scale includes an overall visual-spatial integration test and two supplementary tests: visual perception and motor coordination. Visual-spatial integration requires children to copy various geometric figures, from single-line and two-dimensional figures to three-dimensional figures and composite figures; the visual-motor coordination supplementary test requires children to trace various geometric figures. These tasks only require fine muscle control and do not need to copy images on another sheet of paper (Carlson et al., 2013). Beery VMI is currently the most widely used visual-motor integration ability test scale. Existing research shows that its two subcomponents, namely visual-motor coordination (life skills and tracing), drive early childhood cognitive development, while visual-spatial integration (copying) drives cognitive development throughout later childhood (Carlson et al., 2013). Moreover, from the perspective of fine motor skills measurement instrument application, Beery VMI has relatively broad coverage, with relatively comprehensive and complete item content; therefore, this tool measured the highest correlation coefficient between fine motor skills and mathematical ability.

4.3 Limitations and Future Directions

Limitations of this study: (1) Due to the complexity of fine motor skill indicators, the structural classification in various studies was not unified, and the two core components were not separated from the whole. To ensure maximum analysis of the impact of fine motor skills on mathematical ability, this study examined fine motor skills as a whole and could not investigate the association between different components of fine motor skills and mathematical ability. (2) The distribution of moderator variables for subgroup analysis was unbalanced, with more studies using preschool children as participants than those using school-age children, which may affect the research results to some extent. (3) During meta-analysis data coding, due to cultural diversity and non-unified measurement instruments, some studies used self-compiled or borrowed fine motor skills measurement instruments. This meta-analysis categorized these non-unified instruments as 'other instruments,' making it difficult to excavate and discover more appropriate measurement instruments. Future research can continue to focus on measurement instruments as a moderator variable to better explain the relationship between the two.

This study employed meta-analysis and found that fine motor skills and mathematical ability have a moderately positive correlation; cultural background and fine motor skills measurement instruments can significantly moderate the relationship between fine motor skills and mathematical ability; children's age and gender did not significantly moderate the relationship between fine motor skills and mathematical ability.

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Note: Figure translations are in progress. See original paper for figures.