Educational Psychology Review (2026) 38:73
https://doi.org/10.1007/s10648-026-10161-4

META-ANALYSIS

When Fine is Large and Gross is Small: A Meta-Analysis of Links Between Fine and Gross Motor Skills with Academic-Cognitive Skills

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Received: 20 June 2025 / Accepted: 20 April 2026

Abstract

Researchers and practitioners often emphasize the importance of fine motor skills (FiMS) and gross motor skills (GMS) for academic and cognitive development. However, no systematic review of empirical evidence has compared the associations between FiMS and GMS for key academic-cognitive domains (i.e., reading, writing, mathematics, language, general academic, and cognitive skills). A literature search in five databases identified 59 eligible correlational studies measuring both FiMS and GMS ($k = 856$, $N = 40{,}806$) from an initial selection of 34,811 articles. Mixed effects meta-regressions, controlling for methodological and sample factors, revealed moderate to strong correlations between FiMS and writing, reading, mathematics, and general academic skills, as well as moderate links with cognition and language. GMS displayed small to moderate associations with reading, writing, mathematics, language, and cognitive skills, but no statistically significant links to general academic skills. Overall, FiMS showed more substantial correlations with academic-cognitive skills ($r = .302$) than GMS did ($r = .170$, $p < .001$), although the associations were more similar for language and executive functions compared to those for intelligence. Practical implications are discussed with respect to the role motor skills play in child and adolescent education.

Keywords Motor skills · Fine motor skills · Gross motor skills · Academic skills · Cognitive skills · Reading · Writing · Mathematics · Language · Meta-analysis

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Fields such as education, developmental psychology, philosophy, and medicine have long grappled with understanding the associations between motor skills and academic-cognitive skills in child development (Adolph & Hoch, 2019). Historically, motor and cognitive development were often investigated independently, each believed to rely on distinct brain regions (Whitall et al., 2020). However, recent neuroscientific research has demonstrated that brain areas previously considered specifically linked to motor skills are also involved in cognitive processes, and vice versa (Diamond, 2000; Palmis et al., 2021; Pulvermüller, 2005). This neuroscientific evidence is consistent with systematic reviews that report positive correlations between physical activity and cognitive performance (Mavilidi et al., 2025), motor skills and cognition (Van der Fels et al., 2015), as well as motor skills and academic performance (in typically developing children (Macdonald et al., 2018; Suggate et al., 2025).

As reviewed below, a large number of studies have investigated and generally found positive links between motor skills and constructs integral to educational psychology – including aspects of reading, writing, mathematics, and cognition. However, key theoretical and practical questions arise: Are all motor skills equal, or, in other words, is the difference between fine and gross itself, fine or gross? Should educators focus on writing, drawing, and dexterity, or instead focus on sport and larger movements? If positive links between fine motor skills (FiMS) and gross motor skills (GMS) and academic-cognitive skills exist, what might be driving these shared cognitive processes or the functionality of motor skills? Previous studies (e.g., Grissmer et al., 2010) suggest that FiMS are more strongly associated with academic and cognitive skills than GMS. Nevertheless, a definite answer regarding the relative contributions of FiMS versus GMS can only be provided by a meta-analysis of the broad literature, using studies that employ both GMSs and FiMS measures and assess academic and cognitive skills. Before presenting such an analysis, we first define motor and academic-cognitive skills and present relevant theories and evidence.

Defining Motor and Academic-Cognitive Skills

FiMS and GMS

Although there are several different motor skills (e.g., oculomotor and oral motor skills), research has focused on FiMS and GMS, sometimes clustering these together as general motor skills. FiMS are involved in the coordination of movements of smaller muscles in the extremities, particularly the hands (Gaul & Issartel, 2016). Although there are many ways of sub-categorizing FiMS, most studies define and include graphomotor skills (handling of a pen, e.g., drawing), dexterity (e.g., building with blocks, threading beads), fine-motor speed (e.g., tapping tasks) (Martzog, 2015), finger gnosia (e.g., finger sense, finger localization tasks; Noël, 2005), and bimanual skills (e.g., bimanual finger or hand tapping tasks; Summers et al., 1993). In contrast, GMS are understood as skills for activating and coordinating movements, including larger muscle groups, body parts, or the whole body (Tjetjens & Utesch, 2019). GMS include subskills such as whole-body coordination (e.g., coordination wall task), locomotor skills (e.g., galloping, sliding), balance (e.g., walking on a balance beam), gross object manipulation (e.g., throwing and catching), and agility (e.g., shuttle run) (Cools et al., 2009; Khodaverdi et al., 2021). Although gross object manipulation skills, such as catching, involve some manual skills and hence FiMS, these skills extend beyond the hands and are therefore defined as gross motor skills (Cools et al., 2009).

Academic Skills

Previous research on motor skills and academic skills has focused on the key academic domains of writing, reading, mathematics, language, as well as a general academic attainment score (e.g., grade point average) (Liu et al., 2021; Macdonald et al., 2018; Van der Fels et al., 2015; Wang & Wang, 2024). Writing encompasses skills from the beginning of writing development, such as letter and word writing, to more sophisticated writing abilities like spelling and text composition (Berninger et al., 2006; Hutton et al., 2021; Whitehurst & Lonigan, 1998). Similarly, reading includes basic skills such as phonological awareness, letter naming, and decoding of non-words and words at the initial stage, and text reading and reading comprehension in later stages of reading instruction (Hutton et al., 2021; Whitehurst & Lonigan, 1998). Mathematics can be divided into emergent mathematics skills and counting (Manfra et al., 2017), which later develop into arithmetic skills such as subtractions or fractions and include understanding mathematical concepts (Mix et al., 2016).

Cognitive Skills

Cognitive skills refer to general underlying abilities involved in learning and task performance but are pragmatically limited to domains that have likely been studied in relation to motor skills (Kaufman et al., 2022). The first cognitive domain is language skills, specifically receptive and expressive vocabulary, as these, unlike pragmatics, phonology, and syntax, have been widely studied in motor research (Gonzalez et al., 2019). The second domain, intelligence and general cognitive skills, comprises spatial and verbal information processing (Kaufman et al., 2022). Finally, executive functions refer to the ability to plan, execute, monitor, inhibit, and store information in working memory (Miyake & Friedman, 2012).

Associations Between Motor Skills and Academic-Cognitive Skills

Theoretical Importance of Motor Skills

In the following, the term academic-cognitive skills refers to all academic and cognitive skills described above. Indeed, although research and practice often treat motor and academic-cognitive skills as separate entities, theories of child development describe clear links between the two areas (Adolph & Hoch, 2019; Cameron, 2016). A large body of work examines the effects of engagement in physical activity across the lifespan, finding that, in particular, outdoor and moderately vigorous activity have small, positive effects on cognition from preschool through older adulthood (e.g., Mavilidi et al., 2025). However, the focus of this review is on skill, not activity. Skill has been characterized as the effective use and control of knowledge during task performance, with skill acquisition likely requiring practice and effort, cognition, emotion, and volition (Tomporowski & Pesce, 2019).

Turning specifically to links between academic-cognitive and motor skills, the diverse landscape of theory can be roughly divided into two main ideas: functionalism and shared action-cognition links (Suggate et al., 2025). Functionalism suggests that children with better motor skills can more easily access and engage in learning opportunities. (Penner-Wilger & Anderson, 2013; Suggate et al., 2018). For older children, there appears to be experimental evidence for a functional mechanism whereby higher levels of motor skills facilitate writing acquisition, which in turn improves reading skills (Suggate et al., 2023). Furthermore, children with well-developed motor skills may enjoy learning more than children with motor difficulties, which can undermine learning (see Tomporowski & Pesce, 2019, for a review of motivational factors in motor performance). Children with better motor skills may also experience less cognitive load during tasks that involve simultaneous motor and cognitive demands (Tomporowski & Pesce, 2019), such as note-taking (Zou et al., 2025). In addition, some researchers have proposed that language develops in the context of emerging FiMS and GMS, as these skills enable more sophisticated interactions with the environment (Iverson, 2010; Zou et al., 2025).

Another theoretical explanation for relations between motor skills and academic-cognitive skills is that these share action-cognition links (Pulvermüller, 2005; Ruitenberg, 2013; Siakaluk et al., 2008). In terms of actions, it is believed that motor skill acquisition invokes cognitive processes, such as executive functions (e.g., attention, working memory, response inhibition) and problem-solving (Tomprowski & Pesce, 2019). In line with this idea, academic-cognitive skills share and can recruit motor networks during task performance (Penner-Wilger & Anderson, 2013). For example, it has been found that handwriting networks are often recruited during reading (Palmis et al., 2021), and finger perception networks during mathematics (Fischer et al., 2018; Soylu et al., 2017). In addition, motor skills are involved in the development of number sense and pre-counting and counting skills (Dackermann et al., 2017; Fischer et al., 2018). Also, shared action-cognition links are assumed between language development and motor actions (Pulvermüller, 2005). For instance, words accompanied by gestures are remembered better than words without a concurrent motor connection (Fugate et al., 2019), and motor areas may be involved in processing lexical items with stronger links to body interactions (Suggate & Stoeger, 2014, 2017; Wellsby & Pexman, 2014; Winter et al., 2021). In terms of cognitive skill development, it has been suggested that coordinative and complex motor skills stimulate brain areas that are associated with cognitive skills, particularly executive functions (EF), thereby forming a link between action and cognition (Best, 2010; Serrien et al., 2007). Both theoretical perspectives offer distinct explanations as to why the development of motor and academic-cognitive skills is more closely intertwined than was previously believed in the fields of psychology and education. Importantly, they are not necessarily mutually exclusive.

Empirical Evidence on Links Between Motor and Academic-Cognitive Skills

Empirically, the research on links between motor and academic-cognitive skills appears to be complicated, encompassing studies spread across diverse research fields. Further, as can be seen in the definitions above, motor skills, as well as academic-cognitive skills, comprise an extensive number of subskills, with studies often only focusing on one specific subskill. Consequently, some combinations of motor and academic-cognitive subskills have been examined intensively, whereas others have been neglected. Furthermore, as reviewed below, research in some domains is sparse, encompassing single studies, whereas others have undergone meta-analytical review. In the following, we will provide a brief overview of current evidence on links between motor and academic-cognitive skills, focusing on: (a) motor skills in general without initially differentiating between FiMS and GMS, (b) FiMS, (c) GMS, and (d) both FiMS and GMS and their relation to academic-cognitive skills.

(A) **Studies Investigating Motor Skills in General.** To our knowledge, reviews have established links between academic-cognitive skills and motor skills in general (Hill et al., 2024; Van der Fels et al., 2015; Wang & Wang, 2024). For example, Wang and Wang (2024) reported positive associations of motor skills with overall academic performance and language for 4-to-17-year-old children in their systematic review using a semi-quantitative assessment ($k=78$). Also, Hill et al. (2024), who synthesized observational longitudinal data of typically developing children and adolescents (aged 3–18 years), identified a limited number of studies and found only mixed evidence regarding links between composite motor and academic skills and executive functions. In a review of 21 studies on links between cognitive and motor skills in 4-to-16-year-olds, Van der Fels et al. (2015) found that complex motor skills, in particular, are correlated with higher-order cognitive skills. Gandotra et al. (2022) established moderate correlations ($r = .18$) between general motor skills and executive functions across 32 studies with non-clinical samples, including 4,866 children aged 3–12 years. In a similar vein, a recent meta-analysis of 44 studies reported moderate links ($r = .18$, overall) between GMS and executive functions (Bao et al., 2024).

(B) **Studies Investigating FiMS.** Many individual studies have found links between FiMS and academic-cognitive skills. Preschool FiMS have been shown to predict reading and maths performance in 2nd grade (Dinehart & Manfra, 2013; Suggate et al., 2019), and FiMS measured as early as 9 months have been found to predict English and science skills at age 11 (Zhou & Tolmie, 2024). Grapho-motor skills seem to play an important role in reading and writing (Berninger et al., 2006; James, 2010; Longcamp et al., 2005; Suggate & Stoeger, 2017; Wamain et al., 2012). Further, FiMS may facilitate the development of finger counting and, hence, mathematics (Fischer et al., 2011, 2018; Link et al., 2013). Also, FiMS seem to play a crucial role in the development of cognitive skills in the early years (Martzog et al., 2019). A recent meta-analysis found moderate links between FiMS and reading, writing, mathematics, and cognitive skills in 143 non-clinical samples aged 3 to 16 years (Suggate et al., 2025).

(C) **Studies Investigating GMS.** Regarding GMS, single empirical studies confirm links to academic-cognitive performance (Aadland et al., 2017; Jones et al., 2021; Maurer & Roebers, 2019), including early literacy and language skills (Zhang et al., 2018), as well as math and reading performance (Geertsen et al., 2016). Further, gross motor movement may support the mental representation of numbers and, thus, foster mathematical understanding (Fischer et al., 2011, 2018; Link et al., 2013). Additionally, research has found links between GMS and cognitive skills (Maurer & Roebers, 2019; Zhou & Tolmie, 2024). Intervention studies have further provided evidence indicating that motor skill training can improve cognitive skills. (e.g., executive functions, spatial intelligence, and working memory) (Gai et al., 2021; Moreau et al., 2015). Thus far, although there is evidence indicating positive links between both FiMS and GMS and different aspects of academic-cognitive skills, most of this evidence comes from studies and reviews in which either FiMS or GMS were measured. Nevertheless, some studies do exist that include both FiMS and GMS.

(D) **Studies Investigating Both FiMS and GMS.** There are single studies and analytical reviews that examine both FiMS and GMS and their relation to academic-cognitive skills.

Evidence from Single Studies Although it is difficult to judge without systematic meta-analyses, most empirical research from single studies, including both FiMS and GMS suggests that FiMS show stronger associations with academic-cognitive skills than GMS (Cameron et al., 2016; Escolano-Pérez et al., 2020; Grissmer et al., 2010; Pagani et al., 2010; Son & Meisels, 2006). For example, in a study investigating kindergarten children and their achievement in first grade, kindergarten FiMS showed associations of $r = .40$ and $r = .48$ with first grade reading and mathematics skills, compared to kindergarten GMS, which displayed correlations of $r = .19$ and $r = .22$. At the beginning of kindergarten, both FiMS and GMS significantly predicted achievement, however, effect sizes for FiMS were substantially higher (Son & Meisels, 2006). Pagani et al. (2010) reported correlation coefficients ranging from $r = .34$ to 0.38 between kindergarten FiMS and second grade school performance, including reading, math, general achievement, as well as classroom engagement, whereas GMS showed correlations ranging from $r = .20$ to 0.25. When controlling for kindergarten achievement and attention, FiMS, but not GMS, predicted second-grade school performance (Pagani et al., 2010). Escolano-Perez and colleagues (2020) confirmed this finding in their study, showing that kindergarten FiMS, but not GMS, predicted school performance one year later.

Evidence from Reviews Moving from individual longitudinal studies to reviews, Macdonald et al. (2018) conducted a semi-quantitative systematic review of school-aged students examining the link between FiMS ($k=30$) and GMS ($k=21$) subskills and reading ability. The results showed positive correlations between reading and fine motor integration, total fine motor scores, upper limb coordination, and total gross motor scores. They also found links between FiMS and GMS and mathematics performance, although relations between mathematics and GMS were more variable (Macdonald et al., 2018). Another semi-quantitative systematic review by Wang and Wang (2024) investigated links between FiMS (k = 57) and GMS (k = 42) and various academic-cognitive skills in 4-to-17-year-olds. They concluded that FiMS consistently related to mathematics, reading, writing, spelling, and language skills. For GMS, however, only reliable links with language skills were confirmed, while positive associations with mathematics, reading and spelling remained uncertain. In a meta-analysis, Gandotra et al. (2022) found that balance and dexterity were significantly and moderately correlated with various executive functions (ranging from r = .12 to 0.21), but locomotor and object control skills showed mostly non-significant or small links (r = .06 to 0.19 for locomotor skills, r = .06 to 0.08 for object-control skills).

Current Study

A cumulative picture emerges suggesting that motor skills are associated with academic-cognitive skills (Hill et al., 2024; Van der Fels et al., 2015; Wang & Wang, 2024), with FiMS likely showing stronger links to reading, writing, mathematics, and cognitive skills than GMS (Grissmer et al., 2010; Macdonald et al., 2018; Son & Meisels, 2006; Wang & Wang, 2024). However, quantitative evidence from a systematic meta-analytic review would provide a more robust and unified picture of the links among different motor, academic, and cognitive skills. When comparing FiMS and GMS directly, only one study used a meta-analytic approach (Gandotra et al., 2022), which focused solely on executive functions in children aged 3–12 years. Two other reviews used semi-quantitative methods (Macdonald et al., 2018; Wang & Wang, 2024).

Previous research has included studies in which either FiMS or GMS were measured. Thus, sample characteristics (e.g., age group, gender, or socioeconomic status) and methods vary substantially, potentially introducing confounding variables. An alternative approach is to conduct a meta-analysis using studies that measure both FiMS and GMS in the same sample group. Thereby, effect sizes for correlations between aspects of FiMS *versus* GMS on a range of academic and cognitive skills could be compared directly.

To better understand how motor skills relate to academic and cognitive development, we conducted a broad search across various research fields such as education, sports science, medicine, and psychology, coding for both motor skills and academic-cognitive skills in a differentiated and systematic manner. Additionally, we focused on selecting studies that included both FiMS and GMS to reduce the heterogeneity in study methodology and facilitate the interpretation of comparisons between the obtained effect sizes. Sample characteristics such as age, gender, and socio-economic factors as well as study quality were accounted for in mixed effect meta-regressions. To further reduce the impact of confounding factors in sample characteristics, data from atypically developing samples were excluded (Memisevic & Djordjevic, 2018; Rochelle & Talcott, 2006).

Studies of children aged3 to 16 were included to examine links across a broad period of child development, given indications that these associations may vary with age (Van der Fels et al., 2015; Wang & Wang, 2024). Children younger than three years were excluded, as motor measures mostly comprise parental questionnaires rather than direct behavioral measures (e.g., the Movement ABC starts at age 3). The upper limit of 16 years was chosen to include adolescence and align with the norms of widely used tests (e.g., Movement-ABC, Kaufman-ABC). We excluded measures of physical activity, strength, and endurance because they did not fit with our definition of GMS as the skillful coordination of large body parts.

Research Aims

Using a meta-analytic approach, this research aims to broaden and simultaneously deepen the understanding of the associations between motor skills and academic-cognitive skills. Specifically, the first goal of this meta-analysis is to compare FiMS and GMS associations with overall academic-cognitive skills. Secondly, the nuanced relationship between FiMS and GMS and various academic-cognitive skills is investigated. This involves exploring correlations between both FiMS and GMS and the distinct academic-cognitive domains of reading, writing, mathematics, general academic, language, and cognitive skills, using an exploratory approach. Thirdly, depending on sample sizes, subdomains of cognitive skills will be investigated in more detail, with a particular focus on intelligence and executive functions, given their role in previous research (Bao et al., 2024). Finally, different facets of FiMS (e.g., dexterity) and GMS (e.g., gross object manipulation) will be investigated to determine whether specific FiMS or GMS subskills show differential links to overall academic-cognitive skills.

Hypothesis and Exploratory Analysis

Hypothesis: Comparing Effect Sizes between FiMS and GMS with Overall Academic-Cognitive Skills First, based on functionalism as well as current scientific suggestions (Cameron et al., 2016; Escolano-Pérez et al., 2020; Grissmer et al., 2010; Pagani et al., 2010; Suggate & Stoeger, 2017), we hypothesize that correlations of overall academic-cognitive skills with FiMS are greater than those with GMS.

Exploratory Analysis: Links of FiMS vs. GMS with Reading, Writing, Math, General Academics, Language, and Cognitive Skills In exploratory analyses, we test whether FiMS and GMS link differently to distinct academic-cognitive domains by including a motor (FiMS/GMS) X domain (reading, writing, mathematics, cognition, language, general academic) interaction.

Exploratory Analysis: Links of FiMS vs. GMS with Intelligence and Executive Functions In exploratory analyses, we test the idea that a subset of cognitive skills, namely executive functions, have stronger links with both FiMS and GMS than other cognitive skills, particularly intelligence (Cameron et al., 2016). Intelligence is selected firstly due to its theoretical interest, and secondly because it is a less heterogeneous construct than miscellaneous or general cognitive categories.

Exploratory Analysis: Links of Subskills of FiMS and GMS with Overall Academic-Cognitive Skills Further, we examine whether specific subskills of FiMS and GMS show different links with academic-cognitive skills. We separately investigated graphomotor, dexterity, miscellaneous, and general FiMS skills as well as the GMS subskills of whole-body coordination, balance, gross object manipulation, agility, miscellaneous, and general GMS. Due to sample size limitations, only effect sizes between FiMS and GMS subskills with overall academic-cognitive skills are analyzed.

Method

Study Selection and Screening

The original database for this study resulted from a literature search conducted in 2020 on links between FiMS and academic-cognitive skills in children and adolescents. Based on this dataset, a second search was performed in July 2022 and again in October 2025 to update this database. Consequently, an exhaustive string of search terms was divided into four groups, reflecting motor skills, academic-cognitive skills, study type, and sample age (see Appendix). Within groups, terms were combined with OR command and between groups with AND command. Studies were restricted to human participants and children aged 3 to 16 years old when the database allowed this.

Database Search

Search terms were entered into four databanks, namely PsycINFO, Pubmed, ERIC, and Web of Science. The software CITAVI was used to collate the references and remove duplicates, along with a hand search to remove further duplicates, which resulted in identifying 10,916 duplicates from 34,811 hits. Next, given the large number of hits, the remaining 23,985 titles were screened and removed if they did not allude to measures of FiMS, GMS, and any academic-cognitive skills. Further exclusion criteria included whether the title indicated that the work was entirely of a theoretical nature (i.e., no data collected). Using these criteria, 17,504 titles were removed leaving 5,991.

Abstracts for the remaining 5,991 studies were checked more closely. Studies were excluded if they focused on samples with disabilities or illnesses, as this might introduce greater heterogeneity in prior experiences and physical limitations, thereby increasing uncertainty about the reasons for associations (e.g., functionalism vs. shared processes). We also excluded studies at this stage if they did not contain empirical data, GMS, FiMS, and academic-cognitive measures, or were duplicates. As detailed in Fig. 1, this resulted in 1,248 records identified for retrieval.

Article Coding

Five inclusion criteria were applied during the full-text screening and coding stage. First, the studies had to include measures of both FiMS and GMS, as well as one or more academic-cognitive variables, in order to address the main research questions. Second, the sample needed to be children or adolescents (aged 3–16 years),

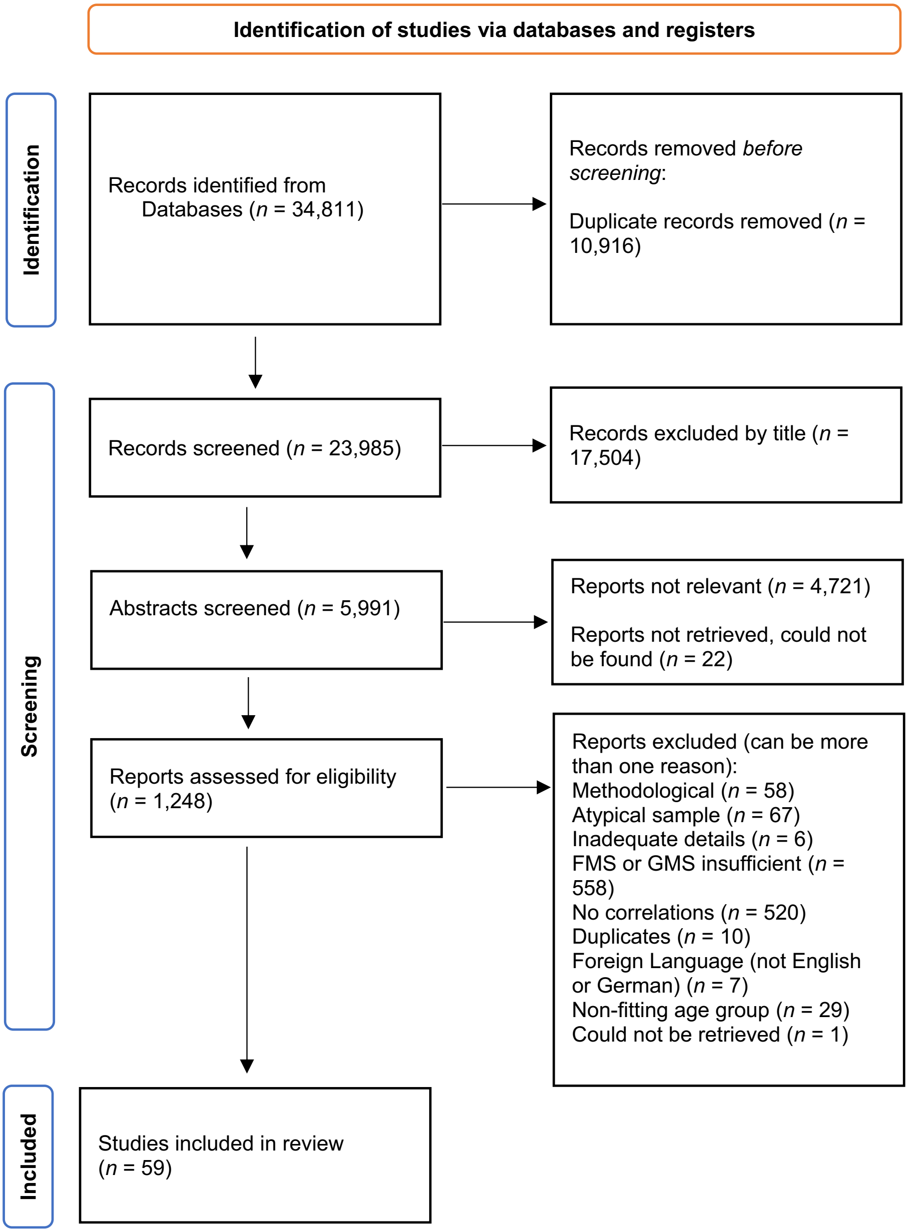

Fig. 1 PRISMA flow diagram for article search and screening

statistically independent, and non-clinical. Third, studies had to report quantitative data, such as correlation coefficients or similar (e.g., partial correlations). Fourth, the publication language had to be English or German to enable the authors to reliably code the studies. Fifth, studies were excluded if the authors only reported statistically significant correlations and completely omitted non-significant ones, as this systematically inflates Type I error.

In cases where effect sizes included measures in which lower scores represent better performance, such as for errors or reaction times, the scores were reverse-coded to ensure that a positive correlation between the two constructs always indicated better performance on both tasks. A list of measures to which this applies is presented in Table S3. Decisions regarding studies that did not meet the predefined coding criteria were made through discussions between the two raters (the first author and a research assistant). Any remaining disagreements were settled by mutual agreement with guidance of the second author. Interrater reliability between the two raters was calculated on a subsample of 24 of the searches and indicated excellent agreement, IRR = 0.98 (agreements over disagreements plus agreements). All remaining articles were screened for eligibility according to the specified criteria and coded if the measures fit into a motor or academic-cognitive skill category. Motor skills that did not fit were primarily related to measures of physical activity levels, strength, endurance, or flexibility. A total of 59 studies containing 63 samples were included.

Measures

Studies were coded for publication features, sample features, and study quality. Correlation coefficients were taken from the original studies' reports, together with additional information on whether the correlation had been controlled for (i.e., age or gender).

Publication Features

Studies were coded for publication year, publication language, publication type (peer-review), title, and author.

Sample Features

Sample features included the percentage of female participants, whether participants were normally achieving vs. at-risk (sample status), the country where the study was conducted, sample language(s) spoken, sample age, and grade. Whenever the sample age was missing but the grade was present, the correlation between the two was used to predict and impute age. If provided in the study information, we additionally coded variance (*SD*) around sample age to test whether this moderated effect sizes.

Methodological Quality

To provide methodological quality indicators alongside publication type, studies were coded according to the National Institute for Health's (2013) Study Quality Assessment Tools. The Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies was selected as it best matches the study designs targeted in this meta-analysis. However, seven of the items were not relevant to the current study and were hence dropped (i.e., items 6–10, and 12 relating to treatment exposure, and item

13 to follow-up attrition) and one double-barreled item was split into two smaller items (i.e., item no. 4). This left 8 items pertaining to specification of (a) research objectives, (b) study samples, (c) participation rate, (d) participant recruitment, (e) inclusion criteria, (f) sample size justification, (g) outcome measures, and (h) confounders. Up to two points for each item were awarded, giving a possible score range of 0–16 points. The second and third authors both rated 10 studies, achieving an intraclass correlation absolute agreement for the average measures ICC = 0.837 and an interrater reliability (agreements/agreements + disagreements) of 74%.

Motor Skill and Academic-Cognitive Measures

Correlation coefficients were collected from various measures relating to the different categories of FiMS, GMS, and academic-cognitive skills. Due to the large number of measures included in the meta-analysis, these are listed and described in the supplementary materials.

FiMS Measures were initially categorized into different domains of FiMS, focusing first and foremost on graphomotor skills, manual dexterity, speed-based FiMS, finger gnosia, and bimanual skills. Additionally, we included a miscellaneous category for skills that did not fit into these specific domains and a general motor skills category (e.g., where graphomotor and manual dexterity were inseparable). However, speed-based FiMS, finger gnosia, and bimanual skills were classified in the miscellaneous category due to the paucity of studies on these. Manual dexterity was typically measured with tasks involving fine object manipulation, most commonly pegboard and peg shifting tasks or bead threading tasks. Measures of graphomotor skills represented the operation of a writing tool (e.g., pencil) to reproduce symbols.

GMS GMS measures were divided into eight categories, namely whole-body coordination, locomotor skills, balance, gross object manipulation, agility, strength, miscellaneous GMS, and general GMS. Locomotor skills were examined in only two studies and were therefore added to the miscellaneous category. Whole-body coordination comprises measures that assess the simultaneous and efficient coordination among various limbs and muscle chains (e.g., coordination wall tasks). Balance included tests that involved maintaining a posture using the vestibular and proprioceptive system (e.g., standing on a balance board) or sustaining balance while in motion (e.g., walking on a balance beam). Object manipulation was assessed using tasks such as ball handling (e.g., throwing, catching, dribbling), which involve broad upper-limb movements and typically larger objects, thereby distinguishing it from manual dexterity. In the agility category, tests were based on the performance of speeded but relatively simple movement patterns such as running or jumping with both legs (e.g., shuttle run, jumping over a beam as fast as possible). Tests measuring endurance without a clear link to agility (e.g., involving short-term, agile locomotion) were excluded. Furthermore, for GMS, a miscellaneous category containing tests that did not fit into the aforementioned categories and a general GMS category with measures that combine tests from different categories into a single score were included.

Academic-Cognitive Skills Academic-cognitive skills encompassed reading, writing, mathematics, general academic, language, and cognitive skills. Reading measures included concepts about print, letter reading, word reading (real and pseudowords), phonemic awareness, reading fluency, reading comprehension, miscellaneous measures, and general reading tests that did not report constituent constructs. Writing measures included writing individual letters, words, sentences, and passages, as well as spelling. Miscellaneous writing comprised measures that did not fit into any other writing category. General writing included a combination of writing tests combined into a single overall score. Mathematics measures were grouped into six categories. First, early mathematical skills before school entry were combined into a pre-math category. A second category referred to children's ability to count, and a third focused on arithmetic (i.e., addition, subtraction, division, and multiplication of numbers). Conceptual understanding constituted a fourth category, followed by a fifth, miscellaneous category and a sixth general category.

Language measures comprised receptive vocabulary, expressive vocabulary, a miscellaneous language category, and a general language category. The general language category combined multiple language measures, whereas the miscellaneous category included all measures that did not fit into the other three categories. Since some studies only reported reading, writing, mathematics, and language combined into a general academic score, tests comprising more than one academic field were collected in a separate general academic category. Cognitive measures were grouped into four categories: intelligence, executive functions, miscellaneous skills, and general cognitive scores. Intelligence comprised tests such as general knowledge, problem solving, pattern recognition, and verbal or spatial reasoning. Based on relations between motor skills and executive functions, thought to arise from the shared control of motor and learning processes (Cameron et al., 2012; Hill, 2001), the executive functions domain included working memory, inhibition, cognitive flexibility, attention, planning, monitoring, and metacognitive skills (Cartwright, 2012; Diamond, 2013; Miyake & Friedman, 2012). Tests that did not fit in one of the other cognitive skill categories were collected in a miscellaneous cognitive skill category. Finally, general cognitive scores represented a combination of the above cognitive tests where the authors only provided a general score.

Transparency and Openness

Data were analyzed using R, version 4.3.0 and the package metafor, version 4.6-0 (Viechtbauer, 2010) with additional analyses conducted in JASP (2025). We adhered to the MARS guidelines for meta-analytic reporting (Appelbaum et al., 2018). All meta-analytic data, analysis code, and additional research materials (including our coding scheme) are available (see https://osf.io/4vky3/?view_only=7d3009f5e5c34abda0866220fb7d1410).

Data Analysis

The effect sizes analyzed were correlation coefficients drawn from the original studies (or a related statistic that could be converted into correlation coefficients). Because correlation coefficients are not equal interval scales, they were transformed into *z*-scores using the Fisher's *r*-to-*z* transformation. Initial analyses focused on detecting publication bias via funnel plots, calculating descriptive statistics of effect sizes, and the influence of predictor variables. To test for publication bias, we conducted an Egger's mixed effects test because this method best accommodates dependent effect sizes inherent in nested data (Rodgers & Pustejovsky, 2021). Additionally, we ran PET-PEESE to adjust for publication bias. This two-step procedure first uses linear regressions to test for a relation between standard errors and effect size, and if this relation is significant ($\alpha < 0.10$), a second model is run to correct the effect size (Bartoš et al., 2022).

Given that we derived multiple effect sizes from single studies, we could not assume that each effect size was statistically independent. Accordingly, we analyzed the data using mixed-effects meta-regression models performed with the Metafor package in R (Viechtbauer, 2010). Mixed-effects models are ideal for estimating the effect size of moderators while accounting for nested effects of sample and study features. To account for non-independence (i.e., correlated residuals) and small sample sizes, robust estimation (of effect sizes and confidence intervals, etc.) was performed using the clubSandwich package (Pustejovsky & Tipton, 2022) via the metafor package, employing the "robust" function.

Analyses modeled the study and individual effect sizes as random effects. Level 1 predictors were the measures (motor and academic-cognitive skills). Level 2 variables were features of the individual studies and samples, including publication year, study quality, sample status (normal-achieving or at-risk), percentage of females in samples, and sample age (in years). Restricted maximum likelihood estimation was used, and model heterogeneity was examined to investigate model fit.

Results

Description of Reviewed Literature

In total, 63 samples from 59 different studies with 856 effect sizes and 40,806 participants in total were included. The dataset included mostly peer-reviewed (93.2%) studies, with a mean publication year of 2015 ($M = 2015.1$; $SD = 11.94$; range: 1967 and 2025). Samples were between 3.5 and 15 years old ($M = 6.90$; $SD = 2.63$), and included, on average, 49.45% females ($SD = 6.19\%$). A total of 29.4% of the samples involved at-risk children (i.e., low SES or low achievement). Studies were mainly conducted in the US, Australia, Germany (each > 10%), Switzerland (8.5%), and the UK (5.1%), with the remaining studies distributed across the world. A breakdown of these studies and sample features as a function of motor skills and academic-cognitive domains is presented in Supplementary Tables 1 and 2.

Publication Bias

Due to current uncertainty around selective reporting of publication bias indicators, it is recommended to triangulate across different tests of publication bias (van Aert et al., 2019). To follow this recommendation, a funnel plot was first constructed

(Fig. 2), and a mixed-effects Egger's test for funnel plot asymmetry was run, which indicated no publication bias ($z = -1.267$, $p = .205$). However, a second analysis using Kendall's rank test revealed significant publication bias ($\tau = 0.080$, $p < .001$). Finally, a PET-PEESE analysis was performed. In the first step (PET), standard errors were found to correlate significantly and negatively with effect sizes, $p = .002$. This was confirmed in the PEESE analysis, $p = .018$, which is depicted in Fig. 3. The corrected Fisher's Z was 0.226, which is slightly lower than an estimate from a null mixed effect regression, Fisher's $Z = 0.239$.

Influence of Publication Features, Sample Features, and Methodological Quality

To determine the influence of publication features, sample features, and methodological quality on effect sizes, mixed-effects meta-regressions were conducted. A separate model was run for each predictor. The models are presented in Table 1. For the categorical predictors, tests (ANOVAs) for differences between the levels were conducted.

Fig. 2 Funnel plot

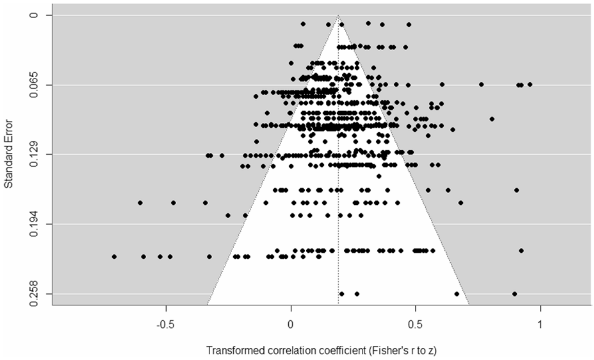

Fig. 3 Estimated PEESE regression to correct for publication bias

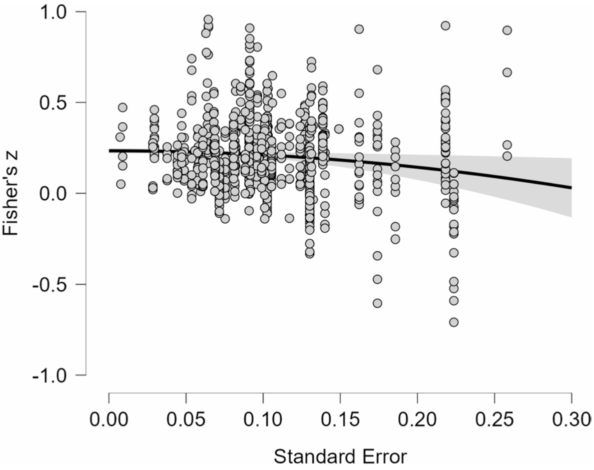

Table 1 Summary of effect sizes as a function of study descriptives using cluster-robust estimates

Predictor	*r*	Z_f	SE	t	df	*p*	CI_{lower}	CI_{upper}	$Q_{model\ heterogeneity}$	df	*p*
Publication year	−0.030	−0.030	0.031	−0.954	6.190	0.376	−0.106	0.046	17439.983	855	<0.001
Age	0.031	0.031	0.039	0.792	12.440	0.443	−0.054	0.116	15952.198	855	<0.001
Percent female	−0.068	−0.068	0.035	-1.984	12.020	0.071	−0.144	0.007	14769.966	767	<0.001
Study quality	0.025	0.025	0.002	10.301	50.670	<0.001	0.020	0.030	6479.767	855	<0.001
Sample											
Normal	0.238	0.243	0.024	10.045	50.860	<0.001	0.195	0.292	5992.843	854	<0.001
At-risk	0.217	0.220	0.035	6.324	9.770	<0.001	0.142	0.298			
Peer-reviewed											
No	0.311	0.322	0.055	5.875	3.930	0.004	0.169	0.475	6088.047	854	<0.001
Yes	0.229	0.233	0.022	10.566	56.720	<0.001	0.189	0.277			

Predictors were Z-transformed, all *Q* tests for model heterogeneity were statistically significant, $p < .0001$

Year of publication, age, and percentage of females in the samples were not significantly associated with effect sizes. Study quality was significantly related to effect sizes. Post-hoc ANOVAs indicated that non-peer-reviewed papers did not significantly differ from peer-reviewed papers, $p = .274$, nor did at-risk samples produce different effect sizes compared to normal samples, $p = .685$. Heterogeneity was high, suggesting that the models left substantial variance unexplained, although this was much lower for study quality, sample status, and publication type.

Testing Links Between FiMS, GMS, and Academic-Cognitive Skills

In the remaining analyses, mixed effects meta-regressions estimated the effect sizes as a function of sample and study features (Table 1), FiMS and GMS (Table 2), and type of motor skill (Table 4). These regressions accounted for the influence of study quality by including it as a z-transformed continuous predictor. Furthermore, effect sizes for FiMS and GMS as a function of the academic-cognitive domain were calculated (Table 3) and compared using separate ANOVAs for each domain (Fig. 4).

Hypothesis: Comparing Effect Sizes Between FiMS and GMS with Overall Academic-Cognitive Skills

The effect sizes for FiMS and GMS, using the robust and clubsandwich functions (Pustejovsky & Tipton, 2022) from the metafor package, were calculated and are presented in Table 2. As Table 2 shows, FiMS resulted in greater effect sizes than GMS did, a difference confirmed by a post-hoc ANOVA, $p < .001$. An explorative analysis that included an interaction term between age and motor skills was not statistically significant, neither for the main effect of age, $p = .974$, nor for the interaction with motor skill, $p = .262$.

Exploratory Analysis: FiMS vs. GMS with Reading, Writing, Mathematics, General Academics, Language, and Cognitive Skills

Table 3; Fig. 4 present effect sizes for a model including an interaction between motor skills and academic-cognitive skill domains. The model also controlled for study quality, which was not significant, $Z = -0.036$, $p = .089$. As Table 4 shows, the effect sizes were all significantly above zero for both FiMS and GMS, except for the association between GMS and general academic skills. Post-hoc ANOVAs revealed that FiMS related more strongly to reading, $p < .001$, writing, $p = .012$, mathematics, $p < .001$, general academics, $p < .001$, and cognition, $p < .001$, but not language, $p =$

Table 2 Overall effect sizes of Fine motor (FiMS) and Gross motor (GMS) skills

Predictor	r	Z_f	SE	t	df	p	CI_{lower}	CI-upper	$Q_{model\_heterogeneity}$	df	p
FiMS	0.302	0.312	0.030	10.474	57.790	<0.001	0.252	0.371	4913.664	853	<0.001
GMS	0.170	0.172	0.025	6.869	57.860	<0.001	0.122	0.223			

$k = 856$, $j_{studies} = 59$, effect of study quality as continuous predictor, $p = .121$

Table 3 Links between FiMS versus GMS with academic and cognitive skills

Academic-cognitive skill	Motor skill	*r*	Z_f	SE	t	df	*p*	CI_{lower}	CI_{upper}	$Q_{model\_heterogeneity}$	df	*p*
Reading	FiMS	0.275	0.282	0.023	12.063	47.120	< 0.001	0.235	0.329	4170.365	843	< 0.001
	GMS	0.116	0.117	0.048	423	46.680	0.019	0.020	0.214			
Writing	FiMS	0.243	0.248	0.074	3.331	3.550	0.035	0.031	0.465			
	GMS	0.143	0.144	0.027	5.259	4.190	0.006	0.069	0.218			
Maths	FiMS	0.331	0.344	0.054	6.389	48.970	< 0.001	0.236	0.452			
	GMS	0.151	0.152	0.031	4.895	46.990	< 0.001	0.090	0.215			
General academic	FiMS	0.399	0.423	0.067	6.335	2.940	0.008	0.208	0.638			
	GMS	0.171	0.173	0.073	2.361	2.950	0.101	−0.062	0.408			
Language	FiMS	0.251	0.254	0.058	4.403	17.390	< 0.001	0.132	0.375			
	GMS	0.209	0.211	0.055	3.821	13.710	0.002	0.092	0.329			
Cognition	FiMS	0.262	0.269	0.025	10.724	56.820	< 0.001	0.219	0.319			
	GMS	0.208	0.211	0.022	9.718	57.050	< 0.001	0.168	0.254			

$k = 856, j_{studies} = 59$, effect of study quality as continuous predictor, $p = .089$

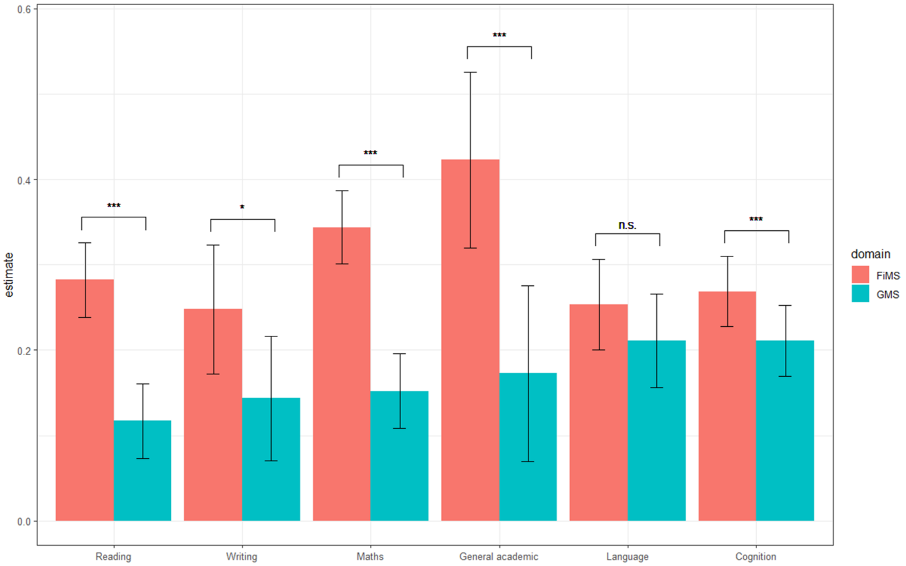

Fig. 4 Comparison of effect sizes between FiMS and GMS as a function of academic-cognitive skill

.083. Comparing sample heterogeneity (*Q*) across models in Tables 1, 2, 3 and 4, the model in Table 3 had the least unexplained heterogeneity.

Exploratory Analysis: FiMS vs. GMS with Intelligence vs. Executive Functions

For most academic-cognitive domains, namely reading, writing, mathematics, general academic skills, and language, data sets were insufficient for a more detailed investigation. However, for cognitive data, a differentiation between intelligence ($k=69$) and executive functions ($k=438$) was both numerically feasible and theoretically informative. A mixed-effects regression containing study quality and an interaction between motor (FiMS/GMS) and cognitive skill (intelligence/executive functions) was conducted. Study quality did not contribute significantly, $p = .810$. Fisher's Z scores and post-hoc ANOVA comparisons indicated that FiMS linked more strongly to intelligence than GMS did, $Z = 0.291$ vs. 0.128, $p < .001$, with a similar albeit much smaller difference for executive functions, $Z = 0.229$ vs. 0.208, $p = .007$.

Exploratory Analysis: Individual Motor Subskills with Overall Academic-Cognitive Skills

Results for each motor subskill are presented in Table 4, with study quality once again included as a control variable. The greatest associations between overall academic-cognitive skills and individual FiMS subskills were found for general FiMS and graphomotor skills. For individual GMS subskills, miscellaneous GMS and balance showed the strongest links to overall academic-cognitive skills. An additional model was run that included age as a continuous predictor variable. However, this did not make a significant contribution, $p = .506$.

Table 4 Links between motor subskills and academic-cognitive skills

Predictor	*r*	Z_f	SE	t	df	*p*	CI_{lower}	CI_{upper}	$Q_{model\_heterogeneity}$	df	*p*
Fine motor skills									4464.525	845	<0.001
Dexterity	0.253	0.259	0.034	7.531	52.970	<0.001	0.190	0.329			
Graphomotor	0.289	0.297	0.035	8.369	41.430	<0.001	0.225	0.369			
FiMS miscellaneous	0.229	0.233	0.064	3.661	18.380	0.002	0.099	0.366			
General FiMS	0.303	0.313	0.031	10.204	56.340	<0.001	0.251	0.374			
Gross motor skills											
Whole-body coordination	0.216	0.219	0.050	4.384	12.000	<0.001	0.110	0.328			
Balance	0.232	0.236	0.024	9.892	56.700	<0.001	0.188	0.284			
General GMS	0.118	0.119	0.036	3.282	55.280	0.002	0.046	0.191			
Object manipulation	0.190	0.192	0.021	8.964	52.720	<0.001	0.149	0.234			
Agility	0.223	0.227	0.040	5.620	19.070	<0.001	0.143	0.312			
GMS miscellaneous	0.298	0.307	0.059	5.184	4.120	0.006	0.145	0.470			

$k = 856, j_{studies} = 59$, effect of study quality as continuous predictor, $p = .109$

Discussion

We analyzed data from 59 studies, containing 63 samples, 40,806 participants, with 856 effect sizes spanning multiple research fields, allowing us to be the first to comprehensively examine relations between FiMS, GMS and academic-cognitive skills (cf. Hill et al., 2024; Wang & Wang, 2024). By using mixed-effects meta-regression models controlling for publication, sample, and study quality features, this meta-analysis provides clear and unique insights. First, FiMS showed an association of $r = .302$, and GMS of $r = .170$, with overall academic-cognitive skills. In the context of meta-analytic data (see Gignac & Szodorai, 2016), empirically derived effect sizes indicate that $r = .10$, 0.20, and 0.30 correspond to small, medium, and large correlations, respectively. Accordingly, the observed correlations between overall academic-cognitive skills and FiMS can be considered large, whereas those for GMS are small.

Our meta-analysis also provides the first comprehensive comparison of relations between FiMS and GMS in relation to academic-cognitive skills, demonstrating that FiMS exhibit stronger associations with overall academic-cognitive skills than GMS. These findings are unlikely to have arisen due to a third variable driving all links indiscriminately, given that the links were highly differentiated, varying as a function of motor and academic-cognitive skills. Stronger associations between FiMS and academic skills could be seen as support for functionalistic theories that emphasize the importance of FiMS in engaging with learning materials and dealing with fine motor demands of school tasks. However, the shared action-cognition theory is also likely to come into play, as brain areas related to both sets of activities show shared neural activation (Anderson, 2007; Fischer et al., 2018; Penner-Wilger & Anderson, 2013; Soylu et al., 2017).

In addition, FiMS and, by extension, fine motor activities are cognitively and coordinatively challenging tasks for children (Best, 2010; Serrien et al., 2007). Thus, engaging in such tasks may not only foster FiMS but also cognitive skill development, especially for executive functions (Tomporowski & Pesce, 2019). Specifically, FiMS may co-activate and stimulate neural areas relevant to reading, writing, mathematics, language, and cognitive skills. Gross motor activities can also be cognitively challenging (Mavilidi et al., 2025), which may explain why the links between GMS and executive functions were stronger, as discussed below.

Interestingly, correlations between GMS and academic-cognitive skills were generally small to moderate, whereas associations between GMS and language as well as cognition were mostly moderate. Perhaps the role of GMS can also be explained by shared motor-cognition theory, whereby greater GMS, in conjunction with coordinatively demanding motor tasks, utilize areas that overlap with those used for cognitive skills (Cameron et al., 2016; Hill et al., 2024). Conceivably, GMS may also play an important functional role in everyday exploratory behavior, particularly among younger learners (Iverson, 2010). However, what makes this latter suggestion unlikely is the lack of an age moderating effect in the analyses: although it is conceivable that younger children with greater GMS might explore and learn more, it is less clear how this functionalist mechanism would still operate during middle childhood and adolescence.

We compared the effect sizes for FiMS and GMS for each academic-cognitive skill domain separately. Effect sizes for FiMS were medium to strong across the different academic-cognitive skill domains, ranging from r = .243 to 0.399. In contrast the effect sizes for GMS were small to medium, spanning r = .116 to 0.209. Regarding reading, writing, mathematics, and general academic skills, as well as cognition, FiMS displayed stronger connections than GMS. However, there was no significant difference between FiMS and GMS for language skills. Our results are in line with Wang and Wang (2024), who reported that FiMS were related to reading, writing, spelling, and mathematics, whereas little association was found between these academic domains and GMS. They only found positive associations between language and general academic skills and both FiMS and GMS (Wang & Wang, 2024), which for language is consistent with our results. However, regarding the associations with general academic skills our analysis shows a significant difference between FiMS (r = .399) and GMS (r = .171). This suggests that FiMS are a relevant factor for overall academic skills.

FiMS and GMS both showing moderate links to language as well as cognition is partly in line with the shared motor-cognition theory as it suggests that both FiMS and GMS utilize overlapping neural areas and processes. Alternatively, if greater GMS are caused by engaging in more physical activity, it could be that the latter mediates the link between GMS and cognition through a number of mechanisms (Mavilidi et al., 2025). Even though functionalism is likely to play a significant role, there may still be a place for shared action-cognition processes in the development of academic skills. For instance, previous research has demonstrated the effects of motor programs on the stimulation of multisensory storage and retrieval during letter learning (Bara & Bonneton-Botté, 2018), as well as the influence of visual-spatial information when teaching numeric representations in children (Fischer et al., 2016; Link et al., 2014). However, as alluded to, functionalism theory may better explain the links between motor skills and reading, writing, mathematics, and general academic skills, given that FiMS, compared to GMS, are particularly important for learning tasks in school (Caramia et al., 2020). Therefore, the more academically driven skills get, the more importance may shift towards FiMS.

This is supported by findings from physical activity intervention studies, which emphasize the importance of aligning interventions with learning content and integrating them into the learning setting to maximize learning outcomes while also accounting for cognitive load (Mavilidi et al., 2018; Zou et al., 2025). Appropriately designed interventions can enhance cognitive engagement, support the externalization of abstract information, and help offload cognitive demands, thereby facilitating learning. Consequently, the integration of FiMS, which are more closely linked to academic contents (e.g., gestures for vocabulary or manipulating objects in geometry and chemistry) may be more effective than non-integrative gross motor activities (e.g. movement breaks), which may impose additional cognitive load and potentially impede learning (Zou et al., 2025).

Sufficient data were available to examine two subdomains of cognitive skills, namely intelligence and executive functions. An exploratory analysis showed that FiMS correlated more strongly with intelligence than GMS did; however, this difference was smaller for executive functions, albeit still statistically significant. Thus, executive functions seem to be involved in both motor skills. This finding is also consistent with executive functions being a mediator linking motor and academic skills. Unfortunately, domain-specific executive functions are often overlooked in research on academic outcomes despite their relevance for motor–academic links (Zhang et al., 2025). For instance, a five-to-ten-minute bout of physical activity prior to a math class improved performance in a math-specific inhibitory task, but not in a general inhibitory task (Zhang et al., 2026).

Turning to specific fine motor subskills, both dexterity ($r = .253$) and graphomotor skills ($r = .289$) showed moderate links with academic-cognitive skills. As mentioned, in previous studies graphomotor skills were found to be relevant for reading and writing (Berninger et al., 2006; James, 2010; Longcamp et al., 2005; Suggate & Stoeger, 2017; Wamain et al., 2012), whereas manual dexterity was related to executive functions (Gandotra et al., 2022). Both subskills seemed to have specific links with academic-cognitive skills, such that a combined FiMS measure may result in stronger correlations. This idea is partially supported as general FiMS showed a stronger correlation to academic-cognitive skills than graphomotor skills or dexterity alone ($r = .303$).

Of all GMS, balance ($r = .232$) and miscellaneous GMS ($r = .298$) displayed the highest associations with academic-cognitive skills. The correlation with balance is consistent with Gandotra et al. (2022); however, Macdonald et al. (2018) found no association between balance and mathematics performance and reported inconclusive links with reading. This finding appears counterintuitive because balance tasks typically require lower cognitive demands than coordinative GMS tasks. One explanation may lie in vestibular cognition, an offshoot of embodied cognition, whereby some cognitive tasks benefit from vestibular processing (Li et al. 2024a, b). The large effect sizes for the miscellaneous GMS category with academic-cognitive skills are somewhat surprising and may be due to the small number of studies (4) and effect sizes (19), warranting caution despite our use of robust modelling.

Limitations

Our study offers new and unique insight into the differentiated connection between academic-cognitive skills and FMS as well as GMS. Nevertheless, there are some limitations that must be addressed. First, we analyzed correlational studies and cannot, therefore, conclude that motor skills are causally linked to academic-cognitive skills. The decision to focus on correlational data was made due to the limited available data from experiments, interventions, and longitudinal studies (Hill et al., 2024; Macdonald et al., 2018).

Second, the models generally had high heterogeneity, indicating unexplained variance. This is likely due to differences in measures, samples, and the collapsing of different constructs. By only using studies that included both FiMS and GMS, we ensured equal samples and methodological approaches per study. Although this was an important decision to facilitate comparisons between FiMS and GMS, between-study samples and methodological differences due to variation in test instruments still exist. We tried to counteract this variability by carefully constructing skill categories and inclusion criteria. In doing so, we enabled interpretation of results based on consistent motor and academic-cognitive skill categories.

Third, due to insufficient data, some motor categories had to be collapsed, thereby possibly inflating heterogeneity and precluding the examination of associations for speed-based FiMS, bimanual skills, finger gnosia, and locomotor skills. Regarding academic skills, a more detailed examination of subskills (e.g., splitting reading into preliteracy, word reading, connected text reading, and reading comprehension) would have given even more insight into links between FiMS and GMS with academic-cognitive skills. However, aside from data on cognitive skills, not enough data were available to investigate academic-cognitive skills in even more detail. Despite this, to our knowledge, this meta-analysis provides the most comprehensive investigation of the links between FiMS and GMS with academic-cognitive skills.

Fourth, we could have expanded our search terms to include common FiMS and GMS tests; this may have provided even more than nearly 35,000 titles to screen. To estimate the extent to which adding these terms might have resulted in more hits, we conducted a post-hoc additional search from 2022 to 2025 in PsycINFO. This resulted in 187 hits, five of which had already been included in the meta-analysis. Further screening of the remaining 182 titles did not yield any additional studies, providing confidence that the current search strategy is comprehensive.

Lastly, we only included children and adolescents aged 3 to 16. This decision was partly pragmatic and partly theoretical. Pragmatically, a widely used measure of motor skills that we suspected would be used in many studies is normed for this range (i.e., the Movement ABC). Theoretically, we also sought to situate this study within the literature on childhood and adolescence. However, this cut-off is somewhat arbitrary and could be extended in future research.

Future Research

Future studies should employ longitudinal, experimental, and intervention designs to further elucidate the mechanisms underlying the links between motor and academic-cognitive skills. Longitudinal studies, including both FiMS and GMS measures matched for cognitive challenge, would help disentangle whether FiMS relate more strongly to academic-cognitive skills because they inherently place greater demands on cognition. An inclusion of assessments of both domain-general and domain-specific executive functions would contribute to a clearer understanding of the role of executive functions as a mediator in motor-academic links (Zhang et al., 2025). Furthermore, given the literature on the role of physical activity in cognition, physical activity should be included as a mediator in longitudinal research. Additionally, a more detailed investigation of motor and academic subskills (e.g., writing, number concepts) could provide further insight into specific links. Regarding intervention programs, initial evidence comes from studies examining complex motor skill training (e.g., Gai et al., 2021; Moreau et al., 2015; Pesce et al., 2013); however, more intervention studies that include diverse age groups and at-risk samples are needed. In addition, when planning physical activity-based interventions, their relevance to the learning content and integration into the learning setting as well as its cognitive load should be considered (Mavilidi et al., 2018; Zou et al., 2025). In particular, the influence of such interventions on various academic skills warrants further investigation.

Practical Implications

The current findings are also particularly relevant for practice, given the reduction in physical activity in childhood and adolescence and the corresponding probable decline in FiMS in recent generations (Gaul & Issartel, 2016; Sulzenbruck et al., 2011), a phenomenon accelerated by the lockdowns during 2020–2021 (Ayubi & Komaini, 2021). Thus, preschool and school practitioners are urged to consider the role of GMS and FiMS in their curricula.

Evidence on the role of motor skills in educational settings is found across various literatures, which are sometimes vast and other times underdeveloped. The current meta-analysis demonstrates that there are robust links between motor skills and academic-cognitive skills. Notably, links between FiMS and academic skills were considerably stronger than GMS. This strongly suggests that FiMS remain an important prerequisite for learning in academic settings (Suggate et al., 2023). Accordingly, educators may use FiMS as an additional indicator of school readiness and, in particular, select appropriate learning materials. Further, it is estimated that 5% of children meet the criteria for Developmental Coordination Disorder, with the prevalence rising to 7% in North America (Li et al. 2024a, b). Given that it is unrealistic for teachers to wait for motor skills to develop in these children before beginning academic instruction, this further underscores the need to ensure that learning materials do not hinder participation (e.g., by imposing high demands on note-taking speed). Conversely, experimental evidence shows that writing consolidates learning (Suggate et al., 2017, 2023; Mueller & Oppenheimer, 2014), indicating that appropriate demands on FiMS should remain.

We also found that links between GMS and language and cognition, particularly executive functions, were nearly as high as for FiMS. This finding supports the idea that all motor skills are linked to cognition, suggesting a shared mechanism across both processes, as posited in action-cognition theory. Crucially, this is consistent with a large body of work demonstrating that physical activity improves cognition across all age groups (Mavilidi et al., 2018, 2025). As has been argued elsewhere (Mavilidi et al., 2018), research on links between physical activity or motor skills and cognition has emerged from two traditions: one focusing on activity and exercise and the other on embodied cognition emphasizing overlapping functionality. Research has documented the processes by which exercise and sports benefit cognition (Tomporowski & Pesce, 2019), and the current research focuses on underlying cognitive mechanisms.

Accordingly, we agree with other researchers that a combined benefit of purposeful physical activity embedded into academic instruction is a promising path forward with practical implications for learning and development (Mavilidi et al., 2018). Research has begun to study the benefits of coupling movement with learning activities in children's numeracy (Link et al., 2013) and literacy (Glenberg et al., 2011). Indeed, a recent meta-analysis found that embodied learning programs in schools show moderate effects, including in secondary schools, for both the humanities and mathematics (Liu et al., 2025). Thus, when considering the relevance of physical activity for learning content as well as ensuring its suitable integration into the learning setting at an appropriate cognitive load, practitioners could maximize learning outcomes and provide an engaging and enjoyable learning environment (Mavilidi et al., 2018; Zou et al., 2025).

Summary

In summary, there is now a large body of research showing that motor skills meaningfully relate to academic-cognitive skills, which, when coupled with findings on the importance of physical activity, strongly suggests that researchers, practitioners, and care workers should take the role of motor skills in development and education into account. In academic learning, and to a lesser extent in language and cognition, FiMS appear to play a stronger role. Indeed, as the current study shows, what is fine can be large. Perhaps, at least in terms of language and cognition, what is gross can also be fine, in a different sense of the word!

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10648-026-10161-4.

Funding Open Access funding enabled and organized by Projekt DEAL. This work was supported by the German Research Council under STO 481/10-1 and SU 766 7/1, awarded to the final and second authors, respectively.

Declarations

Competing interests The authors report there are no competing interests to declare.

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