Educational Research Review 49 (2025) 100748

Contents lists available at ScienceDirect

Educational Research Review

journal homepage: www.elsevier.com/locate/edurev

Review

Keep the hands in mind: A meta-analysis of correlations between fine motor skills and reading, writing, mathematics, and cognitive development in children and adolescents

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ARTICLE INFO

Keywords:
Fine motor skills
Graphomotor skills
Reading
Cognition
Vocabulary
Writing
Academic achievement

ABSTRACT

Evidence suggests that fine motor skills (FMS) relate to academic and cognitive development; however, findings are unclear, strewn across multiple disciplines, and lack adequate synthesis. We conducted the first comprehensive meta-analysis examining the links between different FMS facets (i.e., dexterity, speed, graphomotor, bimanual, general) and a broad range of academic-cognitive skills (i.e., sub-categories of reading, writing, mathematics, and cognition). A literature search identified 21,225 articles resulting in 118 eligible correlational studies (j = 143, k = 1110, N = 79,856). FMS exhibited significant and moderate relations with academic-cognitive skills (r = .329, d = .697). Graphomotor skills and writing showed the largest effect sizes. Mediation analysis suggested that cognitive skills mediated the link between FMS and academic skills. Overall, findings suggest that FMS share cognitive processes with academic skills, but that FMS are still related functionally to academic skills, especially writing. The discussion focuses on educational implications, moving beyond establishing *if* links exist to investigating *why*.

Motor development has been a constant, albeit occasionally overlooked, aspect of educational, psychological, and developmental research for over a century (Adolph & Hoch, 2019). It has been reported that children's fine motor skills (FMS) have been declining (Gaul & Issartel, 2016), and there has been a move away from manual subjects in school curricula, exemplified by many countries replacing handwriting with typing in curricula (Dinehart, 2014; Must, 2014). Historically, due to the dominance of cognitivism and modular theories of motor development and cognitive control (Whitall et al., 2020), the hand has been relegated to a purely functionary tool for centrally occurring cognition (Wilson, 1999). Renewed interest in FMS and their relations to cognition and academic achievement has arisen through findings linking sensorimotor skills and neural regions to language, cognition, and executive functioning (Diamond, 2000; Hauk et al., 2001; Suggate & Stoeger, 2017). However, there has been little conceptual clarity about the role that FMS play in educational attainment, specifically for the key domains of reading, writing, and mathematics. Unfortunately, research appears chaotic and fragmentary, scattered across multiple fields, and studied under different names and theoretical perspectives. Accordingly, no research synthesis has gathered this body of evidence, and, therefore, relations between FMS and academic-cognitive skills have not been investigated in a sufficiently systematic and differentiated manner (Gandotra et al., 2021; Macdonald et al., 2018; van der Fels et al., 2015).

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https://doi.org/10.1016/j.edurev.2025.100748
Received 6 December 2024; Received in revised form 13 November 2025; Accepted 19 November 2025
Available online 21 November 2025
1747-938X/

1. Fine motor, academic, and cognitive skills

We analyze key academic and cognitive skills that have been identified as important for school attainment (Ferrer et al., 2007) and which have been studied in relation to FMS (Cameron et al., 2016; Fischer et al., 2018; Roebers et al., 2014).

1.1. Definitions of FMS, academic, and cognitive skills

Terminology is a difficulty when synthesizing literature across multiple disciplines and over many decades of research. This is further compounded by the lack of factor analytic validation across FMS, leaving us to draw together terminology and measurement methods across a challengingly diverse literature.

FMS. Generally, FMS represent small, goal-directed movements predominantly of the fingers and hands, usually involving close hand-eye coordination (Luo et al., 2007). Although this definition is appealing because of its broad and inclusive nature, on the one hand, and its specific foci on the other (i.e., the fingers and hands, purposeful), a cursory glance at the literature suffices to see the multitude of ways in which FMS have been defined and operationalized (Chien et al., 2009). FMS generally encompass a raft of skills and processes that implicate sensory (i.e., haptic, visual, proprioceptive, sensory-integrative), motor (i.e., speed, flexibility, object manipulation), and cognitive (i.e., attention, planning, monitoring) aspects. Based on our review of the literature on the relations between FMS and academic-cognitive skills (Brookman et al., 2013; Martzog et al., 2019) and on task analysis, it appears that FMS show different features, allowing them to be clustered. First, there is the general ability to perceive the position of one's fingers (finger gnosia), to then move one's fingers and hands accurately (dexterity), to do this rapidly (speed), and perhaps also involve both hands (bimanually). Finally, given the importance of writing tools in school and learning, a final aspect pertains to pencil and pen operation (graphomotor skills), and if such measures were widely employed, could easily be expanded to include any tool.

Accordingly, we differentiate the following categories of FMS: (a) dexterity, as skillful and varied manual actions usually involving an object, (b) speed, with a focus on cognitively non-taxing and rapid movements such as tapping, (c) graphomotor skills, requiring pencil/pen usage to draw symbols, (d) finger gnosia, the perception and corresponding movement of individual fingers, and (e) bimanual skills, whereby both hands are involved in coordinated actions, such as tapping rhythms. There is some overlap among these five FMS domains, although these different factors have been widely used (Brookman et al., 2013) and, in some instances, factor-analytically validated (Martzog et al., 2019; Suggate et al., 2025). Nevertheless, it remains an open empirical question whether differences are meaningful and whether different FMS relate differentially to academic and cognitive outcomes. Such a question is ideally addressed with meta-analyses.

Academic skills. Although academic skills refer to a broad range of skills that can develop rapidly over the course of child, adolescent, and adult development (e.g., motivation, learning strategies, scientific knowledge, historical reasoning), research has focused most on reading, writing, and mathematics. In addition to being key determinants of school success (Lonigan & Phillips, 2012), reading, writing, and mathematics have been studied in relation to FMS, whereas other academic skills (e.g., motivation, scientific reasoning) have generally not been investigated (Grissmer et al., 2010; Pagani et al., 2010).

Reading. Skilled reading reflects the ability to decode the symbols present in text effortlessly while deriving meaning (Cain et al., 2001), often forming situation models (Kintsch, 1988). This encompasses a range of preliteracy, decoding, and comprehension skills. Relevant preliteracy skills include: (a) concepts about print (Clay, 1993), which is knowledge of reading conventions, such as text directionality (e.g., left to right, front to back); (b) phonemic awareness (Adams, 1990), referring to an understanding that words comprise sound units; (c) letter recognition (National Early Literacy Panel, 2008), being able to name and sound out letters; and (c) word reading (Herman et al., 2006), being able to derive words and sounds from written symbols. In primary school and beyond, important reading skills include: (e) reading fluency (Therrien, 2004), being able to read connected text rapidly; and (f) reading comprehension, deriving meaning from text.

Writing. Writing is still a key facet of academic development (Berninger et al., 2006), with better writers having more free resources to follow lessons more closely, being more accomplished readers, and receiving higher grades. Writing (by hand) broadly encompasses a mechanical production of letters and a compositional component. Beginning with the mechanical aspect, this refers to the ability to translate language into its corresponding orthographic symbols following writing conventions particular to the given language, encompassing subskills such as letter copying, letter production, word writing, written spelling, and sentence writing (Berninger et al., 2006; Cornhill & Case-Smith, 1996). At a more advanced level, once these mechanical aspects have been sufficiently mastered, compositional writing to express ideas in different genres becomes important (Berninger et al., 2006).

Mathematics. Mathematical and numeracy skills encompass understanding, representing, and performing calculations with numbers and quantities, as well as formal and conceptual knowledge of mathematical operations (Bryant & Nunes, 2012). In terms of specific subskills, this includes pre-mathematics skills involving representations of number and quantity, counting skills, and arithmetic (Manfra et al., 2016; Mix et al., 2016; Pieters et al., 2012; Verdine et al., 2014). More advanced mathematics includes conceptual problem-solving skills (Mix et al., 2016; Swanson, 2006; van Garderen & Montague, 2003).

Cognitive Skills. Cognitive skills—particularly vocabulary, intelligence, and executive functions—have been studied in relation to FMS and are also predictors of later academic achievement (McClelland & Cameron, 2019). We use the term cognitive skills to broadly reflect the acquisition and processing of information (Fry & Hale, 2000), which is clearly of great importance for human development and functioning. Specifically, we define cognitive skills as measures of intelligence, which often include general knowledge, spatial reasoning, pattern recognition, and verbal reasoning.

Additionally, we include executive functions because evidence suggests that these link to both academic and FMS (Cameron et al., 2012). Executive functions refer to "a family of top-down mental processes needed … to concentrate and pay attention" (Diamond, 2013, p. 136). Typically, a three-factor approach to executive functions is taken, with this entailing inhibitory control, working memory, and cognitive flexibility (Cartwright, 2012; Diamond, 2013), although a single factor appears to fit the data well also (Karr et al., 2018).

Finally, language is an important aspect of cognition in its own right, constituting one of the crowning achievements of childhood, and being central to conceptual processing (Inhelder & Piaget, 1968) and communicative skill (Catts et al., 1999; Pexman, 2019). Due to a lack of studies looking at broader aspects of language (i.e., syntax, pragmatics), we consider vocabulary as a key aspect of cognition and include both receptive and expressive vocabulary.

1.2. Theories on the relation between FMS and academic-cognitive skills

One problem facing research on relations between FMS and academic-cognitive skills is that theoretical accounts are strewn across many disciplines, are often underspecified, not empirically tested, or completely neglected. Accordingly, we have tried to summarize poignantly what we perceive as the four main likely and contrasting theoretical possibilities existing in the literature.

Amodal Theories and Maturation. The first empirical and theoretical possibility is that FMS have no relation with academic and cognitive skills, and hence, FMS and cognitive skills only correlate in studies due to spurious findings and Type I error. At a theoretical level, amodal theories of cognition have a long tradition (Wilson, 2002) and see FMS as simply the executors of centrally informed intentions (see also Whitall et al., 2020). When measured offline, that is, when motor processes are being measured in a spatially and temporally distinct context from cognitive performance (e.g., a FMS test now, an IQ test in 2 h), there should be no link between the two domains. This does not preclude links during online processing (i.e., performance on FMS and IQ tests conducted simultaneously), due to interference. In other words, according to amodal theories, FMS and cognitive skills are modular functions, orthogonal and bearing little relation to one another.

A second possibility is that, given that the majority of FMS research deals with children, any links between FMS and academic-cognitive skills are confounded by maturation effects (Krampe, 2002). Specifically, FMS undergo rapid development at a time when cognitive skills are also emerging rapidly (McClelland & Cameron, 2019). Accordingly, correlations between FMS and academic-cognitive skills might be by-products of age variance in studies; the larger the age variance, the larger the variance in concomitant FMS and academic-cognitive skills. Accordingly, links between FMS and academic-cognitive skills should disappear when sample variance in age is accounted for. Further, it would follow that links between FMS and academic-cognitive skills would be constrained to (early) childhood when both aspects are concomitantly undergoing rapid development.

Functionalism and Shared Processes. Two theories propose links between FMS and academic-cognitive skills, namely functionalism and shared processes. Although both theories posit links between FMS and academic-cognitive skills, they differ in the role they afford to cognitive skills. Accordingly, depending on the precise theoretical mechanism, we differentiate between academic and cognitive skills, with functionalism emphasizing the links between FMS and academic skills, and shared processes emphasizing the links between FMS and cognitive skills (Suggate & Stoeger, 2017).

Functionalism claims that FMS provide unique opportunities to engage in skillful actions that benefit academic learning and to some extent cognitive skills (Suggate & Stoeger, 2017). For instance, a child who can manipulate and explore objects can better develop mental representations of those objects (Martzog & Suggate, 2019), or children who can use their fingers for counting can have advantages in representing numbers (Butterworth, 1999). Additionally, if children can competently utilize tools requiring FMS, such as writing objects or electronic devices, different experiences are possible compared to those available to a less FMS-able child. Therefore, according to functionalism, links between FMS and academic skills are caused by increased and enriched opportunities to engage in new learning experiences through more advanced FMS during child development. Thus, FMS should directly relate to academic skills according to functionalism.

Finally, both FMS and cognitive skills may share key processes, rendering greater performance in one domain linked to greater performance in the other domain (Cameron et al., 2016; Voyer & Jansen, 2017). These shared processes likely have both behavioral and neurological dimensions. Beginning with the neural side, numerous areas of the motor cortices (Kiefer & Pulvermüller, 2012; Pulvermuller, 2005), as well as the cerebellum and frontal lobe (Diamond, 2000), are active during both academic-cognitive and FMS tasks. A key idea is that some neural areas can be used for FMS and redeployed for skills (Anderson, 2007; Penner-Wilger & Anderson, 2013). At a behavioral level, it is conceivable that skills required for planning and carrying out FMS and academic activities rely on underlying central cognitive processes. A key candidate here is executive functions, which appear to link to both FMS and cognitive skills (Roebers et al., 2014). Others have proposed that mental representations contain a sensorimotor component (Glenberg et al., 2004; Glenberg et al., 2008; Martzog & Suggate, 2019), suggesting that greater FMS may facilitate more subtle mental concepts. This idea has been coined the nimble-hands (make for) nimble-minds hypothesis (Suggate & Stoeger, 2017). Accordingly, shared-processes would predict that executive functions and cognitive skills directly link to FMS, mediating links between FMS and academic skills.

2. Research on relations between FMS and academic-cognitive skills

The primary aim of the current study is to gain clarity on links between FMS and academic-cognitive skills. Indeed, a seemingly large number of studies investigated links between various facets and sub-categories of FMS and academic-cognitive skills in children (Cameron et al., 2012; Davis et al., 2011; Grissmer et al., 2010; Martzog et al., 2019). However, studies are spread across many fields, including developmental, cognitive, educational, and sport psychology, along with occupational therapy, dentistry, medicine, anatomy, and education. This breadth makes it difficult to evaluate the evidence, and consequently, findings appear contradictory. For example, some studies find robust links in large samples (Grissmer et al., 2010), while others find that links disappear when control variables are accounted for (Michel et al., 2011; Wassenberg et al., 2005). Furthermore, no studies capture FMS and academic-cognitive skills in their different facets with enough breadth to definitively answer the question of which, if any, FMS are related to which, if any, academic-cognitive skills.

In short, meta-analyses are needed to draw the diverse literatures together and answer the question of whether and how FMS are linked to academic-cognitive skills. Currently, there appears to be no meta-analysis capable of answering how different FMS relate to different academic and cognitive skills, and therefore, help to understand the underlying theoretical mechanisms. For instance, two research syntheses have examined the effect of training programs on FMS (Eddy et al., 2019; Strooband et al., 2020), but these do not provide insight into the links with academic and cognitive skills. Only a few comprehensive reviews have been conducted that included measures of FMS and some academic-cognitive skills, but unfortunately, these did not synthesize the findings quantitatively (Gandotra et al., 2021; Gonzalez et al., 2019; Macdonald et al., 2018; van der Fels et al., 2015).

Three non-quantitative reviews looked at associations between FMS and academic-cognitive skills. Macdonald et al. (2018) identified 55 studies that measured FMS and/or gross motor skills in school-age children, concluding that there was evidence for positive associations with mathematics and reading performance. Gonzalez et al. (2019) focused specifically on preschool children and relations between FMS and language, finding only 16 studies, with the research indicating positive links. The third study found evidence from 21 studies that there may be small correlations between some complex motor skills and cognition that disappear around puberty (van der Fels et al., 2015).

To our knowledge, only one quantitative meta-analysis exists that investigated the effect of (gross and) FMS on cognitive skills, namely executive functions (Gandotra et al., 2021). Focusing on developmentally typical samples between three and 12 years, 32 studies were found, of which 17 examined manual dexterity. Generally, effect sizes were small but significant for executive function measures ($r \approx .20$). However, no other academic-cognitive skills were investigated, and the authors appear to have aggregated multiple effect sizes from each paper, whereas current recommendations would instead treat these with a multilevel model (Cheung, 2019; Fu et al., 2011).

3. Current study

The multiple fields that study FMS lack a definitive meta-analysis looking at a broad range of academic and cognitive skills, while treating FMS in a differentiated manner, with previous reviews based on a relatively small number of studies (Gandotra et al., 2021; Gonzalez et al., 2019; Macdonald et al., 2018). Accordingly, we attempted to cast our net broadly and deeply, to dredge out every last study examining links between FMS and academic-cognitive skills from the at times murky depths in which they lie, strewn across multiple disciplines. Our focus was on correlational studies, as a provisional search and our knowledge of the literature indicated that there are only a very small number of FMS intervention studies, too few for a comprehensive meta-analysis. We suspected that such an endeavor would yield a far greater number of studies than those previously identified, allowing us to examine both FMS and academic-cognitive skills in a differentiated manner, while accounting for methodological and sample features. Moreover, we modelled effect sizes using multilevel meta-regressions, thus allowing us to account for the nesting of effect sizes within samples and within studies while controlling for key variables (e.g., age, gender, methodological features). In addition, we used the comprehensive dataset to test different theoretical approaches for the first time, with the aim of clarifying the links between FMS, academic and cognitive abilities.

3.1. Research questions

Our study has two main goals: (a) the systematic investigation of associations between FMS and academic-cognitive abilities in a large number of correlation studies, in which we—unlike existing meta-analyses—take a differentiated look at both FMS and academic cognitive abilities and examine the associations with multilevel meta-regressions, an approach that aligns with recent methodological advancements; (b) in addition, we use the comprehensive data to test different theoretical approaches against each other for the first time. Our analyses are certainly not sufficient for a final conclusion, especially since many of the theoretical approaches overlap. Nevertheless, they hopefully provide initial indications of which mechanisms might play a relatively more critical role in the correlations between FMS and academic-cognitive skills. The following research questions relate to the attempt to verify existing theoretical explanatory mechanisms with the help of our meta-analysis.

1. **Are there statistically significant links between FMS and academic-cognitive skills after controlling for confounding variables?** First, we sought to explore links between FMS and academic-cognitive skills, including their sub-domains. Because links are likely confounded by methodological and sample features, the role of these variables will be tested before calculating effect sizes for the relations between FMS and academic-cognitive skills. Thereby, amodal theories positing no links between FMS and academic-cognitive skills, once confounding methodological moderators are controlled for, will be investigated.
2. **Descriptive Analyses of Differentiated Links between FMS and Academic-Cognitive Skills.** The main focus of the current meta-analysis is to investigate links between multiple domains of FMS and academic-cognitive skills. Thus, a key research question is whether different facets of FMS relate differentially to academic-cognitive skills. Next, exploring the converse question is a high priority, namely, whether different aspects of academic-cognitive skills relate to FMS, both at the domain (i.e., reading, writing, mathematics, cognition) and the sub-domain level (e.g., letter reading, word reading, spelling, counting, etc.). We expect a particular role to be afforded to skills that functionally overlap, particularly graphomotor skills with academic skills, and here

specifically with writing skills. In addition to examining overall effect sizes, we also examine moderations to determine whether specific academic domains and subdomains serve as unique predictors of effect size.

3. **Does age moderate any links between FMS and academic-cognitive skills?** By investigating whether age moderates effect sizes, the theory that maturational influences lead to an initial link between FMS and academic-cognitive skills can be tested. Furthermore, studies with a larger age range should, according to this theoretical approach, also show a stronger link between FMS and academic-cognitive skills, as age is a proxy for both FMS and academic-cognitive skills. Hence, attenuating age variance should reduce the obtained effect sizes.
4. **Are the data more consistent with shared processes or functionalism?** Both functionalism and shared-processes predict links between FMS and academic-cognitive skills. However, functionalism assumes direct links between FMS and academic skills, because FMS facilitate engagement in academic learning. In contrast, shared-processes predicts that FMS link to academic skills via cognitive skills, because both FMS and cognitive skills may use the same planning skills and networks (Cameron et al., 2016; Roebers et al., 2014) and cognitive processes (Martzog et al., 2019). By collecting data on links between FMS and academic skills, academic skills and cognitive skills, and FMS and cognitive skills, we will be able to conduct meta-analytical structural equation models (MASEM) to test whether FMS link directly to academic skills, or whether these are mediated by cognitive skills.

4. Methods

The review was conducted in accordance with PRISMA guidelines (Page et al., 2021).

4.1. Study selection and screening

To identify studies for potential inclusion, an exhaustive string of search terms was compiled and used in three domains pertaining to FMS, academic-cognitive skills, and methodology. Search strings were divided into three groups. Within groups, terms were combined with OR command and between groups with AND (or the equivalent commands in the respective databanks). Studies were restricted to those with children aged between 3 and 16 years, when the database allowed this.

4.1.1. Search string for FMS

The search string for FMS was: dexterity, fine manual skills, fine motor skills, finger agility, finger dexterity, finger gnosia, finger speed, graphene production, graphomotor skills, gross motor skill, hand-eye coordination, handwriting, manipulative skill, manual coordination, manual dexterity, manual skills, motor development, motor performance, motor skills, psychomotor skill, symbol copying, symbol production, tapping, visual motor skills, visuo-motor skills.

4.1.2. Search string for academic-cognitive skills

The search string for academic-cognitive skills was: Phonological awareness, receptive vocabulary, expressive vocabulary, lexicon, syntax, reading fluency, reading comprehension, word reading, symbol decoding, word recognition, fluency, letter writing, name writing, sentence writing, word writing, composition, typing, spelling, literacy, phonemic awareness, pseudo-word reading, letter-sound, letter sound, alphabet decoding, alphabet, oral language, self-regulation, mathematics, numerical cognition, numeracy, arithmetic, subitizing, finger counting, abstraction, counting, calculation, numbers, shapes, intelligence, reasoning, problem solving, matrices, memory, working memory, pattern recognition, mental imagery, language, reading, writing, preliteracy, pre-mathematics, cognition, knowledge, attention, matrixes, pre-mathematics, preliteracy, pre literacy, executive function, executive functioning, maths, academic, achievement, cognitive, visual discrimination.

4.1.3. Search string for methodology

The search string for methodology was: Correlation, correlational study, experiment, longterm, follow-up, intervention, quasi-experimental, assessment, measure, control, test, treatment group, predictive, predictive study, prediction, control group, randomized controlled trial, randomized control, cross-sectional, sample, effect, survey, effectiveness, association, relationship, link, relation, efficacy. Note that we included search terms not relating directly to our correlational design (i.e., experiment) because authors often report correlation coefficients in such studies.

4.1.4. Database search

Search terms were entered in May 2020 into five different databanks spanning medical, educational, and psychological literature. The search in PsycINFO netted 4826 hits, PubMed 3,127, MEDLINE 2,959, ERIC 3,336, and Web of Science 8500. The software CITAVI (Swiss Academic Software, 2022) was used to collate the references and remove duplicates, along with a hand search to remove further duplicates, which resulted in identifying 7277 duplicates from 21,225 hits. Next, given the large number of hits, titles were screened and removed if they did not contain an indication that FMS and an academic-cognitive skill were alluded to. 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, 10, 237 titles were removed, leaving 3711.

Abstracts for the remaining 3711 studies were now checked more closely. Studies were excluded for one or more of the following reasons: participants' ages were under three years ($k = 647$) or over 16 years ($k = 81$), if the samples centered on those with a disability or illness ($k = 855$), if parents were the participants not their children ($k = 90$), if papers were review articles ($k = 80$), if the paper was otherwise clearly outside of the scope of the meta-analysis ($k = 1277$), and in the case of further double ups ($k = 18$). This resulted in

718 articles that were selected for a full-text screening. Fig. 1 shows the PRISMA flow diagram for article screening and selection of papers for the meta-analysis.

Our decision to exclude samples with a diagnosed disability was taken because of the breadth of our search in medical, psychological, and educational settings. Each of these disciplines has different medical and diagnostic criteria and traditions, not to mention the complicated etiologies entailed in these samples, potentially bringing confounds into the analysis. The decision to limit the sample to children aged three to 16 years was taken due to three reasons. First, FMS measures that are reliably normed and developed are extremely rare in adult samples, except as screening instruments (e.g., in the case of neurological problems). Second, FMS measures for children under three years of age also do not exist, except in the form of adult ratings, with the same adults also often providing cognitive ratings, hence confounding associations. Third, we also have clearer assumptions about the theoretical mechanisms pertaining to children (i.e., functionalism and maturation), making studying children and adolescents an important first step.

4.1.5. Article coding

Five criteria were used for inclusion during the full-text screening and coding stage, namely whether (a) FMS were investigated and one or more cognitive/academic variables, (b) the sample met criteria (i.e., right age, contained a non-disabled sample, independent sample), (c) quantitative data were collected, (d) the study reported at least one correlation coefficient between a fine motor and an academic-cognitive skill and (e) bias was not evident. Regarding bias, the study was excluded if only significant correlations were reported, and non-significant ones were omitted. Effect sizes were reverse-coded, where appropriate, such that, if errors or reaction

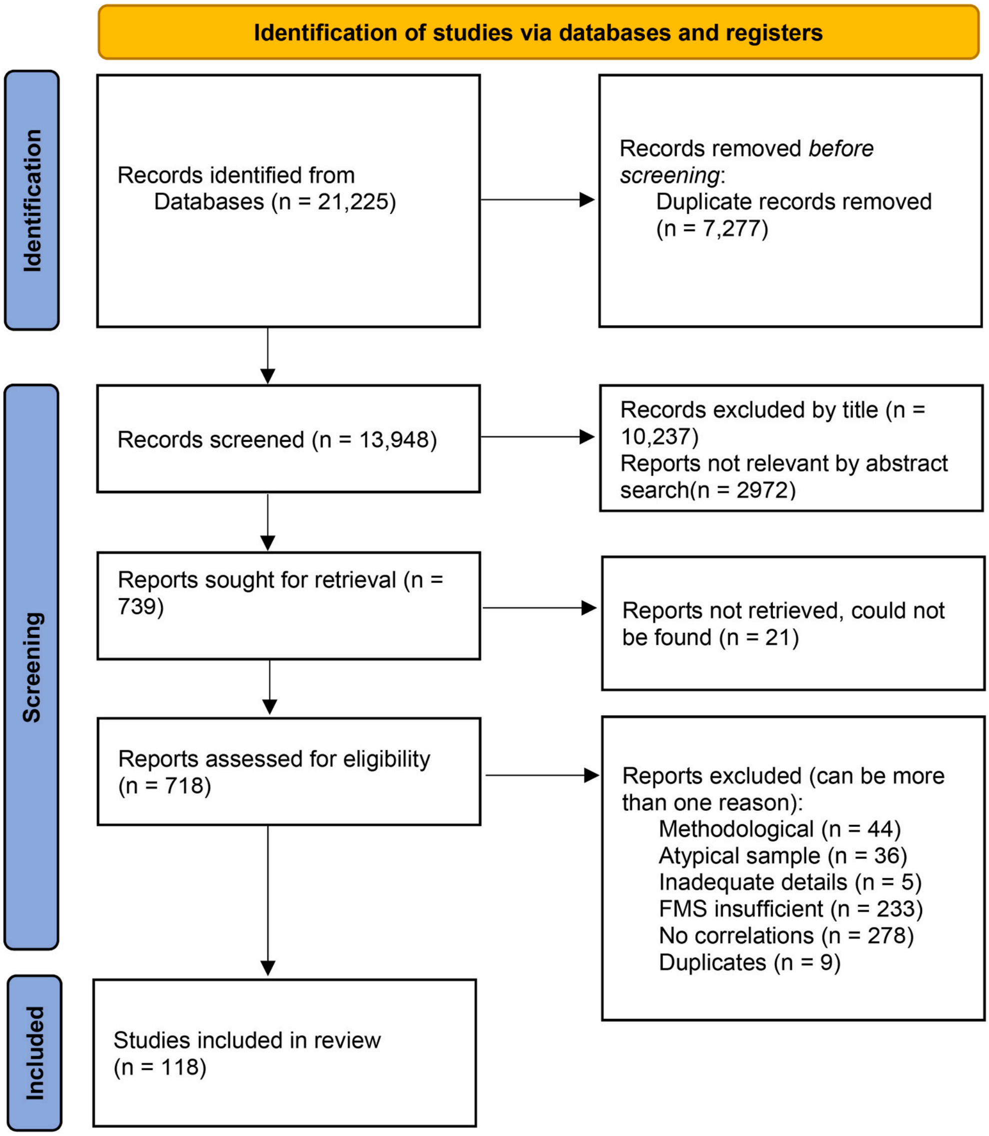

Fig. 1. PRISMA flow diagram of search, screening and coding process.

times were the dependent variable, a positive correlation between two constructs always indicated better performance on both tasks. Interrater reliability between two raters (the second and third authors), calculated on a subsample of 24 of the searches, indicated excellent agreement, IRR = .98 (agreements over disagreements plus agreements). Disagreements were then resolved between the two raters by mutual agreement. All remaining articles were coded, unless it became clear that one of the five criteria applied, or the measures did not fit into an academic-cognitive skill under question. A total of 118 articles containing 143 samples were included.

4.2. Measures

Studies were coded for publication features, sample features, and methodological quality. Correlation coefficients were taken from reports in the original studies, together with extra information on whether the correlation was adjusted (i.e., for age or gender).

4.2.1. Publication features

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

4.2.2. Sample features

Sample features included the percentage of female participants, whether participants were low achieving/at-risk/low SES vs. normally achieving (sample achievement status), the country in which the study was conducted, sample language(s) spoken, sample age, and grade. Where sample age was missing but grade was present, the correlation between available age and grade was used to predict and impute age. We additionally coded variance (*SD*) around sample age to test whether this moderated the effect sizes.

4.2.3. Methodological quality

To provide methodological quality indicators alongside the publication type already mentioned, studies were coded as to whether the study design was correlational or longitudinal to serve as a proxy for methodological quality. The reasoning here was that authors who conducted a longitudinal study were more likely to have worked rigorously, given the added demands and careful planning required for longitudinal work. Measurement quality was determined by calculating the percentage of measures that constituted previously published and/or normed instruments (versus unpublished author-developed tests). Our reasoning here was that measures published by an independent outlet from the authors of the papers themselves were likely to have undergone more rigorous development, and be less likely to be general to the skill domain (i.e., not designed with a specific academic-cognitive skill in mind).

4.2.4. FMS and academic-cognitive measures

Correlation coefficients were collected from a variety of measures pertaining to the different facets of FMS, reading, writing, mathematics, and cognitive skills. Due to the large number of measures included in the meta-analysis, these are listed and described in the Supplementary Materials of Tests Included.

FMS. Measures were grouped into seven different domains of FMS, relating to manual dexterity, speed, graphomotor skill, bimanual coordination, finger gnosia, general FMS, and a miscellaneous category. Manual dexterity was typically measured with tasks involving object manipulation, most commonly pegboard and peg shifting tasks or bead threading tasks. Speed was generally measured using tapping tasks. Measures of graphomotor skills represented operation of a writing tool to reproduce symbols. Bimanual tasks involved using both hands in a coordinated manner. Measures of finger gnosia (i.e., finger sense/representation) involved movement and perception of individual fingers (Noël, 2005). General FMS referred to measures that included a combination of dexterity, speed, graphomotor, bimanual, or finger gnosia measures and thus could not fit separately into the other facets. Finally, miscellaneous tasks represent a category of measures that did not fit into the other facets.

Academic Skills. Academic skills included reading, writing, mathematics, and combined measures. Since some studies only reported reading, writing and math combined in a general academic score, tests comprising more than one academic field were initially collected in a separate general academic category but then later discarded due to the small number of these ($j = 3$).

Reading measures included concepts about print, letter reading, word reading for 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 of individual letters, words, sentences, passages, and spelling. Miscellaneous writing comprised measures that did not fit in any other writing category. General writing includes a combination of writing tests to a general score.

Mathematics measures were grouped into six sub-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. Fifth, miscellaneous and sixth, general sub-categories were included.

Cognitive Skills. Cognitive skill measures were grouped into five sub-categories: intelligence, executive functions, vocabulary, general cognitive scores, and miscellaneous. Measures of intelligence included all tasks measuring children's intelligence and their capabilities in problem-solving, matrices, reasoning, general knowledge, and verbal tasks. Working with a broad concept of executive functions, this domain included the domains of working memory, inhibition, and cognitive flexibility. However, to extend the number of effect sizes and encapsulate a broader conception of executive functions (e.g., Karr et al., 2018), we also included the closely related subordinate construct of attention and the more global construct of planning (Diamond, 2013). Vocabulary included both receptive and expressive vocabulary. General cognitive scores represented the above cognitive tests, but the authors only provided a general score. Finally, tests that did not fit in one of the other cognitive skill sub-categories were collected in a miscellaneous cognitive skill category.

4.3. Transparency and openness

We adhered to the MARS guidelines for meta-analytic reporting (Appelbaum et al., 2018). All meta-analytic data, analysis code, and research materials (including our coding scheme) are available (https://osf.io/sdpvm/?view_only=97fccf6e477c4820beab9ed719a62d28). Data were analyzed using R, version 4.2.1 (R Core Team, 2022) and the package metafor, version 3.0–2 (Viechtbauer, 2010).

4.4. Data analysis

The effect sizes analyzed were correlation coefficients drawn from the original studies. Because correlation coefficients are not equal interval scales, they were transformed into *z*-scores using the Fisher's *r*-to-*z* transformation (Cox, 2008). Initial analyses focused on detecting publication bias via funnel plots, calculating descriptive statistics of effect sizes, and the influence of predictor variables, initially treating the effect sizes as being statistically independent, simply to provide a face validity check on the more complicated models reported below.

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) and maximum likelihood estimation. Further, some studies reported multiple samples, necessitating a nesting of effect sizes within samples, the latter of which were in turn nested within studies. To test for publication bias, we conducted an Egger's mixed effects test because this method appears to best accommodate dependent effect sizes inherent in nested data (Rodgers & Pustejovsky, 2020). To account for non-independence (i.e., correlated residuals) and small sample sizes, cluster-robust estimation (of effect sizes and confidence intervals etc.) using the robust package was used (Wang et al., 2024).

Analyses modelled study, sample, and individual effect sizes as random effects (Harrer et al., 2021). Level 1 predictors were measure type, modelled by two parameters because a correlation is by its nature between two variables. Specifically, on the FMS side whether it was dexterity, speed, graphomotor skills, finger gnosia, bimanual skill, general FMS, and miscellaneous. On the academic-cognitive side this referred to the domains and facets of reading, writing, mathematics, and cognitive skills. Level 2 referred to any individual samples nested within studies with corresponding predictors of sample status, percentage of females in samples, measure quality, sample age (in years), and the variance (*SD*) in sample age (in months). Level 3 was defined by the individual studies in the meta-analysis, and predictors at this level included publication year, whether the study was peer-reviewed, and study design (cross-sectional or longitudinal). Restricted maximum likelihood estimation was used. When entered into the models, age, age variance, methodological quality, and publication year were *z*-transformed to facilitate interpretation of the model coefficients.

To test the fourth research question, MASEM were conducted. MASEM uses available data from the studies reporting correlations between third variables to estimate complex interrelations between the key variables of interest (Cheung, 2014, 2019). Because only 18 studies included correlations between academic skills and intelligence, and 27 between executive functions and academic skills, the main MASEM was run with all reading, writing, and mathematics variables collapsed into a mean academic score. Further, only the cognition and executive function variables were separated out from each other to allow specific testing of the influence of each. At a study level, correlation coefficients were aggregated and transformed with Fisher's *r*-to-*z*. These analyses were conducted using the package MASEM (Cheung, 2014). The MASEM regressed FMS, cognitive, and executive functions on academic skills, while regressing FMS on cognitive skills and executive functions.

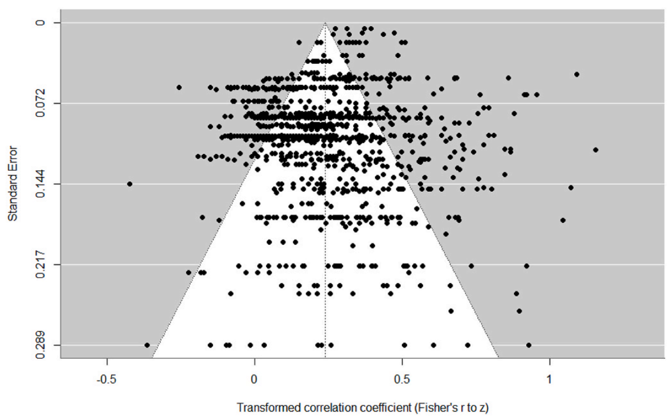

Fig. 2. Funnel plot of all effect sizes included in meta-analysis.

5. Results

5.1. Description of the reviewed literature

In total, 143 samples from 118 different studies provided a total of 1110 effect sizes. The literature comprised mostly of cross-sectional (71.5 %) peer-reviewed studies (88.2 %). Studies were mostly conducted in the US (30.9 %), Germany (15.4 %), Australia (4.9 %), Switzerland (4.9 %) and Taiwan (4.1 %), with the rest being spread around the world. Mean publication year was 2006.55 ($SD = 15.32$, between 1952 and 2020). Samples were between 3 and 17 years old ($M = 7.16$, $SD = 2.59$), with the age variance within each study being around 7.90 months ($SD = 6.96$), on average. Female participants comprised 48.89 % ($SD = 10.41$), and most measures were published and/or normed ($M = 85.24$ %, $SD = 24.30$). A breakdown of these study and sample features as a function of FMS and academic-cognitive skill domains is presented in the Supplementary Tables S1–S3.

5.2. Publication bias

To investigate publication bias, a funnel plot was constructed, and this appears in Fig. 2. A mixed-effects Egger's test for funnel plot asymmetry found evidence for publication bias, $z = 2.132$, $p = .033$, which was also found using Kendall's rank test, $\tau = .171$, $p < .001$. A Duval and Tweedie trim-and-fill analysis was run, which was completed on the first iteration, concluding that there were no missing studies on the left side ($SE = 18.349$).

5.3. Data analyses of research questions

Research Question 1: Are There Statistically Significant Links between FMS and Academic-Cognitive Skills after Controlling for Confounding Variables?

To estimate the overall link between FMS and academic-cognitive skills, the average correlation coefficient between FMS and academic-cognitive skills across all studies was calculated, $Z_f = .228$ ($SD = .182$, median $= .220$). A null mixed-effects model without any predictors was used to estimate the baseline link between FMS and academic-cognitive skills once nesting effects between the studies were taken into account. The model resulted in an intercept estimate of $r = .329$, $Z_F = .318$, CI $= .283$ to $.352$, $p < .0001$. A test for residual heterogeneity indicated that the null model left a significant amount of variance unexplained, $Q(1103) = 8290.725$, $p < .001$. Within-level variance indicated utility in retaining three levels, $\sigma_{\text{studies}} = .028$, $\sigma_{\text{samples}} = .004$, $\sigma_{\text{es}} = .010$, and $ICC_{\text{studies}} = .669$, and $ICC_{\text{samples}} = .085$. Thus, an overall positive medium effect size was found.

Next, we tested whether this overall medium effect was moderated by publication, sample, and methodological features by adding these individually to the mixed-effects meta-regressions. For the continuous variables, Omnibus tests for moderating effects found that publication year, $Q_M(1) = 1.613$, $p = .204$, percent female, $Q_M(1) = .003$, $p = .959$, and measure quality, $Q_M(1) = 2.112$, $p = .146$, were not significant moderators. The categorical moderators of sample disability, $Q_M(1) = .006$, $p = .937$, publication type, $Q_M(1) = .002$, $p = .968$, and study design, $Q_M(1) = .139$, $p = .710$, were also not statistically significant. Therefore, none of these potential confounding variables moderated effect sizes.

Research Question 2: Descriptive Analyses of Differentiated Links between **FMS and Academic-Cognitive Skills.**

Mixed effects meta-regressions estimated the effect sizes between subdomains of FMS and academic-cognitive skills using cluster-robust estimation of effect sizes and confidence intervals (Table 1). First, we investigated whether different subdomains of FMS related differently to academic-cognitive skills generally (i.e., the average of all investigated academic-cognitive skills). The findings presented in the upper section of Table 1 indicated that graphomotor skills and finger gnosia were the strongest predictors, followed by speed, general FMS, and dexterity. Of the FMS subdomains, graphomotor skills showed the strongest links, so we conducted ad-hoc tests

Table 1
Links between FMS sub-domains and overall academic-cognitive skills (upper part) and academic-cognitive sub-domains and overall FMS (lower part).

	r	Z_f	*SE*	*t*	*df*	*p*	CI lower	CI upper
Fine motor skills by subdomain								
Dexterity	.289	.297	.023	12.724	56.54	<.001	.251	.344
Speed	.301	.311	.042	7.335	6.87	<.001	.210	.411
Graphomotor	.338	.352	.024	14.919	73.54	<.001	.305	.399
Bimanual skill	.235	.240	.038	6.362	1.43	.051	−.002	.482
Finger gnosia	.319	.331	.046	7.183	12.15	<.001	.230	.431
Miscellaneous	.239	.244	.078	3.127	3.58	.041	.017	.471
General FMS	.290	.299	.030	9.929	19.99	<.001	.236	.361
Academic-Cognitive skills by subdomain								
Reading	.310	.321	.021	15.504	77.37	<.001	.280	.362
Writing	.343	.357	.027	13.060	48.02	<.001	.302	.412
Maths	.337	.351	.023	14.980	38.16	<.001	.304	.399
Cognition	.291	.300	.019	15.612	105.61	<.001	.262	.338

Note. FMS = fine motor skills, CI = confidence interval. For FMS model: $k = 1110$, $j_{studies} = 118$, $j_{samples} = 143$, $\sigma_{\text{studies}} = .028$, $\sigma_{\text{samples}} = .003$, $\sigma_{\text{es}} = .010$, for Academic model: $k = 1110$, $j_{studies} = 118$, $j_{samples} = 143$, $\sigma_{\text{studies}} = .028$, $\sigma_{\text{samples}} = .004$, $\sigma_{\text{es}} = .010$.

comparing these against the other FMS skills. These post-hoc tests (using the function 'ANOVA' in *metafor*) found that the effect sizes for graphomotor skills were greater compared to dexterity ($p < .001$), general FMS ($p < .001$) and FMS miscellaneous ($p = .027$), but not significantly different to speed ($p = .173$), bimanual ($p = .095$), general FMS ($p = .099$), or finger gnosia ($p = .336$).

Second, we investigated whether different domains of academic-cognitive skills relate differently to FMS (i.e., the compound variable of FMS). The findings presented in the lower section of Table 1 indicate that links with FMS were strongest for writing and mathematics. Post-hoc ANOVA comparisons found that FMS correlated lower with reading than with writing ($p = .029$). FMS correlations with writing did not differ significantly from those with mathematics ($p = .805$), but FMS linked more strongly to maths than to cognition ($p = .006$) in the post-hoc analyses.

Third, we investigated whether different subdomains of academic-cognitive skills relate differently to FMS (i.e., the average across all FMS domains). Table 2 presents a breakdown of the subdomains of academic and cognitive skills as they relate to FMS, revealing several interesting trends. First, the strongest significant correlation in the reading domain was for nonword reading, and the smallest for letter reading. Second, in the domain of writing, links between FMS and the subdomains letter/word/sentence writing, as well as general writing, were strongest. Third, in the domain of mathematics, the links with the conceptual subdomain were strongest, followed by counting, arithmetic, and general mathematics. In the cognitive domain, intelligence correlated the strongest with FMS, showing stronger links to FMS than executive functions ($p < .001$) or vocabulary ($p < .001$) did.

Finally, we conducted a moderation analysis that included predictors from all of the FMS and academic-cognitive domains to test which domains of each are uniquely predictive of overall effect sizes. We also included a measure of quality to account for the contingency that this might differ across FMS and academic-cognitive domains. The full model is presented in Table 3. Findings in Table 3 suggest that graphomotor skills were the strongest predictor, showing significantly greater links with academic-cognitive skills than dexterity (which was the reference predictor). A similar finding existed for the moderator variable writing, which was associated with greater correlations between FMS and academic-cognitive skills. The remaining FMS and academic-cognitive domains showed non-significant independent effects, above and beyond the overall intercept.

Research Question 3: Does Age Moderate Links Between FMS and Academic-Cognitive Skills?

Mixed-effects moderator analyses with three levels showed that neither age, $Q_M(1) = 2.297$, $p = .130$, nor age variance, $Q_M(1) = .016$, $p = .899$, moderated the overall effect size between FMS and academic-cognitive skills, inconsistent with maturation. Next, a more differentiated explorative analysis tested whether age and age variance moderated links between FMS and the academic-cognitive domains of reading, writing, mathematics, and cognitive skills. Thus, separate mixed-effects models were run with age X academic-cognitive domain and age variance X academic-cognitive domain interaction terms as predictors. However, none of the interaction terms involving age or age variance and academic-cognitive domain were statistically significant (all *ps* > .216).

Table 2
Effect sizes for links between fine motor skills and subdomains of academic and cognitive skills.

	r	Z_f	*SE*	*t*	*df*	*p*	CI lower	CI upper
Reading								
Concepts about print	.518	.574	.305	1.884	1.04	.304	−2.998	4.146
Letter reading	.282	.290	.035	8.374	4.86	<.001	.200	.380
Word reading	.289	.298	.021	13.995	12.43	<.001	.252	.344
Nonword reading	.332	.345	.032	10.779	7.78	<.001	.270	.419
Reading fluency	.301	.311	.028	10.963	3.43	<.001	.227	.395
Reading comp.	.299	.308	.025	12.191	9.89	<.001	.252	.364
Reading misc.	.308	.318	.035	9.181	3.32	.002	.214	.422
Reading general	.302	.312	.037	8.343	16.36	<.001	.233	.392
Phonemic awareness	.286	.294	.032	9.104	19.87	<.001	.226	.361
Writing								
Writing letters	.373	.392	.078	5.000	5.57	.003	.197	.588
Writing words	.357	.374	.036	10.457	7.61	<.001	.290	.457
Writing sentences	.355	.371	.053	7.036	5.58	<.001	.240	.503
Writing composition	.303	.313	.030	10.511	9.22	<.001	.246	.380
Writing spelling	.295	.304	.031	9.758	22.77	<.001	.239	.368
Writing misc.	.296	.305	.023	13.431	28.66	<.001	.259	.352
Writing general	.367	.385	.023	16.792	1.49	.011	.245	.524
Mathematics								
Pre-maths	.176	.178	.025	7.197	20.51	<.001	.126	.229
Maths counting	.347	.362	.035	10.300	3.52	<.001	.259	.465
Maths arithmetic	.346	.361	.044	8.205	7.47	<.001	.258	.463
Maths conceptual	.388	.410	.085	4.824	1.84	.047	.013	.808
Maths misc	.284	.292	.057	5.101	6.21	.002	.153	.431
Maths general	.346	.361	.034	10.533	18.23	<.001	.289	.433
Cognition								
Vocabulary	.267	.274	.038	7.285	36.68	<.001	.198	.350
Intelligence	.366	.384	.055	6.964	21.94	<.001	.269	.498
Executive functioning	.267	.274	.025	11.068	69.54	<.001	.225	.324
Cognitive misc.	.303	.313	.043	7.276	12.18	<.001	.219	.406
Cognitive general	.315	.326	.042	7.790	13.00	<.001	.236	.417

Note. CI = confidence interval, $k = 1110$, $j_{studies} = 118$, $j_{samples} = 143$, $\sigma_{studies} = .024$, $\sigma_{samples} = .003$, $\sigma_{es} = .010$.

Table 3
Moderator model testing independent contributions of the domains for fine motor skills and academic-cognitive skills in a single model.

	Estimate	*SE*	*Z value*	*p*	CI lower	CI upper
Intercept	.290	.025	11.830	<.001	.242	.338
Reading	–	–	–	–	–	–
Writing	.035	.017	2.141	.032	.003	.068
Maths	.038	.021	1.790	.073	−.004	.079
Cognition	−.024	.015	−1.559	.119	−.053	.006
Dexterity	–	–	–	–	–	–
Speed	.013	.031	.402	.688	−.049	.074
Graphomotor	.055	.016	3.382	.001	.023	.088
Bimanual skill	−.058	.068	−.850	.395	−.190	.075
Finger gnosia	.033	.025	1.344	.179	−.015	.081
Miscellaneous	−.057	.048	−1.173	.241	−.152	.038
General FMS	.006	.034	.173	.863	−.060	.072
Measure quality	.034	.017	1.953	.051	.000	.068

Note. CI = confidence interval, $k = 1110$, $j_{studies} = 118$, $j_{samples} = 143$, $\sigma_{studies} = .028$, $\sigma s_{amples} = .003$, $\sigma_{es} = .010$.

Research Question 4: Are the data more consistent with shared processes **or functionalism?**

Next, a two-stage MASEM (Jak & Cheung, 2020) was conducted to test functionalism (i.e., FMS link to academic skills) against shared processes (i.e., the link between FMS and academic skills decreases after controlling for cognitive skills and executive functions). To achieve a sufficiently large sample size, academic skills were grouped together in the first model. The fixed-effects estimated correlations are presented in Table 4. The data in Table 4 show similar associations to those presented in Tables 1 and 3, with the exception of executive functions, which appear to be slightly more correlated in Table 4 than in Table 2 ($r = .340$ versus .267). The number of effect sizes and samples in each path are presented in Table S4. Next, the MASEM tested the strengths of the correlations between FMS, academic skills, cognitive skills, and executive functions and showed excellent model fit, $\chi^2(6) = 43.671$, $p < .0001$, CFI = .955, RMSEA = .023, SRMR = 1.007, TLI = .729, AIC = 41.671, BIC = 32.384. The model appears in Fig. 3. The corresponding pathways were all statistically significant, $p < .0001$. Comparing the relationship between FMS and academic skills in the fixed-effects correlations in Table 4 with the MASEM, which dropped from $r = .334$ to .200, gives an indication of the extent of the mediation.

Identical models were run looking at the academic skills separately, with further reduced sample sizes for correlations between executive functions and cognitive skills with writing, $n = 12$, $n = 13$, reading, $n = 18$, $n = 19$, and mathematics, $n = 16$, $n = 19$, respectively. Model fit indices were highly similar for reading and mathematics compared to those reported for academic skills in Fig. 3. Again, the number of effect sizes and samples in each path are presented in Tables S5–S7. Given the hypothesized functional link between FMS and writing, this model is reported in more detail. The writing model showed good fit, $\chi^2(6) = 40.9501$, $p < .0001$, CFI = .947, RMSEA = .022, SRMR = 1.062, TLI = .682, AIC = 38.950, BIC = 29.663. The path coefficients showed three notable differences to the general academic model, namely the link between: (a) FMS and the academic domain of writing was greater (.264), (b) cognitive skills and writing was lower (.138), and (c) executive functions and writing was also lower (.084).

7. Discussion

The current meta-analysis was by far and away the largest—amassing 1110 direct effect sizes between FMS and academic-cognitive skills from 118 studies—to investigate links between different facets of FMS and academic-cognitive skills. We synthesized studies from diverse fields, accounted for methodological features, and tested which aspects of FMS relate to different academic and cognitive skills in children and adolescents. Thereby, given that meta-analysis is optimal at detecting effects that may be elusive in individual studies (Hunter & Schmidt, 2004), we hoped to answer fundamental questions that have driven researchers for some time.

Before interpreting the correlation coefficients, it may be fruitful first to consider guides to interpreting the strength of associations found. Cohen's (1988) widely used criteria suggested that $r = .10$, $r = .30$, and $r = .50$ corresponded to small, medium, and large effects, respectively. However, in a meta-analysis of individual differences research, Gignac and Szodorai (2016) found that only three percent of reported correlation coefficients were ever at the level of "strong", according to Cohen's criteria. Instead, they suggest that more appropriate criteria for individual differences would be $r = .10$ for small, $r = .20$ for medium, and $r = .30$ for strong links, which correspond to the 25th, 50th, and 75th percentiles of all obtained coefficients in individual differences research, respectively.

Table 4
Fixed-effects estimates correlation matrix for the meta-analytical structural equation model in Fig. 2.

	Variable	1	2	3	4
1	Fine motor skills	–	.340* (52)	.304* (101)	.334* (90)
2	Executive functions		–	.381* (12)	.286* (27)
3	Cognitive skills			–	.316* (18)
4	Academic skills				–

Note. Number of aggregated sample effect sizes appears in parentheses.
* = $p < .001$.

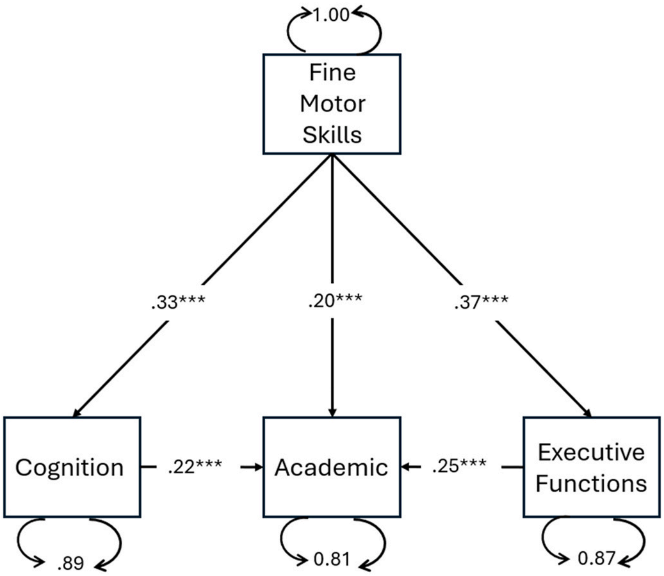

Fig. 3. Meta-analytical structural equation model depicting the indirect effect of fine motor skills on academic skills via cognitive skills and executive functions (EF).

Turning to the first, second, and third research questions, one key finding was the generally moderate (according to Cohen, 1988) to strong (Gignac & Szodorai, 2016) link between FMS and academic-cognitive abilities ($r = .329$). This link was not explained by study, sample, or measure features, and was not moderated by age or age variance. Converted into the commonly used effect size metric, Cohen's *d*, this would be a large effect ($d = .697$). Findings were, therefore, not consistent with amodal or maturation theories – with links between FMS and academic-cognitive skills existing across the entire sample age range tested here, namely from 3 to 16 years of age. This finding has particular significance, contradicting the idea that FMS are developmentally time-limited skills that lose their relevance across time.

The primary objective of this meta-analysis was to estimate the differentiated relationships between various facets of FMS and different domains and subdomains of academic-cognitive skills. The most robust finding was that FMS were linked strongest to writing, and among the FMS, graphomotor skills were linked strongest to academic-cognitive skills. A second key finding was—consistent with a previous meta-analysis (both $rs \approx .20$; Gandotra et al., 2021)—the smaller link between FMS and executive functioning compared to the link between FMS and intelligence.

Turning to the fourth research question on a reduced sample, the MASEM provided insights on both shared-processes and functionalism theories. Specifically, the link between FMS and academic skills was smaller once executive functions and cognitive skills were modelled. This provides evidence that FMS share processes with both cognitive skills and executive functions, which in turn relate to academic skills. However, there was still a direct link between FMS and academic skills, consistent with a functional role of FMS that exists once cognitive skills mediation is accounted for. This notion was further strengthened in the domain-specific MASEM. Although the pattern of findings was similar for reading and mathematics, for writing, the findings pointed towards a greater role of functionalism. This is evidenced by the stronger direct links between FMS and writing, compared to FMS and other academic skills, in the MASEM. Furthermore, the links between cognition and executive functions on writing were correspondingly lower once these multiple pathways were taken into account.

The current findings build on an emerging line of work suggesting that FMS are a key part of school readiness (Grissmer et al., 2010) and may play a particular role in early reading and writing development (Cameron et al., 2012). For instance, recent experimental studies suggest that having some FMS engagement can increase early literacy acquisition (Suggate et al., 2016, 2023), presumably because this enhances letter representations with sensorimotor information (e.g., Palmis et al., 2021). This would suggest that reading instruction may profit from including concurrent writing instruction, although more work is needed (cf. Mayer et al., 2019). Additionally, research and practice should continue to explore the role of movement in learning, including mathematics (Link et al., 2013) and reading (Glenberg, Brown, & Levin, 2007a, 2007b).

Taken together, the findings are not consistent with maturation but with functionalism and shared processes. The functionalism component appeared more relevant for writing, potentially being driven by the stronger correlations between graphomotor and writing skills. Interestingly, this is consistent with a dynamic systems theory, which was not directly investigated here, whereby fine motor actions emerge out of the affordances of the environment, providing a functional link between the system and the organism (e.g., Farrokh et al., 2025; Thelen, 1987, 2000).

7.1. Limitations

Despite the differentiated insight provided by this meta-analysis, there are several limitations. First, due to a lack of experimental intervention studies, this is a meta-analysis of correlational studies, so we cannot conclude whether FMS causally link to academic and cognitive skills. Potentially, cognitive skills mediate the relationship between FMS and academic skills to some extent. However, given the current and previous findings (Martzog et al., 2019), this is unlikely to be a complete mediation. In terms of FMS themselves, there might be a general processing factor that underlies the various FMS, such as sensorimotor integration (Gori et al., 2008), which then links to the various FMS. Conversely, by exploring links between several academic, cognitive, and FMS domains, we garnered indications for future work to pursue in a more differentiated manner, using methodology targeting causal inference.

Second, it is possible that the age variance in the original samples was not a sufficiently sensitive method to test the maturation theory. Thus, extending the sample to adults might provide further reassurance that maturation effects are not the main driving links, as developmental changes slow into adulthood.

Third, we would have been interested in cross-tabulating different aspects of FMS with the various academic-cognitive subskills. However, this would have been beyond the scope of a single meta-analysis but could be pursued in future work.

Fourth, some measures required rapidity of response, while others required accuracy, with the majority requiring both simultaneously. As with many behavioral measures, one concern is that speed and accuracy represent different constructs (e.g., quality vs. quantity). In terms of functionalism, speed may be preferable in one context (e.g., note-taking), but disadvantageous in others (e.g., drawing). Likewise, if motor skills lie at the heart of cognitive representations, FMS speed might facilitate processing, but accuracy might relate to the richness of concepts, for instance.

Fifth, the sample sizes for the MASEM were smaller, involving in some cases as few as 12 studies (e.g., for the link between executive functions and cognitive skills). This may explain why the patterns of findings differ slightly from the meta-regressions, which accounted for nested variance in 1110 effect sizes from 143 different samples. Accordingly, the mediation analyses should be replicated and extended to longitudinal studies. In a similar vein, functionalism posits that fine motor activities, not skills beyond a certain level of competence, relate to academic achievement. Therefore, there was some mismatch between the functionalism theory and our operationalization of the mechanism.

Finally, some of our constructs were more heterogeneous than others, particularly for the cognitive category and sub-categories. For instance, intelligence included spatial, reasoning, general knowledge, and verbal tasks. In turn, executive functions included working memory, attention, planning, inhibition, and cognitive flexibility. Although beyond the scope of the current study, a more differentiated analysis of subdomains might have yielded a more nuanced picture.

7.2. Educational implications

Despite the lack of causal inference possible from correlational designs, the current study has potential implications for educational practice. First, cognitive skills and executive functions mediated academic skills, particularly reading and mathematics, suggesting that these are key drivers of academic development. Accordingly, these cognitive domains remain key areas to target in interventions (e.g., Scionti et al., 2019).

Further, as alluded to, children have experienced significant changes in terms of their FMS experience (Dinehart, 2014; Gaul & Issartel, 2016; Martzog & Suggate, 2022). Early education programs have, not without controversy, introduced academic standards focusing on mathematics and reading, in particular (Clements et al., 2019), arguably at the expense of more traditional and perhaps motorically involved childhood activities (e.g., artistic or crafting activities). Particularly in light of the current findings, academic and FMS may not need to be mutually exclusive, with research indicating that both reading and mathematics can benefit from concurrent and purposeful motor activity (Gunraj et al., 2014; Link et al., 2013).

Indeed, graphomotor skills were the strongest FMS predictor of academic skills, and in turn, writing was the academic outcome most strongly linked to FMS. Taken together, there appears to be a significant functional overlap between graphomotor and writing skills, as well as with general academic skills. Handwriting is functionally important for academic development, allowing students to take notes and complete exercises more quickly (Mueller & Oppenheimer, 2014), and also appears to be linked to reading and language development (Abbott et al., 2010; Jones & Christensen, 1999; Palmis et al., 2021; Rastle, 2019), also via shared neural processes (James, 2017). Although based on correlational data, the current findings would support the idea that FMS generally, and graphomotor skills more specifically, are potential targets for educational programs, perhaps through both writing and drawing activities.

Against this backdrop and in light of the current findings, it would appear that the links between FMS and academic-cognitive skills indicate that academic learning may not be as emancipated from motor skills as modular theories of cognition posit (see Glenberg & Gallese, 2012; Thelen, 2000). Further, it could be argued that links between FMS and academic-cognitive skills have been seen as something mainly relevant for early childhood. In contrast, the current findings suggest that links remain constant across the age ranges investigated here, that is, well into adolescence. Some research has found positive effects of movement on learning using experimental (Suggate et al., 2016) and intervention designs (Cunningham et al., 2025; Glenberg et al., 2007a, 2007b); however, this is different from the current finding that actual skill level, not engagement in movement, links to cognitive outcomes.

7.3. Future research

Turning to future research, our study primarily consisted of typically developing samples because we aimed to test for associations in the absence of confounding influences. However, given hypotheses around comorbidity between motor disturbances and cognitive disabilities (Irannejad & Savage, 2012; Reynolds & Nicolson, 2007), it would be important to extend this work to additional samples. Of particular interest would be developmental coordination disorder (Michel et al., 2011), dyslexia (Reynolds & Nicolson, 2007), and dyscalculia (Aster & Shalev, 2007).

We also restricted the focus to FMS, whereas extending a meta-analysis to gross motor skills might provide important insight. A recent study proposed that general motor competence mediated links between physical activity with cognition and socio-emotional health (Hill et al., 2024). Specifically, having better gross motor skills should facilitate cognitive skills from a functionalism perspective (Iverson, 2010) and advanced gross motor skills might involve shared processes at a cognitive level (Wassenberg et al., 2005).

Experimental and intervention studies should tentatively look to investigate whether improving FMS also improves academic-cognitive skills (Eddy et al., 2019). Motor difficulties are reported in many instances of learning and development disorders and some educational concepts seek to incorporate movement to enhance learning (Edwards, 2007; Glenberg et al., 2007a, 2007b). Previous research has documented cognitive benefits from physical activity (Mavilidi et al., 2018), also for combining movement with learning (e.g., Cunningham et al., 2025). However, to our knowledge, no study has definitively demonstrated that cognitive skills are improved by developing more sophisticated FMS. Importantly, such approaches would not render interventions directly targeting academic skills less important (Ehri et al., 2001) but might complement these. Further, longitudinal work could test hypotheses about how links between FMS and academic-cognitive skills are established and influenced by contextual and developmental factors, as has been begun with general motor skills (Hill et al., 2024). Longitudinal studies can focus on multiple variables simultaneously, while accounting for explanatory variables, in a manner that is difficult using randomized intervention designs.

One difficulty in conducting this meta-analysis was the large number of definitions of FMS, spanning multiple disciplines, leading to definitional blurring. Accordingly, it was at times challenging to code measures and reach consensus on which facets of FMS exist. Thus, we drew upon previous attempts to classify and differentiate various FMS (Chien et al., 2009) and encourage future research to agree upon and adopt consistent terminology. Additionally, further factor analytical work is required to investigate the existence of distinct FMS facets and constructs. Such work might also examine the extent to which FMS are theoretically distinct from other sensorimotor skills, such as gross motor skills, proprioception, haptic exploration, and visual performance.

8. Conclusions

To the best of our knowledge, we conducted and reported findings from the largest and most differentiated meta-analysis on relations between FMS and academic-cognitive skills in the published literature. Despite being studied (Whitall et al., 2020) and discussed for a long time in relation to the mind (Adolph & Hoch, 2019), the status of FMS as contributors to cognitive development has been uncertain. However, based on the evidence collected here, a number of FMS—in particular graphomotor skills—show, compared to what is usually found in individual differences research (Gignac & Szodorai, 2016), moderate to strong links with a range of important academic and cognitive skills, particularly writing, mathematics, and intelligence. Moreover, due to the large-scale mediation analysis, we were able to directly test functionalism and shared-processes theory, finding more substantial evidence for both via mediation analyses. It is the task of future research to expand and specify this work so that it can be incorporated into educational practice.

Credit author statement

Sebastian Suggate: Conceptualization, Methodology, Formal analysis, Writing – Original Draft, Writing - Review & Editing, Supervision, Funding acquisition.

Viktoria Karle: Conceptualization, Methodology, Investigation, Writing - Review & Editing.

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Acknowledgements

This research was supported by grants from the German Research Council awarded to the first (SU 766/7-1) and fourth authors (STO 481/10-1). We thank Yaroslava Gelbert for help coding the effect sizes.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.edurev.2025.100748.

Data availability

Data and syntax is available, cited in the manuscript at: https://osf.io/sdpvm/?view_only=97fccf6e477c4820beab9ed719a62d28

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