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Executive functions mediate fine motor skills' contribution to literacy achievement: a longitudinal study of Arabic-speaking children

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Abstract

Fine motor skills (FMS) are among the most studied nonlinguistic factors influencing early literacy acquisition. Although developmental studies have often supported the presence of a relationship between FMS and emergent literacy, the underlying mechanisms have not always been adequately explored. In this study, we used structural equation modeling to investigate the longitudinal relationship between FMS in kindergarten and reading and spelling in first grade among 212 Arabic-speaking children. We also used structural equation modeling to examine the contribution of executive functions (EFs) measures as the possible mediators of this relationship. The first structural equation model suggested that FMS (assessed by the functional dexterity test, copying letters, and pure copying) at kindergarten was a significant predictor ($\beta = 0.33$, $p < 0.05$) of literacy achievement (assessed by spelling and reading words and pseudowords) in first grade. The second structural equation model suggested that EFs measures (as assessed by *The Head–Toes–Knees–Shoulders* self-regulation task and the digit-span forward and backward tests) fully mediated the relation between FMS and reading and spelling in the first grade. Results of the bootstrap method also supported the statistically significant effect of FMS on reading and spelling achievement through EFs, 95% CI [0.182, 0.802]. This study emphasizes the importance of screening young children with non-academic and non-language-based measures in order to identify the factors underlying difficulties with reading and spelling.

Keywords Fine motor skills · Executive functions · Early literacy · Kindergarten · First grade

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Introduction

Early reading and spelling skills among preschoolers and kindergarteners are important and strong predictors of children's later literacy skills and school achievement (Whitehurst & Lonigan, 2001). Identifying the precursors of children's early literacy skills can help early childhood educators to understand what knowledge and skills should be emphasized in promoting reading and spelling at different learning stages.

In recent years, there has been a renewed interest in the role of fine motor skills (FMS) in children's reading and spelling (Diamond, 2010; Grissmer et al., 2010; Mohamed & O'Brien, 2022). For example, it has been found that children with motor coordination disorders or motor insufficiency had a higher probability of low academic achievement than children without motor difficulties (Lopes et al., 2013). Other studies report that early kindergarten FMS can predict later literacy (Grissmer et al., 2010; Son & Meisels, 2006; Wang et al., 2015). However, the relationship between FMS and early literacy remains unclear (Cameron et al., 2016). Apart from FMS being an important predictor of pre-academic skills, early childhood professionals noted that executive functions (EFs) may also be an important determinant of school readiness (Connor et al., 2016; Lê et al., 2021). In most of the studies, the results of the strength of the relationship between FMS and reading and spelling do not indicate if the relationship is direct or indirect, or mediated by EFs (Cameron et al., 2016; Libertus & Hauf, 2017). The purpose of this paper is to clarify the relationship between FMS, EFs and literacy achievement, using a mediation model that obtains a deeper understanding of the potential interrelations between FMS and EFs and early literacy in Arabic-speaking children.

Fine motor skills and literacy achievement

It is estimated that preschoolers and kindergarteners spend between 27 and 66% of the school day working on some form of fine motor activity (Marr et al., 2001), which makes FMS an important aspect of early school readiness. FMS represents a skill set linked to several similar constructs, including tasks that integrate motor with spatial abilities (e.g., copying a geometric shape) (Carlson et al., 2013) and graphomotor skills. In the current work, in line with Suggate et al., (2019) and Mohamed and O'Brien, (2022), we define three discrete terms, namely visuomotor control (manual dexterity), visual-spatial integration, and graphomotor skills like handwriting. Visuomotor control or manual dexterity is defined as "small muscle movements requiring close eye-hand coordination" (Luo et al., 2007, p. 596). Measures of manual dexterity usually revolve around manipulating blocks or small objects, threading beads, shifting pegs, or posting coins. Visual-spatial integration refers to a subset of FMS that directly involves skills closely tied to writing (e.g., copying characters/symbols) without requiring cognitive knowledge. Finally, handwriting skills are graphomotor abilities coupled with the cognitive knowledge of letters leading to the ability to produce letters in a copying task fluently and with correct form.

Mastery of FMS can be framed in the context of the Theory of Automaticity, which posits that the more skilled an individual becomes at performing a particular task, the more "automatic" this process becomes – thus freeing up cognitive resources that would otherwise be used to focus on its execution (Savage, 2004). In the context of fine motor skills and school performance, this means that a child who possesses higher levels of mastery of basic motor skills (i.e., writing letters) may be better able to focus his/her attention on higher-order concepts like spelling words correctly or composing sentences (Cameron et al., 2012). In contrast, a child low in fine motor skills may struggle with these more basic classroom activities and thus be less able to allocate his or her attention to the content of lessons or the execution of more complex tasks.

Moreover, most influential models of writing assume that spelling and handwriting (graphomotor skills) are different processes but closely related (Hayes, 1996; Van Galen, 1991). The spelling module involves the retrieval and maintenance of the orthographic representation of words; and the motor modules are engaged in allograph selection, size control, and muscular adjustment. From a developmental point of view, the importance of automating both spelling and handwriting processes has been highlighted (Berninger & Amtmann, 2003), in order to ensure that resources are available for higher-order processes (McCutchen, 2011).

Many studies of school-age children have examined the link between children's FMS and learning to read or write (Chung et al., 2018; Khng & Ng, 2021; Lam & McBride, 2018; Wang et al., 2015), Hindi (Bhide, 2018), English (Cunningham & Stanovich, 1991), German (Suggate et al., 2018, 2019) and Arabic (Khoury-Metanis & Khateb, 2022). McBride-Chang et al., (2011) found that visual-spatial integration (e.g., copying unfamiliar script) uniquely and significantly explained children's spelling ability. The researchers suggested that the importance of copying for Chinese literacy acquisition might be due to several integrated processes. Visual-spatial integration is important in spelling due to the visual complexity of logographic forms in Chinese characters, which require a clear focus on spatial configuration and order of strokes. Failure to attend to the details of the components of the characters might result in poor handwriting, which may lead to poor character recognition and poor performance in reading and spelling.

Consistent with McBride-Chang et al., (2011), Wang et al., (2014) found that copying skills using unfamiliar scripts were also related to children's reading and writing. Moreover, in a correlational study on kindergarten children, examining links between FMS and early reading skills (Suggate et al., 2018), FMS (visuomotor control) was found to be correlated uniquely only to spelling skills, not to early word reading and letter naming. However, when a graphomotor skill was added to the regression analyses, FMS ceased to be a predictor even of reading skills. Interestingly, a recent work by Khoury-Metanis and Khateb, (2022) did not show any direct contribution of fine motor skills to spelling and reading at kindergarten, probably due to a still nonstable relationship between FMS and reading and spelling over the years. Children in kindergarten didn't get instructions for reading and spelling, these remain difficult tasks even for normally developed children. Because, the relationship between FMS and early literacy is still not clear, more studies with a longitudinal design are needed to better understand this relationship.

Executive functions and literacy achievement

In the kindergarten years, EFs (inhibitory control, working memory, cognitive flexibility) are frequently linked to children's literacy achievement (Best et al., 2011). It is thought that improvements in executive functioning facilitate improvements in academic achievement (Best et al., 2009) or that adequate executive functioning develops before behaviors affecting academic achievement (Blair & Razza, 2007). EFs, also known as cognitive control, underpinned by the prefrontal cortex, are defined as a set of high-level cognitive processes that are needed when individuals must pay attention to achieve a goal and/or when an automatic process cannot be used to achieve a goal (Diamond, 2013). Researchers generally agree that three core EFs exist: working memory (WM; mentally holding and using information), inhibition (suppressing prepotent or dominant responses), and shifting (switching between tasks or mental sets; Bull & Lee, 2014; Diamond, 2013). In this study, the Head–Toes–Knees–Shoulders (HTKS) task (McClelland et al., 2015; Ponitz et al., 2008) and the Digit Span Task from the Kaufman Assessment Battery for Children (Kaufman & Kaufman, 2013) were used to assess kindergarteners' EF skills. In particular, the HTKS task was used because it is thought to integrate different aspects of EFs (i.e., inhibitory control, working memory, and cognitive flexibility) that interact actively with each other to regulate behavior outcomes toward a future goal (Cameron et al., 2012). Also, working memory tasks have been shown in previous studies to be related to early literacy (Michel et al., 2019).

Researchers have shown that EFs and their component processes are centrally involved in literacy (Becker et al., 2014; Connor et al., 2016). Learning to decode and comprehend text requires inhibitory control to persist through challenges; cognitive flexibility to learn all the associations between letter forms and sounds, word meanings, and working memory to enable the individual to combine sounds into words and words into paragraphs. In addition, as students advance in school, EFs predict comprehension rather than decoding (Connor et al., 2016; Fuhs et al., 2014). This shift reflects EFs' role when tasks are new, not yet automated, and require deliberate attention (Blair et al., 2011).

Although EFs have been robustly linked to decoding and comprehension aspects of literacy over the school transition, there are fewer studies on the relations between EFs and spelling. The available research has found that aspects of EFs significantly predict early spelling development (Hooper et al., 2011; Kent et al., 2014; Kim et al., 2013) and that students who struggle with are likely to have low EFs abilities (Hooper et al., 2002). Thus, like early reading development, previous research supports the notion that children who demonstrate strong EFs (e.g., can focus and pay attention) are more likely to develop stronger spelling skills.

The relationship between FMS, EFs and literacy achievement

The association of FMS with reading and spelling is often viewed as an indirect one, a point that is central to this study. EFs are a common variable that may affect both

FMS and academic skills. EFs, such as that measured as working memory, or self-regulation, might underlie the apparent correlation between skills in motor and academic domains. EFs play a key role in fine motor skills development, as mastering manual dexterity requires sustained attention, planning, and deliberation (Adolph et al., 2010; Conners, 2009; Diamond et al., 2007; McClelland & Cameron, 2019).

Recent research indicates that EFs and FMS are highly related and co-develop (Cameron et al., 2015; McClelland & Cameron, 2019; Roebers et al., 2014).

Donnelly and Lambourne, (2011)'s conceptual model hypothesized that EFs were direct indicators of successful academic achievement. Most recently, Donnelly et al., (2016)'s substantial review indicated that EFs and FMS are the underlying mechanisms contributing to reading proficiency and that moderate to strong associations were found between EFs and reading proficiency. Children who evidence automaticity in certain FMS may have greater processing capacity to learn through empowered EFs, which may enhance their academic performance in reading (Donnelly & Lambourne, 2011; Stipek & Valentino, 2015).

Suggate et al., (2018) designed a longitudinal cross-panel to test the unique contribution of kindergarten FMS to reading in grade 1, while controlling for IQ and EFs. Importantly, the simple SEM indicated that FMS uniquely relate to later reading development. Additionally, Chang and Gu, (2018), identified indirect effect of FMS on reading proficiency through EF, suggesting that the influence of motor skill proficiency on reading is dependent on a child's development of executive function ability. First, children with better manual dexterity might demonstrate better handwriting skills and thus, might easily copy letters, leading to an advantage in early reading development. For children who can already decode, having greater graphomotor skills enables them to consolidate their reading skills by practicing their handwriting (Wamain et al., 2012). Indeed, children with greater FMS, as measured by symbol or letter copying tasks, perform better on literacy tasks (Cameron et al., 2012; Suggate et al., 2018). Second, reading and FMS might share common underlying cognitive processes, such as EFs (Cameron et al., 2016; Michel et al., 2019; Suggate et al., 2018), the same sets of cognitive skills associated with reading are also strongly correlated with fine motor abilities (Becker et al., 2014). This perspective suggests that once executive functions are accounted for, fine motor abilities should not contribute any unique variance to literacy. This standpoint suggests that executive functions might mediate the relationship between FMS and academic achievement.

EFs play a key role in fine motor skills development, as mastering manual dexterity requires sustained attention, planning, and deliberation (Adolph et al., 2010; Conners, 2009; Diamond et al., 2007; McClelland & Cameron, 2019). Similarly, EFs' contribution to literacy development is supported by findings of a strong correlation between word reading performance and cognitive factors such as inhibition, working memory, and self-regulation (National Early Literacy Panel, 2008). Furthermore, the same sets of cognitive skills associated with reading are also strongly correlated with fine motor abilities (Becker et al., 2014), such as attention (Conners, 2009), inhibitory control, and working memory (Cartwright, 2012). This perspective suggests that fine motor abilities do not contribute any unique variance to literacy once general cognitive skills are considered. In this respect, Grissmer et al., (2010), reporting on a joint analysis of three large longitudinal data sets, addressed the question of whether the executive function demands of fine-motor tasks were responsible for the significant link between motor skills and academic achievement or whether there was a unique contribution of FMS for later achievement. The authors concluded that the relative predictive power of FMS compared to measures of EFs was so varied across data sets that the question remains unanswered.

However, findings in previous literature may not necessarily be generalizable to Arabic script, especially considering the unique features of the Arabic writing system. Because Arabic orthography is characterized by a certain degree of visual complexity, one might assume that cognitive capabilities may be essential for developing Arabic word reading and spelling and mediating the relation between FMS and literacy achievement. Indeed, one major aspect of visual complexity in Arabic is the visual similarity between letters. This visual similarity is evidenced by the fact that the Arabic writing system comprises several dyads or triads of letters that have the same basic form but are differentiated by the presence or absence of dots, by their number and location (1 to 3 dots, inside or below the letter). For example, such a differentiation appears in the letters <ب > ,<ت> and <ث> for the letters /B/, /T/ and / TH/ and in the letters <ج> <خ> <ح> for /ħ/, /x/ and /dʒ/ (Asadi et al., 2017). This visual similarity and other phonological similarities increase orthographic ambiguity (Taha & Khateb, 2013). Another aspect of orthographic complexity in Arabic is that 22/28 letters connect to preceding and following letters (i.e., from the right and left), and six letters connect only to the preceding one. Written letters change their basic forms when connected based on their location (: at the beginning, middle, or end) in the word (Khateb et al., 2013, 2014). These and other features are thought to pose serious challenges for children during the early stages of literacy development and might be at the origin of reading and spelling difficulties (Abdelhadi et al., 2011; Asaad & Eviatar, 2013; Asadi et al., 2017; Khateb et al., 2014; Taha & Khateb, 2013).

Kindergarten literacy instruction in Israel

In Israel, children enter first grade (elementary) school the year they reach age six, following a year of compulsory kindergarten. In Israeli kindergartens, children write their names on their artwork and find their names printed on items such as clothes hooks and personal lockers. Lists of letters, magnetic letters, printed words, and texts are displayed around the room. Children frequently read to from storybooks, view TV programs based on storybooks, and voluntarily browse books. Games that promote phonological awareness, such as segmenting words into syllables, counting syllables, and rhyming, abound. Worksheets encouraging training in visual discrimination (including letter discrimination) and letter copying are commonplace. The curriculum for teaching Arabic in preschool includes training in various alphabetic skills, including phonological awareness and letter knowledge, and book reading to expose children to the linguistic structures of the standard language. Children learn to read short-vowelized words, which follows relatively consistent letter-sound conversion rules (Asadi et al., 2017). Writing instruction in kindergarten focuses exclusively on transcription. By the end of kindergarten, most students can name, sound, and form all letters. It is also expected that students leave kindergarten with knowledge of phoneme-grapheme correspondence and can write syllables and simple words (Levin et al., 2008).

The current study

Building on Donnelly and Lambourne's, (2011) conceptual model, the present investigation aimed at examining the longitudinal relationship of FMS and EFs in kindergarten to first-grade literacy achievement among a typically developing sample of Arabic-speaking children. For this purpose, data collected from Kindergarteners' included FMS (visuomotor control, visual-spatial integration, and graphomotor skills) and EFs tasks (self-regulation task and the digit-span forward and backward tests). Data from first graders included a literacy achievement measure based on word reading, pseudoword reading, and spelling, together with a measure of nonverbal intelligence. Based on prior research, we hypothesized: i) that FMS will directly influence spelling and reading among first-grade children, when not entering EFs to the analysis, and that ii) EFs would have a positive direct effect on literacy, and FMS would have a positive effect on literacy through an indirect path with executive functions mediating this relationship.

Material and methods

Population and procedures

A sample of 212 children was followed for one year (mid-kindergarten to mid-first grade) in the context of a longitudinal study in [was removed for review]. The sample comprised 100 boys and 112 girls, with a mean age of 75 months (SD = 3.41). The study sample was recruited from 20 kindergartens in the north of Israel and around the Haifa area. These kindergartens were selected to represent a wide range of socioeconomic backgrounds.

With the consent of the school principals, parents received a flyer with information about the purpose of the study and the procedure (number of sessions, activities during the sessions). Parents were asked to provide a signed written consent form for their child's participation. At the first measurement point (kindergarten), intelligence, FMS, and EFs were assessed, and early school achievement in reading and spelling were assessed at the second point (first grade). Intelligence was measured with Raven Colored Progressive Matrices test, a standardized non-verbal intelligence test. FMS were selected as previous studies revealed that FMS are related to literacy achievements (Cameron et al., 2012; Grissmer et al., 2010; Rigoli et al., 2012).

All measures were individually administered by the first author or one of five trained occupational therapists in a spare room at school. The preschool tests were spread over two sessions of about 15–20 min that took place in May and June. In first grade, testing took place during the second trimester (February and March) in one session lasting about 25 min.

Kindergarten measures

Fine motor skills (FMS)

Visuomotor control This skill was assessed using the Functional Dexterity Test (FDT: North Coast Medical, Gilroy, CA). This test uses a pegboard having 16 cylindrical pegs arranged in a four-by-four matrix. A tripod pinch is used to turn over each peg and replace it in the pegboard in a standardized pattern. A height-adjustable table was used, and hand dominance was determined by asking the child to draw a circle with a pen that had been placed in the center of the table. The hand that the child spontaneously used was considered the dominant one. A practice trial was performed after test instructions were given. The second trial was timed using a stopwatch. If a peg was dropped, the timer was paused, and the peg was returned to its original position. The timing was resumed once the child resumed turning pegs. The overall time elapsed to turn over all pegs was measured.

Visual-spatial integration This skill was assessed with the straightforward task of copying unfamiliar Chinese-script words of which children had no prior cognitive or orthographic experience or knowledge (i.e., participants didn't know Chinese at the beginning of the study). Chinese word captures different elements of the integration of visual and motor skills. The task consisted of 5 items (2 items for practice and 3 items were scored) and was time-limited, with children allotted 5 min to finish the task (McBride-Chang et al., 2011). Each component of the items was scored based on its shape and position. Different items contained different numbers of components, so the score carried by each item varied. The total score for the task was 20. The reliability of this test in the current study is determined as Cronbach's $\alpha = 0.81$.

In order to check inter-rater agreement, fifty assessments from among the 212 completed were randomly selected to be double-coded. The inter-rater agreement for the raw score for this subsample was 92% with a weighted Cohen's kappa of 0.79 and correlated at $r = 0.93$, $p < 0.001$.

Grapho-motor skill: This ability was assessed based on the task of replicating Arabic letter forms from models printed on paper. The scoring was adapted to Arabic letters from a letter form copying test, the Scale of Children's Readiness In PrinTing (SCRIPT), which was developed for kindergarten children by Weil and Amundson, (1994). The letters on the SCRIPT are scored as correct or incorrect according to following criteria:

1. The letter is quickly and easily recognized as itself, and no gross errors in proportion are present.
2. The letter has no missing parts or dots and no extra parts.

3. No lines extend beyond the intersection by more than two millimeters.
4. Dots must not touch the letter, and have no more than the three-millimeter distance for the letters (خ/x/, ج/dʒ/, غ/ɣ/, ف/f/, ق/k/, ض/d̪ˤ/, ب/B/, ي/i:, /ظ/ðˤ/,ذ /ð/, ع/ʕ/ت, /t/, ن/n/, ث/θ/).
5. Letter forms must be closed correctly, with no more than a two-millimeter gap, used for the letters (و/u:/ ظ / ðˤ / ق/q/ ف/f/ -ه/h/ ض/ d̪ˤ / ط/t̪ˤ / م/M/ ص /sˤ/).
6. Curved lines must be curved, and straight lines must be able to fit within a two-millimeter space.
7. Angles must be present, used for the letters خ /x/ ح /ħ /ج/ dʒ / ك/k/ د/d/ ذ/ ð /.
8. There is no rotation of more than 45° in any part of the letter: no reversals are present.

Each letter must pass each criterion to be awarded one point. Failure on any one criterion results in a score of zero for that letter (Marr et al., 2001). The handwriting sample was judged by grading each letter individually and then calculating the overall score of correct letters for legibility (maximum score of 29).

Each letter must pass each criterion to be awarded one point. Failure on any individual criterion results in a score of zero for that letter (Marr et al., 2001). The maximum score is seven. Inter-rater agreement was checked for 48 randomly selected assessments for the copying letters task. The inter-rater agreement for the raw score for this subsample was 93% with a weighted Cohen's kappa of 0.81 and correlated at $r = 0.95$, $p < 0.001$.

Executive functions

The Head–Toes–Knees–Shoulders (HTKS) (Ponitz et al., 2009) This task is considered a core measure of behavioral self-regulation (McClelland & Cameron, 2012) and is thought to incorporate aspects of EF into a short game for children aged 4–8 years. The task is designed as a Simon-Says-like game in which participants are instructed to touch the area—head, toes, knees, shoulders—opposite the one in the examiner's oral instruction. Children were first told to follow the examiner's commands (e.g., touch your head) but then to "be silly and do the opposite. If I say, 'touch your head,' touch your toes instead." In Phase I, children were given several practice commands with feedback about two rules (e.g., head or toes) and then 10 test commands in a pseudorandom, fixed order. In Phase II, children were taught to follow two additional commands (e.g., knees or shoulders) and then do the opposite. After four practice commands with feedback, the children were told they would hear one of four commands (touch your head/touch your toes/touch your knees/touch your shoulders) and should touch the "opposite" body part. They were then given another 10 test commands with body parts fixed in a pseudorandom order. The task requires attention to instructions, remembering which parts are paired, and inhibiting the natural tendency to touch the named part and touch a different part instead. Strong reliability and predictive validity have been demonstrated for the HTKS, with 20 items scored as follows: no points for an incorrect response, one for a self-corrected action, and two for a correct response. (Ponitz et al., 2009). The HTKS was shown to predict academic achievement, indicating that it taps the executive processes associated with success in educational settings (Matthews et al., 2009). In the current sample, the HTKS demonstrated strong internal consistency; Cronbach's alpha = 0.91.

Digit recall test (Forward and backward) In this verbal short-term/working memory test, the participants are required to recall immediately a series of auditorily presented digits in the same order (forward) and in reversed order (backward). The Digit Span Forward Task from the Kaufman Assessment Battery for Children (Kaufman & Kaufman, 2013) was used as an indicator of short-term memory. In this task, the child repeated the heared numbers in the same order. The test started with one practice item of two digits similar to the first level and increased by one digit at each subsequent level (two items per level) until level seven, where two eight-digit numbers were presented. The test was discontinued if a child made an error in two consecutive items of the same length. The score represented the number of correct responses. In the Backward Digit Recall (modified from Kaufman & Kaufman, 2013), there was also a total of seven experimental blocks (2 trials each), which progressed from a block with two digits to a block of eight digits. In each trial, the subject listened to a series of numbers (e.g., 5, 2) and had to repeat the numbers verbally in backward order (e.g., 2, 5). The research assistants recorded the children's answers as correct or incorrect. The final score was the total number of correct trials. The reliability of this test in the current study is determined as Cronbach's $\alpha = 0.89$ for forward digit span and Cronbach's $\alpha = 0.83$ for the backward digit span.

First grade measures

Literacy achievement tasks:

Spelling A word dictation task was used to assess children's Arabic spelling ability. Eight one- to three-syllable words (for example <سام> /sa:m/, <رازي> /ra:ze>, <هَرَبَ> / hara:ba>), chosen on the basis of familiarity as assessed by frequency-of-use in materials studied in first grade, were dictated to each child individually. The child then had to write the corresponding graphemic representation of the orally presented words following the orthographic rules, such as choosing the right allograph and correctly connecting the letters. Responses were scored as either correct or incorrect on this measure. Cronbach's alpha reliability for this task was 0.89. Inter-rater agreement was checked for 55 randomly selected assessments for the spelling task. The inter-rater agreement for the raw score for this subsample was 94%, with a weighted Cohen's kappa of 0.93 and correlated at $r = 0.94$, $p < 0.001$.

Real word reading This task, developed for this study (Authors removed for review), determined the most common words and syllable structures in four reading instruction books used in the first semester of first grade. The task comprised 25 words with predetermined consonant (C) verb (V) structures. Five words had CVC structure [e.g., /da:r/ ("house')]. Four words had CV.CV.CV structure [e.g., */rasama/* ('drew'). Twelve words had CV.CVC structure [e.g., */raza:n/* ('Razan, a given name')]. Four words had CV.CV structure [e.g., */fa:di:/* ('Fadi:, a given name')]. Children were instructed to read these words aloud in a clear voice, as quickly and accurately as possible, and to pay attention to diacritics. The score was the number of correctly read items. The Cronbach's alpha reliability for this task was 0.91. Inter-rater agreement was checked for 55 randomly selected assessments for the real word reading task. The inter-rater agreement for the raw score for this subsample was 94%, with a weighted Cohen's kappa of 0.91 and correlated at $r=0.95$, $p<0.001$.

Pseudoword reading In this task, all frequent words (derived from the previous task) were modified so that the words' letters were reversed in their order or substituted by other letters to transform the real words into pseudowords (Authors removed for review) without altering the syllabic structure of the words. Children were given the same instructions as for the previous task (Real Word Reading), except that it was emphasized that these words have no meaning. As in the previous task, the score was the number of correctly read items. The Cronbach's alpha reliability for this task was 0.92. Inter-rater agreement was checked for 55 randomly selected assessments for the pseudoword reading task. The inter-rater agreement for the raw score for this subsample was 93% with a weighted Cohen's kappa of 0.90 and correlated at $r=0.94$, $p<0.001$.

Control variable

Nonverbal intelligence was assessed using the Colored Raven's progressive matrices (Raven, 2003). This test comprises three sets of 12 items each (Sets A, AB, and B), with items within a set becoming increasingly complex. This test assesses children's reasoning abilities. This study used a shortened test version, including six items of each set. One point was given for each correct item, thus providing a maximum score of 18.

Statistical analysis

Before starting the analyses, the dataset was inspected for normality and homoscedasticity of the residual distribution, including checking for outliers. Following the normality assumptions testing methods of Larson-Hall, (2015), histograms and p–p plots were charted for each variable. Acceptable values of skewness (between -1 and $+1$) and kurtosis (ranging from -1 to $+1$) (Brown, 2015) were found for all variables. All variables formed histograms with a normal distribution. Intra-class correlation coefficients (ICC) were estimated and used to calculate a design effect for each outcome (reading and spelling) to determine whether the school had significant effects on the dependent measures. This effect was below 2 for all outcomes (Real word reading = 1.52, Pseudoword reading = 1.23, spelling = 1.40), indicating that between school effect would not need to be accounted for (Maas & Hox, 2005), and school was, therefore not included in the analyses.

After confirming the normality assumption, multiple steps were taken for data analysis. First, descriptive statistics of the study variables were examined, and Cronbach's alphas were used to assess the internal consistency of the scale scores of the FMS, EFs, and literacy achievement tests. Second, descriptive statistics, including means and standard deviations, were computed for all measures in the present study. Third, bivariate correlational analyses were performed to examine correlations among the study variables. Fourth, confirmatory factor analysis was used to examine if the manifest variables significantly represented their respective latent variables. Fifth, structural equation modeling (SEM) procedures were used to assess the relationship between FMS and literacy achievement. Sixth, SEM procedures were used to assess the hypothesized mediation model in which EFs mediate the relationship between FMS and literacy achievement. Seventh, a comparison between the models was conducted to determine significant differences. We tested the three models: (1) direct effect only (FMS → EFs, and EFs → Literacy fixed to zero, and FMS → Literacy estimated); (2) indirect effect only (FMS → Literacy fixed to zero, FMS → EFs, and EFs → Literacy estimated) and (3) direct and indirect model (all 3 paths estimated).

The score of the Raven test, as general non-verbal ability, was controlled for in the SEM model. Goodness-of-fit statistics, including chi-square, normed fit index (NFI), Tucker–Lewis Index (TLI), incremental fit index (IFI), comparative fit index (CFI), and root mean squared error of approximation (RMSEA), were used to test model fit (Markus, 2012). A bootstrapping technique (Preacher & Hayes, 2008) was used to test the mediation effect's statistical significance and magnitude and estimate the effect's 95% confidence interval.

Results

Descriptive statistics and correlations

Descriptive statistics for the study variables are presented in Table 1. Table 2 shows the correlation between all collected measures. As seen in this table, the reading and spelling measures correlated highly with each other and moderately with FMS and EFs, but reading is less correlated to the FDT measure.

Confirmatory factor analysis

Before testing the mediation of EFs, confirmatory factor analysis was conducted with nine latent variables: fine motor skills, the three literacy variables (word reading, pseudoword reading, and spelling), and the three potential EFs variables (Fig. 1). The model presented a good fit with the data, $\chi^2/df = 1.587$, $p = 0.034$, CFI = 0.978, RMSEA = 0.053. All the manifest variables significantly represented their respective latent variables ($p < 0.005$). The analysis showed that literacy is

Table 1 Descriptive statistics

	Mean	SD	Min–Max
Spelling	4.29	2.87	0–8
WR	15.77	7.43	0–25
PWR	11.52	8.5	0–25
Raven	10.06	2.97	2–17
FDT	38.72	7.58	24.50–60
Copying	6.22	3.55	0–20
Pure Copying	15.43	3.05	4–20
HTKS	30.92	7.42	9–40
Digit (Fwr)	4.41	1.57	1–8
Digit (Bwr)	2.43	1.05	0–6

WR for real word reading; PWR for pseudoword reading; FDT for the functional dexterity task; Copying for copying letters; HTKS for *The Head–Toes–Knees–Shoulders* task; Digit (Fwr) for the forward digit span test; Digit (Bwr) for the Backward digit Span test

strongly correlated with EFs, and moderately with FMS. The correlation between FMS and EFs is moderate (Fig. 1).

Structural equation modeling

SEM was conducted to test the relationship between FMS and literacy achievement (Fig. 2). Initial evaluation of the fit indices for the proposed measurement model indicated a good data fit: ($\chi^2/df = 1.476$, $p = 0.12$; NFI = 0.97; IFI = 0.985; TLI = 0.982; CFI = 0.99; RMSEA = 0.047). The results showed that FMS were a significant predictor of literacy achievement $\beta = 0.35$, $p < 0.005$, explaining 24% of the variance.

Structural equation modeling–mediating model

SEM was conducted to test whether EFs mediate the relationship between FMS and literacy achievement (Fig. 3). Initial evaluation of the fit indices for the proposed measurement model indicated a good data fit: ($\chi^2/df = 1.727$, $p = 0.008$; NFI = 0.93; IFI = 0.969; TLI = 0.953; CFI = 0.968; RMSEA = 0.059). The results showed that FMS was a significant predictor of EFs ($\beta = 0.53$, $p < 0.01$), and EFs were a significant predictor of literacy achievement ($\beta = 0.67$, $p < 0.01$). However, the relationship between FMS and literacy achievement was insignificant in this model ($\beta = 0.09$, $p = 0.48$) after taking EFs into account, suggesting that EFs fully mediated the relationship between FMS and literacy achievement. Results of the

Table 2 Bivariate correlations between variables

	1	2	3	4	5	6	7	8	9	10
1. Spelling	1									
2. WR	0.75**	1								
3. PWR	0.76**	0.81**	1							
4. Raven	0.36**	0.32**	0.31**	1						
5. FDT	− 0.22**	− 0.17*	− 0.08	− 0.21**	1					
6. Copying	0.26**	0.27**	0.24**	0.24**	− 0.29**	1				
7. Pure copying	0.25**	0.23**	0.21**	0.35**	− 0.26**	0.32**	1			
8. HTKS	0.24**	0.24**	0.22**	0.31**	− 0.18**	0.12	0.25**	1		
9. Digit (Fwr)	0.47**	0.46**	0.42**	0.22**	− 0.14*	0.14*	0.12	0.25**	1	
10. Digit (Bwr)	0.24**	0.26**	.29**	0.26**	− 0.12	0.23**	0.09	0.20**	0.33**	1

WR for real word reading; PWR for pseudoword reading; FDT for the functional dexterity task; Copying for copying letters; HTKS for *The Head–Toes–Knees–Shoulders* task; Digit (Fwr) for the forward digit span test; Digit (Bwr) for the Backward digit Span test

*$p < 0.05$; **$p < 0.01$

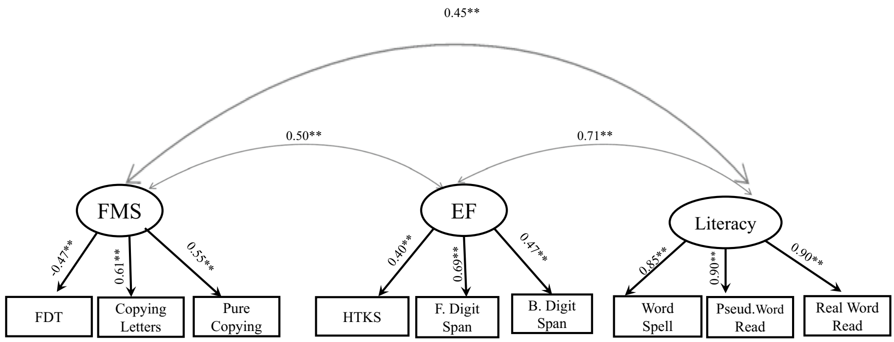

Fig. 1 Confirmatory factor analysis. Abbreviations: EF for executive functions; FMS for fine motor skills; WR for real-word reading; PWR for pseudoword reading; FDT for functional dexterity task; Copying for copying letters; HTKS for *The Head–Toes–Knees–Shoulders* task; Digit (Fwr) for the forward digit span test; Digit (Bwd) for the backward digit Span test. $\chi^2/df = 1.587$, $p = 0.034$, CFI = 0.978, RMSEA = 0.053. $^*p < 0.05$; $^{**}p < 0.01$

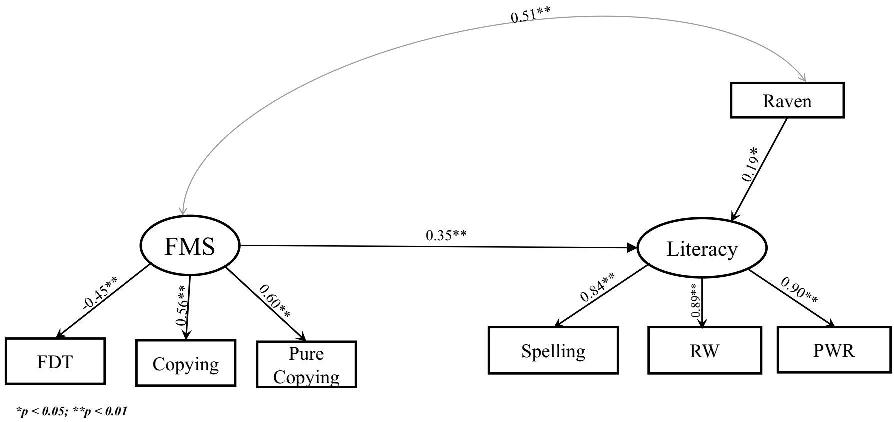

Fig. 2 The structural equation modeling with standardized path coefficients. Abbreviations: FMS for fine motor skills; WR for real-word reading; PWR for pseudoword reading; FDT for functional dexterity task; Copying, copying letters. $\chi^2/df = 1.476$, $p = 0.12$; NFI = 0.97; IFI = 0.985; TLI = 0.982; CFI = 0.99; RMSEA = 0.047. $^*p < 0.05$; $^{**}p < 0.01$

bootstrap method also supported the statistically significant effect of FMS on literacy achievement through EFs, b = 0.363, 95% CI [0.182, 0.802].

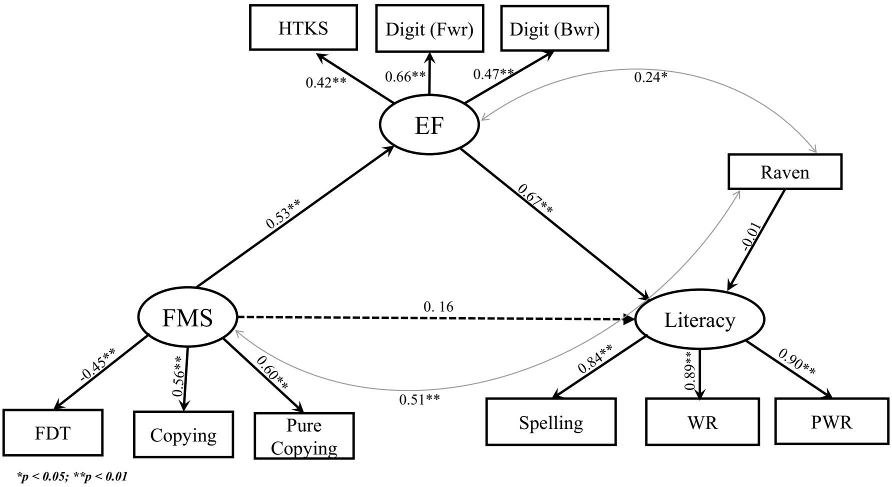

Fig. 3 The structural equation mediation modeling with standardized path coefficients. Abbreviations: EF for executive functions; FMS for fine motor skills; WR for real-word reading; PWR for pseudoword reading; FDT for functional dexterity task; Copying for copying letters; HTKS for *The Head–Toes–Knees–Shoulders* task; Digit (Fwr) for the forward digit span test; Digit (Bwd) for the backward digit Span test. $\chi^2/df = 1.727$, $p = 0.008$; NFI = 0.93; IFI = 0.969; TLI = 0.953; CFI = 0.968; RMSEA = 0.059. $*p < 0.05$; $**p < 0.01$

Table 3 Model comparison for significant differences

Model	CMIN	*DF*	*P*	CMIN/*DF*	NFI	IFI	TLI	CFI
Direct and indirect model	51.80	30	0.008	1.727	0.93	0.96	0.95	0.96
Direct effect model	112.59	32	0.000	3.519	0.84	0.88	0.83	0.88
Indirect effect model	52.23	31	0.010	1.685	0.93	0.97	0.95	0.96

Comparison model for significant differences

As can be seen in Table 3, in the first model, the direct path from FMS to literacy was significant, while in both models, indirect and direct and indirect effects weren't significant. The result strengthens the claim that including EFs in the model was a better model for understanding the relationship between FMS and literacy achievement.

Discussion

The present longitudinal study investigated the direct effect of kindergarten FMS on literacy achievement in first grade, and also examined whether EFs mediate the relationship between FMS and reading and spelling. For this aim, FMS and EFs measures were collected from 212 Arabic-speaking kindergarten children whose first-grade literacy achievement was assessed a year later. Understanding the association between FMS and EFs could provide critical information for understanding developmental variations among young children and differences in their academic readiness for the school years (Cameron et al., 2012).

The first SEM analysis, in the current study, indicated that FMS directly impacted reading and spelling in the first grade. However, their influence vanished when EFs were included in the second model, indicating that their relationship with literacy was fully mediated through EF performance. A direct relationship between FMS and academic achievement was found in other studies (e.g., Doyen et al., 2017; Lê et al., 2021; Mohamed & O'Brien, 2022). It has been argued that handwriting helps children memorize the shape of letters (Longcamp et al., 2005) and helps with literacy acquisition (Mohamed & O'Brien, 2022; Wang et al., 2015). Studies have reported that graphomotor training enhanced letter recognition and pseudoword reading (Longcamp et al., 2005). It could also be that a high level of manual proficiency can help a child learn to write letters, while it is not a positive factor for reading unless there is specific training, such as visuomotor training (Vinter & Chartrel, 2010). Our results are consistent with showing that fine motor performance is linked to word spelling and reading when not considering executive functions (Mohamed & O'Brien, 2022).

The observation of these links between FMS, word spelling, and word reading is also consistent with other previous research (Cameron et al., 2012; Dellatolas et al., 2003; Grissmer et al., 2010), which found indications of links between FMS, graphomotor skills, and emergent literacy skills. These results imply that literacy achievements are significantly related to fine motor experiences when children are learning to write letters. Our observation supports Cameron et al.'s (2016) argument that visual-spatial integration and reading are especially related when children are given opportunities to practice handwriting in their language (Suggate et al., 2018). Moreover, our findings are consistent with Lam and McBride, (2018) and Suggate et al., (2019), who found that graphomotor skills are associated with early literacy achievements.

The second SEM model, in our study, suggests that EFs mediate the effects of FMS on literacy achievement. These results align with previous research that emphasized the vital role of EFs for academic success at the beginning of schooling, independent of intelligence (Blair & Razza, 2007; Roebers et al., 2014). In results similar to ours, Rigoli et al., (2012) found no direct effect of motor skills on academic achievement, but mediation by the working memory was evident. The structural equation modeling in Chang and Gu, (2018) suggested that EFs fully mediated the relation between FMS and reading. This comprehensive EFs role underscores the importance of early diagnosis of EFs problems and the timely implementation of prevention and intervention programs (e.g., Diamond & Lee, 2011).

The present longitudinal approach, chosen to test the mediational role of EFs in the linkage between FMS and literacy achievement, confirms and further strengthens the mediated path found in cross-sectional studies (Chang & Gu, 2018; Rigoli et al., 2012; van der Niet et al., 2014). In the present study and the studies by Chang and Gu, (2018), Rigoli et al., (2012), and van der Niet et al., (2014), there are similarities in path coefficients despite considerable differences in age groups, procedures, and instruments used to operationalize the underlying constructs.

Our findings showed that EFs significantly influenced literacy achievements in the first years of formal schooling. This understanding of EFs' role is consistent with and expands the findings of Roebers et al., (2014) for manual dexterity skills and reiterates the decisive role of EFs. Schmidt et al., (2017) also found that EFs mediated the relationship between motor skills (endurance, strength, and whole-body coordination) and academic achievement. In this later study, strength and endurance did not appear to affect school achievement, while motor coordination fully mediated by EFs had actually a significant indirect effect.

Wassenberg et al., (2005) proposed that the nature of the evaluative tasks used to assess cognitive ability and motor proficiency can influence their relationship. For example, the authors found an association between cognitive and motor functions in 5- to 6-year-old children when cognitive functions included motor skills such as drawing or pointing. However, no association was evident when cognitive function tasks (such as verbal recall of digits or naming) devoid of motor skills were employed. Although we cannot fully apply these findings to our results since only the HTKS demands motor coordination but not the verbal recall of digits, it would be interesting to expand this relevant knowledge in future studies. Also, and beyond the results reported here, the literature cited previously showed that comparisons among the various studies are quite complex and should be made with caution due to the various influencing factors that include differences in sample characteristics, the variety of evaluated motor skills, and the academic competencies assessed using diverse instruments.

This study makes unique contributions to the literature by identifying the EF mechanism that underlies the relationship between FMS and literacy achievement. Our findings suggest that FMS and EFs concomitantly influence the development of young children's spelling and reading proficiency. Curriculum developers, school administrators, and teachers must understand how FMS and EFs enhance kindergarteners' reading and spelling capability. Since the ultimate goal of early schooling is to promote higher spelling and reading proficiency among kindergarteners and primary school pupils, teachers should provide sufficient opportunities for children to learn and practice FMS in game-based activities, which in turn may enhance their cognitive functioning (Chang & Gu, 2018). Moreover, the findings of the present investigation highlight the critical issue of screening young children with non-academic and non-language-based assessment, such as screening specific FMS and EFs components. These skills are known to be associated with literacy achievement and their evaluation might provide a means of identifying underlying reading and spelling difficulties. Early identification and intervention targeting FMS or EFs difficulties should thus be emphasized (Chang & Gu, 2018). Compared to EFs, there is less work that aims to explicitly improve children's FMS and even fewer interventions that make connections to academic skills. Existing evidence suggests that researchers should strive to improve quality and expand intervention efforts to typically developing populations to see if approaches are effective among children with difficulties (McClelland & Cameron, 2019).

Limitations and future work

The present study has limitations that need to be addressed. First, although the present study employed a longitudinal design, not all variables were measured at every wave of data collection, which did not allow for setting up an autoregressive mediation model (Schmidt et al., 2017), in which longitudinal relations among latent variables across 3 or more time points can be tested. The basic three-wave autoregressive mediation model is a path model in which relations among variables one lag (wave) apart are considered, the stability of measures is assessed over time, and only longitudinal relations consistent with longitudinal mediation are considered (Lockhart et al., 2011). Hence, future studies should include measures of all interesting variables at any wave of data collection and account for initial levels, e.g., of FMS and EF at grade 1 and early academic achievement at kindergarten, to reduce the potentially inflated estimates of the causal path of interest. Thus, extending the length of the study might have introduced confounding influences as reading moves away from decoding to vocabulary and from word spelling to composing. Further, it is likely that a longer follow-up would test different pathways about the links between FMS and literacy.

Second, although EFs and FMS are important, they are not the only factors, and it is important to also consider other variables such as early language and vocabulary development (Slot & von Suchodoletz, 2018). Thus, moving forward, research needs to focus on a variety of key domains of development and how they develop together rather than pitting one set of skills against another (McClelland & Cameron, 2019). Third, it is important to ask the question of "How can we best measure these skills?" and "What measure or measures are most appropriate for a given outcome, context, or question of interest?". The current study used the pure copying task (chines characters) as a graphomotor task. The mean of this task was high, and it seems it was easy for kindergarten children. It could be due to the fact that Chinese script has its pattern which might be statistically learned, characters can be visualized as resembling a picture, depending on an individual's imagination In future studies, we need to focus on how to specifically measure domains of interest.

Fourth, this study makes unique contributions to the literature by identifying the EFs mechanism that underlies the relationship between FMS and literacy. Indeed, one can argue that the interpretation of the result regarding reading and spelling respectively still missing, due to considering both as one latent variable. Further studies are needed to understand the contribution to reading and spelling separately. Moreover, it will be interesting to test the relationship between EFs and literacy after taking FMS into account.

Conclusions

The current study is the first to utilize mediational analyses to shed light on the predictive value of common FMS and EFs components on reading and spelling among Arabic-speaking children. The strength of the analysis presented in this study resides in the use of structural equation modeling to provide a causal framework, that allows for a more comprehensive picture of the complexity of the longitudinal relationship between FMS and academic achievement in six-year-old children while controlling for general non-verbal ability measures. While it is generally more tempting in early intervention to focus on reading and spelling skills to ensure literacy achievement, the current results highlight the relevance of assessing and enhancing both fine motor and cognitive abilities. Hence, the results presented here provide new insights into the development of literacy skills among Arabic-speaking children in particular and contribute more generally to the knowledge base regarding the specific relationships extant between the components of FMS and EFs in preschoolers and their later academic competencies. The analysis presented in this study confirms that a child's FMS and EFs are among the necessary abilities for literacy achievement and must receive the necessary attention from educators during the early school years. Sufficient effort must be made to support children's motor and cognitive development before they enter first grade. Additionally, those who are less prepared or have motor difficulties in kindergarten must be more intensively supported to develop their school readiness. Future studies should examine separately the roles of individual areas of motor proficiency in order to better understand the relationship between motor functioning, EFs, and literacy achievement. For this aim, additional measures are needed in future studies to examine the unique contribution of each FMS dimension. In the same vein, future studies should also investigate children with motor coordination difficulties who still show significant strengths in EFs and literacy achievement.

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References

Abdelhadi, S., Ibrahim, R., & Eviatar, Z. (2011). Perceptual load in the reading of Arabic: Effects of orthographic visual complexity on detection. *Writing Systems Research, 3*(2), 117–127. https://doi.org/10.1093/wsr/wsr014

Adolph, K., Tamis-Lemonda, C., & Karasik, L. (2010). Cinderella indeed—A commentary on Iverson's 'Developing language in a developing body: The relationship between motor development and language development.' *Journal Child Language, 37*, 269–273. https://doi.org/10.1017/S0305000909990432

Asaad, H., & Eviatar, Z. (2013). The effects of orthographic complexity and diglossia on letter naming in Arabic: A developmental study. *Writing Systems Research, 5*(2), 156–168. https://doi.org/10.1080/17586801.2013.862163

Asadi, I. A., Ibrahim, R., & Khateb, A. (2017). What contributes to spelling in Arabic? A cross-sectional study from first to sixth grade. *Writing Systems Research, 9*(1), 60–81. https://doi.org/10.1080/17586801.2016.1218748

Becker, D. R., Miao, A., Duncan, R., & McClelland, M. M. (2014). Behavioral self-regulation and executive function both predict visuomotor skills and early academic achievement. *Early Childhood Research Quarterly, 29*(4), 411–424.

Berninger, V. W., & Amtmann, D. (2003). Preventing written expression disabilities through early and continuing assessment and intervention for handwriting and/or spelling problems: Research into practice. In H. L. Swanson, K. R. Harris, & S. Graham (Eds.), *Handbook of learning disabilities* (pp. 345–363). The Guilford Press.

Best, J. R., Miller, P. H., & Jones, L. L. (2009). Executive functions after age 5: Changes and correlates. *Developmental Review, 29*(3), 180–200. https://doi.org/10.1016/j.dr.2009.05.002

Best, J. R., Miller, P. H., & Naglieri, J. A. (2011). Relations between executive function and academic achievement from ages 5 to 17 in a large, representative national sample. *Learning and Individual Differences, 21*(4), 327–336. https://doi.org/10.1016/j.lindif.2011.01.007

Bhide, A. (2018). Copying helps novice learners build orthographic knowledge: Methods for teaching Devanagari akshara. *Reading and Writing, 31*(1), 1–33. https://doi.org/10.1007/s11145-017-9767-8

Blair, C., Protzko, J., & Ursache, A. (2011). Self-regulation and the development of early literacy. In D. Dickinson & S. Neuman (Eds.), *Handbook of early literacy research* (Vol. 3, pp. 20–35). Guilford Press.

Blair, C., & Razza, R. P. (2007). Relating effortful control, executive function, and false belief understanding to emerging math and literacy ability in kindergarten. *Child Development, 78*(2), 647–663.

Brown, T. A. (2015). *Confirmatory factor analysis for applied research*. Guilford publications.

Bull, R., & Lee, K. (2014). Executive functioning and mathematics achievement. *Child Development Perspectives, 8*(1), 36–41. https://doi.org/10.1111/cdep.12059

Cameron, C. E., Brock, L. L., Murrah, W. M., Bell, L. H., Worzalla, S. L., Grissmer, D., & Morrison, F. J. (2012). Fine motor skills and executive function both contribute to kindergarten achievement. *Child Development, 83*(4), 1229–1244. https://doi.org/10.1111/j.1467-8624.2012.01768.x

Cameron, C. E., Brock, L. L., Hatfield, B. E., Cottone, E. A., Rubinstein, E., LoCasale-Crouch, J., & Grissmer, D. W. (2015). Visuomotor integration and inhibitory control compensate for each other in school readiness. *Developmental Psychology, 51*, 1529–1543. https://doi.org/10.1037/a0039740

Cameron, C. E., Cottone, E. A., Murrah, W. M., & Grissmer, D. W. (2016). How are motor skills linked to children's school performance and academic achievement? *Child Development Perspectives, 10*(2), 93–98. https://doi.org/10.1111/cdep.12168

Carlson, A. G., Rowe, E., & Curby, T. W. (2013). Disentangling fine motor skills' relations to academic achievement: The relative contributions of visual-spatial integration and visual-motor coordination. *The Journal of Genetic Psychology, 174*(5), 514–533. https://doi.org/10.1080/00221325.2012.717122

Cartwright, K. B. (2012). Insights from cognitive neuroscience: The importance of executive function for early reading development and education. *Early Education & Development, 23*(1), 24–36. https://doi.org/10.1080/10409289.2011.615025

Chang, M., & Gu, X. (2018). The role of executive function in linking fundamental motor skills and reading proficiency in socioeconomically disadvantaged kindergarteners. *Learning and Individual Differences, 61*, 250–255. https://doi.org/10.1016/j.lindif.2018.01.002

Chung, K. K. H., Lam, C. B., & Cheung, K. C. (2018). Visuomotor integration and executive functioning are uniquely linked to Chinese word reading and writing in kindergarten children. *Reading and Writing, 31*(1), 155–171. https://doi.org/10.1007/s11145-017-9779-4

Conners, F. A. (2009). Attentional control and the simple view of reading. *Reading and Writing: An Interdisciplinary Journal, 22*, 591–613. https://doi.org/10.1007/s11145-008-9126-x

Connor, C. M., Day, S. L., Phillips, B., Sparapani, N., Ingebrand, S. W., McLean, L., Barrus, A., & Kaschak, M. P. (2016). Reciprocal effects of self-regulation, semantic knowledge, and reading comprehension in early elementary school. *Child Development, 87*(6), 1813–1824. https://doi.org/10.1111/cdev.12570

Cunningham, A. E., & Stanovich, K. E. (1991). Tracking the unique effects of print exposure in children: Associations with vocabulary, general knowledge, and spelling. *Journal of Educational Psychology, 83*(2), 264–274. https://doi.org/10.1037/0022-0663.83.2.264

Dellatolas, G., De Agostini, M., Curt, F., Kremin, H., Letierce, A., Maccario, J., & Lellouch, J. (2003). Manual skill, hand skill asymmetry, and cognitive performances in young children. *Laterality: Asymmetries of Body, Brain and Cognition, 8*(4), 317–338. https://doi.org/10.1080/13576500342000121

Diamond, A. (2010). The evidence base for improving school outcomes by addressing the whole child and by addressing skills and attitudes, not just content. *Early Education and Development, 21*, 780–793. https://doi.org/10.1080/10409289.2010.514522

Diamond, A. (2013). Executive functions. *Annual Review of Psychology, 64*, 135. https://doi.org/10.1146/annurev-psych-113011-143750

Diamond, A., Barnett, W. S., Thomas, J., & Munro, S. (2007). Preschool program improves cognitive control. *Science (new York, NY), 318*(5855), 1387. https://doi.org/10.1126/science.1151148
Diamond, A., & Lee, K. (2011). Interventions shown to aid executive function development in children 4 to 12 years old. *Science, 333*(6045), 959–964. https://doi.org/10.1126/science.1204529
Donnelly, J. E., Hillman, C. H., Castelli, D., Etnier, J. L., Lee, S., Tomporowski, P., & Szabo-Reed, A. N. (2016). Physical activity, fitness, cognitive function, and academic achievement in children: A systematic review. *Medicine & Science in Sports & Exercise, 48*(6), 1197–1222. https://doi.org/10.1249/MSS.0000000000000901
Donnelly, J. E., & Lambourne, K. (2011). Classroom-based physical activity, cognition, and academic achievement. *Preventive Medicine, 52*, S36–S42. https://doi.org/10.1016/j.ypmed.2011.01.021
Doyen, A. L., Lambert, E., Dumas, F., & Carlier, M. (2017). Manual performance as predictor of literacy acquisition: A study from kindergarten to grade 1. *Cognitive Development, 43*, 80–90. https://doi.org/10.1016/j.cogdev.2017.02.011
Fuhs, M. W., Nesbitt, K. T., Farran, D. C., & Dong, N. (2014). Longitudinal associations between executive functioning and academic skills across content areas. *Developmental Psychology, 50*(6), 1698. https://doi.org/10.1037/a0036633
Grissmer, D., Grimm, K. J., Aiyer, S. M., Murrah, W. M., & Steele, J. S. (2010). Fine motor skills and early comprehension of the world: Two new school readiness indicators. *Developmental Psychology, 46*, 1008–1017. https://doi.org/10.1037/a0020104
Hayes, J. R. (1996). A new model of cognition and affect in writing. In C. M. Levy & S. Ransdell (Eds.), *The science of writing* (pp. 1–30). Hillsdale, NJ: Lawrence Erlbaum.
Hooper, S. R., Costa, L. J., McBee, M., Anderson, K. L., Yerby, D. C., Knuth, S. B., & Childress, A. (2011). Concurrent and longitudinal neuropsychological contributors to written language expression in first and second grade students. *Reading and Writing, 24*(2), 221–252. https://doi.org/10.1007/s11145-010-9263-x
Hooper, S. R., Swartz, C. W., Wakely, M. B., de Kruif, R. E., & Montgomery, J. W. (2002). Executive functions in elementary school children with and without problems in written expression. *Journal of Learning Disabilities, 35*(1), 57–68. https://doi.org/10.1177/002221940203500105
Kaufman, A. S., & Kaufman, N. L. (2013). Kaufman assessment battery for children. In *Encyclopedia of special education: A reference for the education of children, adolescents, and adults with disabilities and other exceptional individuals*.
Kent, S., Wanzek, J., Petscher, Y., Al Otaiba, S., & Kim, Y. S. (2014). Writing fluency and quality in kindergarten and first grade: The role of attention, reading, transcription, and oral language. *Reading and Writing, 27*(7), 1163–1188. https://doi.org/10.1007/s11145-013-9480-1
Khateb, A., Khateb-Abdelgani, M., Taha, H. Y., & Ibrahim, R. (2014). The impact of orthographic connectivity on visual word recognition in Arabic: A cross-sectional study. *Reading and Writing, 27*(8), 1413–1436. https://doi.org/10.1007/s11145-014-9499-y
Khateb, A., Taha, H. Y., Elias, I., & Ibrahim, R. (2013). The effect of the internal orthographic connectivity of written Arabic words on the process of the visual recognition: A comparison between skilled and dyslexic readers. *Writing Systems Research, 5*(2), 214–233. https://doi.org/10.1080/17586801.2013.834244
Khng, K. H., & Ng, E. L. (2021). Fine motor and executive functioning skills predict maths and spelling skills at the start of kindergarten: A compensatory account. *Journal for the Study of Education and Development, 44*(3), 675–718. https://doi.org/10.1080/02103702.2021.1897232
Khoury-Metanis, A., & Khateb, A. (2022). Exploring the writing-reading connection among Arabic-speaking kindergarten children: the role of fine motor skills and orthographic knowledge. *Reading and Writing, 35*(7), 1525–1547. https://doi.org/10.1007/s11145-021-10235-5
Kim, Y. S., Al Otaiba, S., Sidler, J. F., & Gruelich, L. (2013). Language, literacy, attentional behaviors, and instructional quality predictors of written composition for first graders. *Early Childhood Research Quarterly, 28*(3), 461–469. https://doi.org/10.1016/j.ecresq.2013.01.001
Lam, S.S.-Y., & McBride, C. (2018). Learning to write: The role of handwriting for Chinese spelling in kindergarten children. *Journal of Educational Psychology, 110*(7), 917–930. https://doi.org/10.1037/edu0000253
Larson-Hall, J. (2015). *A guide to doing statistics in second language research using SPSS and R*. Routledge.
Lê, M., Quémart, P., Potocki, A., Gimenes, M., Chesnet, D., & Lambert, E. (2021). Modeling the influence of motor skills on literacy in third grade: Contributions of executive functions and handwriting. *PLoS ONE, 16*(11), e0259016. https://doi.org/10.1371/journal.pone.0259016

Levin, I., Saiegh-Haddad, E., Hende, N., & Ziv, M. (2008). Early literacy in Arabic: An intervention study among Israeli Palestinian kindergartners. *Applied Psycholinguistics, 29*(3), 413–436. https://doi.org/10.1017/S0142716408080193

Libertus, K., & Hauf, P. (2017). Motor skills and their foundational role for perceptual, social, and cognitive development. *Frontiers in Psychology, 8*, 301. https://doi.org/10.3389/fpsyg.2017.00301

Lockhart, G., MacKinnon, D. P., & Ohlrich, V. (2011). Mediation analysis in psychosomatic medicine research. *Psychosomatic Medicine, 73*(1), 29. https://doi.org/10.1097/PSY.0b013e318200a54b

Longcamp, M., Zerbato-Poudou, M. T., & Velay, J. L. (2005). The influence of writing practice on letter recognition in preschool children: A comparison between handwriting and typing. *Acta Psychologica, 119*(1), 67–79. https://doi.org/10.1016/j.actpsy.2004.10.019

Lopes, L., Santos, R., Pereira, B., & Lopes, V. P. (2013). Associations between gross motor coordination and academic achievement in elementary school children. *Human Movement Science, 32*(1), 9–20. https://doi.org/10.1016/j.humov.2012.05.005

Luo, Z., Jose, P. E., Huntsinger, C. S., & Pigott, T. D. (2007). Fine motor skills and mathematics achievement in East Asian American and European American kindergartners and first graders. *British Journal of Developmental Psychology, 25*, 595–614. https://doi.org/10.1348/026151007X185329

Maas, C. J., & Hox, J. J. (2005). Sufficient sample sizes for multilevel modeling. *Methodology, 1*(3), 86–92. https://doi.org/10.1027/1614-2241.1.3.86

Markus, K. A. (2012). Principles and practice of structural equation modeling by Rex B. *Kline*. https://doi.org/10.1080/10705511.2012.687667

Marr, D., Windsor, M. M., & Cermak, S. (2001). Handwriting readiness: Locatives and visuomotor skills in the kindergarten year. *Early Childhood Research and Practice, 3*(1), 1–17. https://eric.ed.gov/?id=ED452998

Matthews, J. S., Ponitz, C. C., & Morrison, F. J. (2009). Early gender differences in self-regulation and academic achievement. *Journal of Educational Psychology, 101*(3), 689. https://doi.org/10.1037/a0014240

McCutchen, D. (2011). From novice to expert: Language and memory processes in the development of writing skill. *Journal of Writing Research, 3*(1), 51–68. https://doi.org/10.17239/jowr-2011.03.01.3

McBride-Chang, C., Chung, K. K., & Tong, X. (2011). Copying skills in relation to word reading and writing in Chinese children with and without dyslexia. *Journal of Experimental Child Psychology, 110*(3), 422–433. https://doi.org/10.1016/j.jecp.2011.04.014

McClelland, M. M., & Cameron, C. E. (2012). Self-regulation in early childhood: Improving conceptual clarity and developing ecologically valid measures. *Child Development Perspectives, 6*(2), 136–142. https://doi.org/10.1111/j.1750-8606.2011.00191.x

McClelland, M. M., & Cameron, C. E. (2019). Developing together: The role of executive function and motor skills in children's early academic lives. *Early Childhood Research Quarterly, 46*, 142–151. https://doi.org/10.1016/j.ecresq.2018.03.014

McClelland, M. M., Geldhof, J., Cameron, C. E., & Wanless, S. B. (2015). Development and self-regulation. In W. F. Overton & P. C. M. Molenaar (Eds.), *Handbook of child psychology and developmental science* (7th ed., Vol. 1, pp. 523–565). Wiley.

Michel, E., Molitor, S., & Schneider, W. (2019). Motor coordination and executive functions as early predictors of reading and spelling acquisition. *Developmental Neuropsychology, 44*(3), 282–295. https://doi.org/10.1080/87565641.2019.1584802

Mohamed, M. B. H., & O'Brien, B. A. (2022). Defining the relationship between fine motor visual-spatial integration and reading and spelling. *Reading and Writing, 35*, 877–898. https://doi.org/10.1007/s11145-021-10165-2

National Early Literacy Panel. (2008). *Developing early literacy: Report ofthe National Early Literacy Panel*. Washington, DC: National Institutefor Literacy. Available at http://www.nifl.gov/earlychildhood/NELP/NELPreport.html

Ponitz, C. C., McClelland, M. M., Jewkes, A. M., Connor, C. M., Farris, C. L., & Morrison, F. J. (2008). Touch your toes! Developing a directmeasure of behavioral regulation in early childhood. *Early Childhood Research Quarterly, 23*, 141–158. https://doi.org/10.1016/j.ecresq.2007.01.004

Ponitz, C. C., McClelland, M. M., Matthews, J. S., & Morrison, F. J. (2009). A structured observation of behavioral self-regulation and its contribution to kindergarten outcomes. *Developmental Psychology, 45*(3), 605.

Preacher, K. J., & Hayes, A. F. (2008). Asymptotic and resampling strategies for assessing and comparing indirect effects in multiple mediator models. *Behavior Research Methods, 40*(3), 879–891.

Raven, J. (2003). Raven progressive matrices. In R. S. McCallum (Ed.), *Handbook of nonverbal assessment* (pp. 223–237). Springer.

Rigoli, D., Piek, J. P., Kane, R., & Oosterlaan, J. (2012). An examination of the relationship between motor coordination and executive functions in adolescents. *Developmental Medicine & Child Neurology, 54*(11), 1025–1031. https://doi.org/10.1111/j.1469-8749.2012.04403.x

Roebers, C. M., Röthlisberger, M., Neuenschwander, R., Cimeli, P., Michel, E., & Jäger, K. (2014). The relation between cognitive and motor performance and their relevance for children's transition to school: A latent variable approach. *Human Movement Science, 33*, 284–297. https://doi.org/10.1016/j.humov.2013.08.011

Savage, R. (2004). Motor skills, automaticity and developmental dyslexia: A review of the research literature. *Reading and Writing, 17*(3), 301–324. https://doi.org/10.1023/B:READ.0000017688.67137.80

Schmidt, M., Egger, F., Benzing, V., Jäger, K., Conzelmann, A., Roebers, C. M., & Pesce, C. (2017). Disentangling the relationship between children's motor ability, executive function and academic achievement. *PLoS ONE, 12*(8), e0182845. https://doi.org/10.1371/journal.pone.0182845

Slot, P. L., & von Suchodoletz, A. (2018). Bidirectionality in preschool children's executive functions and language skills: Is one developing skill the better predictor of the other? *Early Childhood Research Quarterly, 42*, 205–214. https://doi.org/10.1016/j.ecresq.2017.10.005

Son, S.-H., & Meisels, S. J. (2006). The relationship of young children's motor skills to later reading and math achievement. *Merrill-Palmer Quarterly, 52*, 755–778. https://doi.org/10.1353/mpq.2006.0033

Stipek, D., & Valentino, R. A. (2015). Early childhood memory and attention as predictors of academic growth trajectories. *Journal of Educational Psychology, 107*(3), 771. https://doi.org/10.1037/edu0000004

Suggate, S., Pufke, E., & Stoeger, H. (2018). Do fine motor skills contribute to early reading development? *Journal of Research in Reading, 41*(1), 1–19. https://doi.org/10.1111/1467-9817.12081

Suggate, S., Pufke, E., & Stoeger, H. (2019). Children's fine motor skills in kindergarten predict reading in grade 1. *Early Childhood Research Quarterly, 47*, 248–258. https://doi.org/10.1016/j.ecresq.2018.12.015

Taha, H., & Khateb, A. (2013). Resolving the orthographic ambiguity during visual word recognition in Arabic: An event-related potential investigation. *Frontiers in Human Neuroscience, 7*, 821. https://doi.org/10.3389/fnhum.2013.00821

Van der Niet, A. G., Hartman, E., Smith, J., & Visscher, C. (2014). Modeling relationships between physical fitness, executive functioning, and academic achievement in primary school children. *Psychology of Sport and Exercise, 15*(4), 319–325. https://doi.org/10.1016/j.psychsport.2014.02.010

Van Galen, G. (1991). Handwriting: Issues for a psychomotor theory. *Human Movement Science, 10*(2–3), 165–191. https://doi.org/10.1016/0167-9457(91)90003-G

Vinter, A., & Chartrel, E. (2010). Effects of different types of learning on handwriting movements in young children. *Learning and Instruction, 20*(6), 476–486. https://doi.org/10.1016/j.learninstruc.2009.07.001

Wamain, Y., Tallet, J., Zanone, P. G., & Longcamp, M. (2012). Brain responses to handwritten and printed letters differentially depend on the activation state of the primary motor ccortex. *NeuroImage, 63*(3), 1766–1773. https://doi.org/10.1016/j.neuroimage.2012.07.020

Wang, Y., McBride-Chang, C., & Chan, S. F. (2014). Correlates of Chinese kindergarteners' word reading and writing: The unique role of copying skills? *Reading and Writing, 27*(7), 1281–1302. https://doi.org/10.1007/s11145-013-9486-8

Wang, Y., Yin, L., & McBride, C. (2015). Unique predictors of early reading and writing: A 1-year longitudinal study of Chinese kindergarteners. *Early Childhood Research Quarterly, 32*, 51–59. https://doi.org/10.1016/j.ecresq.2015.02.004

Wassenberg, R., Feron, F. J., Kessels, A. G., Hendriksen, J. G., Kalff, A. C., Kroes, M., Hurks, P. P. M., Beeren, M., Jolles, J., & Vles, J. S. (2005). Relation between cognitive and motor performance in 5-to 6-year-old children: Results from a large-scale cross-sectional study. *Child development, 76*(5), 1092–1103. https://doi.org/10.1111/j.1467-8624.2005.00899.x

Weil, M. J., & Cunningham Amundson, S. J. (1994). Relationship between visuomotor and handwriting skills of children in kindergarten. *The American journal of occupational therapy, 48*(11), 982–988. https://doi.org/10.5014/ajot.48.11.982

Whitehurst, G. J., & Lonigan, C. L. (2001). Emergent literacy: Development from prereaders to readers. In S. B. Newman & D. K. Dickinson (Eds.), *Handbook of early literacy research* (pp. 11–29). Guilford.

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