OVERLAPPING COGNITIVE PREDICTORS for MATH and WRITING ACHIEVEMENT

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A thesis submitted to the Department of Psychology,
College of Liberal Arts and Social Sciences
in partial fulfillment of the requirements for the degree of

MASTER OF ARTS

in Clinical Psychology

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University of Houston
December 2023

ABSTRACT

Math and writing both rely on a range of specific cognitive skills, including working memory, phonological processing, and fine motor skills. However, the systemic relations of these cognitive predictors across math and writing outcomes and with one another are not well understood. The current study utilizes a path analytic framework to examine potential mechanisms for how these cognitive skills relate to math and writing, including timed versus untimed outcomes. It does so in a large sample of third through fifth graders (n = 677), many of whom are struggling academically. Hypotheses were tested using a path analytic framework which involved the comparison of individual paths and mediational effects. While all predictors and outcomes were significantly related at the zero-order level, only partial support was found for hypotheses about the predictors' differential relationships with achievement. Contrary to expectations, WM did not exhibit a stronger effect on math compared to writing, and for timed outcomes, WM had a stronger effect on writing than math. PA was a stronger predictor for writing compared to math for both timed and untimed outcomes and a stronger predictor for untimed math compared to timed math. Results also revealed that WM fully mediated the relationship between FMS and untimed writing, but only partially mediated the relationship between FMS and other academic outcomes. PA partially mediated the relationship between WM and writing and math skills, both timed and untimed. Results of the current study shed light on transdiagnostic mechanisms for comorbid writing and math difficulties and cognitive mechanisms that drive academic achievement in separate topics. The study underscores the importance of FMS, WM, and PA in writing and math achievement and challenges previous assumptions about these cognitive mechanisms,

highlighting their varied impact on timed versus untimed assessments and specific subject areas.

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INTRODUCTION

Over the past few decades, scholars have worked to understand predictors of mathematical learning. In recent years, it has become clear that math ability is related to language development (Dowker & Nuerk, 2016; Michalczyk et al., 2013; Peng et al., 2020), working memory (WM) capacity (Friso-van den Bos et al., 2013; Peng et al., 2016), or a combination of the two (Kyttälä et al., 2014; Swanson & Beebe-Frankenberger, 2004; Viesel-Nordmeyer et al., 2022); fine motor skill (FMS) has also been implicated (Cadoret et al., 2018; Gashaj et al., 2019a, 2019b; Michel et al., 2020). In parallel, researchers have also evaluated predictors of written language, with a similar emphasis on language and WM skills (Kim et al., 2018; Kim & Graham, 2022; Kim & Park, 2019). FMS has been implicated for writing as well (Doyen et al., 2017; Lê et al., 2021; Suggate et al., 2016).

Achievement skills are often related to one another, at the level of disability in terms of comorbidity (Amland et al., 2021; Child et al., 2019; Cirino et al., 2018; Landerl & Moll, 2010; Willcutt et al., 2019), but also across the continuum in terms of correlation (Peters & Ansari, 2019; Peterson et al., 2021). Among achievement skills, reading and writing are often considered together, largely due to their underlying language concomitants (Berninger & Abbott, 2010; Kaufman et al., 2012; Kim, 2022). Math and reading relations and comorbidities are also commonly evaluated (Joyner & Wagner, 2020; Willcutt et al., 2013). However, math and writing are rarely considered together (see Alloway et al., 2005; Peterson et al., 2021, for exceptions).

While math and writing are quite different at the surface, they share several commonalities, including their potential supporting cognitive competencies. Systematically evaluating these is important for identifying how these cognitive skills work together in the service of academic ability. From a comorbidity perspective, the overlap versus separability of these cognitive predictors can uncover common sources of difficulty for both achievement outcomes. To do so, it is first necessary to understand the interrelations of these cognitive predictors themselves.

Relations Among Cognitive Domains

Phonological Awareness and Working Memory. Language is a broad and complex system that involves a variety of functions, including phonological processing (i.e., the retrieval and manipulation of sounds), vocabulary (i.e., the knowledge of word meaning), and comprehension (i.e., making sense of verbal discussion or written passages), and draws input from other cognitive processes including working memory, executive function, attention, and memory (Barre et al., 2011; Catts et al., 2006; Deldar et al., 2020; Levelt et al., 1999; Peng et al., 2020). Producing language, whether written or spoken, requires mental planning based on both internal and external contexts, encoding of semantic (i.e., meaning) and syntactic (i.e., grammar) information, and transformation of mental linguistic forms into motor processes (Deldar et al., 2020; Levelt et al., 1999). The undertaking of mental planning and manipulation, and motoric execution underlying language production and comprehension requires WM. Deficits in WM have been implicated with impaired language processing at multiple levels, such as language development and acquisition among 4-year-olds (Adams & Gathercole, 2000), inferential reasoning (i.e., integrating discourse meaning and world knowledge; (Barnes & Dennis, 2001), language comprehension (Chang, 2020), information processing (Chapman et al., 2006), and verbal learning (Vanderploeg et al., 1994).

Understanding the relationship of language with WM and their effects on academic outcomes requires consideration of the particular language skill being examined.

Phonological awareness (PA), for example, is one aspect of phonological processing and describes an individual's understanding of the phonological (i.e., sound) structure of words (Anthony & Francis, 2005). PA is uniquely associated with WM (r = .30, Peng et al., 2022), and both PA and WM are robust predictors of reading, writing, and math achievement for young children at time of school entry (Alloway et al., 2005). Further, there is evidence that the effects of PA and WM on math specifically are stable through age eleven (Swanson, 2004; Swanson & Beebe-Frankenberger, 2004). Additionally, although WM is implicated in multiple language-related processes, research on individuals with motor speech disorders have demonstrated similar relationships between memory span tasks and phonological processing to those without motor speech disorders (Adams & Gathercole, 2000; Baddeley & Wilson, 1985; Waters et al., 1992). Therefore, the role of WM in language may be uniquely related to internal planning or rehearsal of phonological information. The ability to dissect and manipulate phonological information, a function of PA, depends on adequate WM capacity (Alloway et al., 2005; Engel de Abreu et al., 2011; Martin, 2021; Michalczyk et al., 2013), and thus an individual's PA may be predicted by their WM capacity.

Working Memory and Fine Motor Skills. Motor skills are domain general skills implicated in academic achievement (e.g., Lopes et al., 2013; Westendorp et al., 2011; Wassenberg et al., 2005). Similar to language, researchers have sought to understand the connection between motor skills and WM to better understand academic achievement (Rigoli et al., 2012; Wassenberg et al., 2005). One such study examined the connection between motor and WM development in predicting academic achievement and found that motor proficiency influences academic achievement through the effects of WM (Wassenberg et al., 2005). However, the mechanisms underlying the connection between WM and motor skills is unclear.

The theoretical concept of reciprocity states that skill development in one area influences another (and vice versa; Fry & Hale, 1996). More recently, Masten and Cicchetti (2010) applied a developmental cascade model to motor development in reciprocity to other domains of cognition, and additional work also demonstrates the link between developing cognitive skills with an individual's motoric interactions with their environment (Barsalou, 1999; Gibbs, 2005; Smith & Gasser, 2005). From the perspective of embodiment theory, sensorimotor experiences in early development may influence executive function, of which WM is a key element; the ability to plan and control motor actions is related to later executive function performance (Diamond, 2013; Gottwald et al., 2016). As an individual practices a motor task, it becomes automated and thus fewer cognitive attentional resources are focused on planning and executing motor tasks (Floyer-Lea & Matthews, 2004; Gandotra et al., 2021). Thus, WM processes are drawn from early experiences of motoric functioning (Marvel et al., 2019).

The connection between WM and motor functioning is apparent in multiple empirical contexts. For instance, there is a high comorbidity between WM and motor difficulties for children with developmental disabilities (Pennington & Ozonoff, 1996; Piek et al., 2007). In typically developing populations, the effect of early motor development on later WM capacity can be found in later adulthood as well. Ridler and colleagues (2006) found that the age of onset for walking and standing correlated with their WM capacity as adults. However, the directionality of the relationship between motor functioning and WM is unclear and may vary with context and group in question. For example, while Niederer and colleagues (2011) found that motor skills predicted WM and not vice versa for typically developing preschool children, Rigoli and colleagues (2013) found a reciprocal relationship between motor skills and WM for preschoolers with movement difficulty.

Empirical research has established a link between FMS and WM capacity for typically developing school-aged children. A meta-analysis investigating the relationship between a range of motor skills and executive functioning among 3- to 12-year-old children (mean age = 6 years) detected small but significant effects between WM and different areas of motor proficiency, including balance (r = .18), locomotor skills (r = .19), and FMS (i.e., manual dexterity) (r = .21) (Gandotra et al., 2021). A second study that found that preschoolers who participate in FMS and gross motor skill-based interventions had greater improvements in both numeracy skills and executive function skills, including WM, at a later time point compared to children who did not participate (r = .30, Hudson et al., 2021). To our knowledge, no research has examined the relationship between FMS and WM in older, school-aged children, despite evidence that both WM and FMS continue to develop throughout adolescence (Diamond, 2000).

Phonological Awareness and Fine Motor Skills. PA and FMS demonstrate robust contributions to academic outcomes, especially writing and math (Carlson et al., 2013). However, the nature of the relationship between motor and language skills more generally has long been debated. In contrast to Piaget's (1954) hypothesis that language develops in the context of an infant's sensorimotor environment, Chomsky (1975) described language as innate and universal, isolated from motor and cognitive development. In infancy, the acquisition of motor skills is thought to enable an infant to explore their environment to a greater degree, allowing them to interact with people which facilitates further language development (Iverson, 2010). However, more work must be done to understand the relationship between language and motor skills contributing to academic success (Gonzalez et al., 2019).

There is some support for a connection between language and motor skill development throughout infancy and childhood (Choi et al., 2018; Hernandez & Caçola, 2015; Karasik et al., 2014; Leonard et al., 2015; Libertus & Violi, 2016; Walle & Campos, 2014). Smith and Gasser (2005) describe how the physical and social environment of an infant lays a foundation for subsequent learning ability. The researchers argue that language learning, which is shaped by an infant’s sensorimotor environment, promotes subsequent learning ability in other areas because learning a language confers direct access to knowledge from others. Additionally, the process of language learning primes infants to develop further skills, including categorization and symbolic reasoning. Under this theoretical framework, it is possible that promoting language and motor skills throughout development may improve academic abilities of children and adolescents.

Most research examining the relationship between language and motor skills in childhood comes from research on learning and/or developmental disabilities, and little work has been done to examine this association in typically developing populations (Goffman, 2015). For instance, researchers have theorized that the highly documented co-occurrence of motor difficulties with specific language impairment is due to abnormalities in brain structures of the procedural memory system, which is involved in both linguistic processing and motor learning and performance (Ullman & Pierpont, 2005). From this procedural deficit hypothesis perspective, neither motor nor language impairments come before the other and instead arise from the same neural underpinning. However, more work must be done to determine if motor skills or language-based skills precede one another in the context of academic outcomes for typically developing children. Further, the nature of the relationship between motor and language skills in later stages of development is unclear and understudied.

Rhemtulla and Tucker-Drob (2011) examined longitudinal correlates of academic achievement, examining the effects of linguistic, motor, reading, and math ability from age 3 to 7. Both FMS and linguistic ability were correlated with reading and math achievement at every time point. However, while FMS were significantly correlated with linguistic ability at the first time point ($r = .32$), the two measures were not correlated at subsequent time points ($r = .11$). Results of this study and others (i.e., Oudgenoeg-Paz, et al., 2016) suggest that the reciprocal relationship between motor and language development may become less and less apparent beyond infancy and early childhood. Although no research to date has examined the connections specifically between PA and FMS among typically developing adolescents, it is likely that the mechanism of their interaction mirrors those of language and motor skills more generally.

Cognitive Predictors of Writing

Phonological Awareness. Language skills lay the foundation for writing. The simple view of writing states that writing ability is comprised of lower order skills, including spelling and transcription, and higher order skills, including the generation of ideas and organization of information (Juel, 1988; Juel, et al., 1986). Learning how to spell requires adequate PA (Bissex, 1980; Gentry, 1982; Henderson & Beers, 1980). Treiman (1993) hypothesized that errors in spelling reflects underdeveloped PA, which results in immature segmentation strategies, such as clustering consonants into unanalyzed units (Treiman et al., 1995). As PA improves, spelling becomes more accurate (Caravolas et al., 2001). Caravolas and colleagues (2001) examined phonological abilities and their effect on spelling skills in 153 children (mean age = 5 years, 1 month). Their results showed that phonological abilities were fundamental to spelling development, while other cognitive skills (e.g., visual and verbal memory) were not. Thus, PA may underlie early spelling development above other cognitive abilities.

As children become more accurate spellers, they can adjust their focus toward text generation and idea development in writing (Abbot & Berninger, 1993; Moats, 2005; Moats et al., 2006). Difficulty with spelling may limit a child's capacity to develop ideas and plan, which may limit written expression complexity and coherence (Graham et al.,1997). The simple view of writing describes how writing ability is comprised of lower order skills, including spelling and transcription, and higher order skills, including the generation and organization of information (Juel, 1988; Juel, et al., 1986). There is evidence that PA lays the foundation for spelling and, subsequently more sophisticated writing skills (Diamond et al., 2008). For instance, transcription, which incorporates spelling and handwriting fluency, is derived from an individual's orthographical, semantic, and phonological knowledge (Berninger et al., 1992; Kim et al., 2011). As writing becomes more complex and relies on greater planning, organization, and retrieval of ideas and information, other cognitive skills, such as WM, may play a larger role (Berninger, 1999).

Working Memory. Complex tasks such as writing rely on WM (Berninger, 1999). WM allows individuals to activate and coordinate writing processes through memory and attentional processes (Olive, 2012). Early writing is constrained by limited WM and, thus, limited ability to transcribe and generate text (Berninger, 1999). As children become more efficient in fine motor demands of writing, WM processes emerge allowing for greater planning and revising (Berninger, 1999). Deficits in WM may limit a child's capacity to plan and revise writing (McCutchen, 1996). The ability to generate ideas, organize them, and translate ideas into written expression is drawn from both higher order cognitive ability and language skills; both of which are supported by WM (Kim, 2020). Both spelling ability and writing quality has been related to WM at $r \sim .30$ (Kim, 2020).

Written expression is complex. First, generating ideas involves a planning process, in which ideas are drawn from long-term memory (Olive, 2004). This planning process requires the ability to develop and organize composition plans (Hayes & Grawdol-Nash, 1996). Second, these ideas become translated into a verbal message, which requires grammatical and lexical knowledge in addition to understanding of the properties of words (Bock & Levelt, 1994). Third, a writer must evaluate the conceptual and linguistic quality of their text to ensure it matches their mental representation of their ideas. Finally, execution of writing requires a series of motor planning to produce a graphic representation of their text. The direct and indirect effects model of writing (Kim & Park, 2019) describes how each step involved in written composition are predicted by domain-general cognitive skills, especially WM. Thus, writing requires the integration of various cognitive processes in addition to the retrieval and organization of information, all of which must be managed by and are limited to an individual's WM capacity (Olive, 2004).

Fine Motor Skills. FMS is an indicator for school readiness (Grissmer et al., 2010). Greater FMS in kindergarten has been found to predict literacy skills, including reading and spelling, in higher grades (Dinehart & Manfra, 2013; Doyen et al., 2017; Michel et al., 2020; Suggate et al., 2018). Even in older children, motor skills are linked with literacy (Berninger et al., 1992; Chandler et al., 2021). Berninger and colleagues (1992) found that when controlling for other factors, manual dexterity and figure copying predicts spelling and text production for first through third graders. In grades three through five, figure copying has been found to explain 6% of the variance in higher level literacy measures, including text comprehension and production assessment (Sulik et al., 2018). However, the mechanisms explaining the role of FMS in writing skills has been debated (Lê et al., 2021).

Theories on the connection between FMS and writing posit an indirect effect of other factors (Lê et al., 2021). Specifically, handwriting and higher-order cognitive skills are thought to mediate the relationship between FMS and writing. FMS and handwriting are distinct, but both involve the manipulation of objects with small finger movements. FMS refers to the general ability of an individual to use small movements to manipulate objects (Suggate et al., 2018). Handwriting refers to the specific ability to trace letters and relies on multiple components, including visual, motor, and haptic input (Graham & Weintraub, 1996). In handwriting, the motor system enables writers to create graphic forms by controlling timing and force coordinated between the arm, hand, and fingers (Tseng & Chow, 2000). Handwriting does not become automatic until around ages 9 or 10 (Afonso et al., 2020; Palmis et al., 2017), and automation of handwriting allows for greater availability of cognitive resources related to linguistic and higher-level cognitive processes (Berninger & Winn, 2006; Suggate et al., 2016). The degree to which a child can automatize the handwriting process influences the level of WM capacity available to address higher-order cognitive processes related written expression (Medwell & Wray, 2007). Children who must expend greater cognitive effort on the fine motor movements required to hold a pencil may not be able to progress through the task as quickly and struggle more with decoding and comprehending language and in connecting letters with sounds (Cameron et al., 2012). Empirical evidence for the connection between FMS and word spelling show a significant and moderate correlation ($r = .30$, Doyen et al., 2017).

Cognitive Predictors of Math

Phonological Awareness. A meta-analysis of the relationship between PA and mathematics ability revealed a moderate and significant correlation ($r = .27 \sim .41$), indicating that PA may act as a pre-requisite for mathematics development by enabling children to depict basic math concepts (Yang et al., 2021). Krajewski and Schneider (2009) theorized that math competency is acquired through three developmental levels. In the first level, the ability to differentiate between indiscrete quantities is isolated from the ability to discriminate quantities verbally. The acquisition of language and verbal abilities (e.g., PA) enables children to recite number words, but children do not connect the number words with their understanding of basic numerical skills until later stages.

Empirical evidence for this theory indicates that PA facilitates basic mathematic competencies (i.e., learning number words), but PA becomes less relevant for higher-order competencies (Krajewski & Schneider, 2009). Thus, deficits in PA may predict deficits in mathematic achievement by thwarting an individual's ability to connect math words with discrete quantities, making PA a necessary skill for early mathematic ability but not sufficient as a single predictor for long-term mathematic understanding. This isolated number words hypothesis contrasts with the weak phonological representations hypothesis (Simmons & Singleton, 2008), which asserts that PA deficits are only related to aspects of mathematic processing that directly involves verbal codes (e.g., word problems).

Michalczyk and colleagues (2013) found that PA accounted for nearly 50% of the variance of basic number competencies associated with isolated number words hypothesis's first level (i.e., recitation of number word sequence), but was only indirectly associated with the second level (i.e., children's ability to match quantities with corresponding number word), through their ability to recite number word sequences. These findings provide evidence that PA is directly involved in early mathematic acquisition, and that the relation between PA and mathematic development is not merely a function of math problems relying on verbal cues. Thus, the association between PA and mathematic achievement may be a function of the nature of basic math competency development.

Working Memory. WM has a moderate relationship with mathematics skills (r = .35), and word-problem solving and whole-number calculations have been shown to have the strongest relationship with WM compared to other math problem types (Peng et al., 2016). Mathematics difficulties have also been associated with WM deficits (Allen et al., 2020a, 2020b; David, 2012; Eckrich et al., 2019; Nelwan et al., 2022). Mathematics depends on WM as it involves simultaneous information processing and storage, especially for more complex problems such as multidigit calculations and word problems (Raghubar et al., 2010; Swanson & Jerman, 2006). Extant research suggests that WM remains a strong predictor for mathematics achievement over time (Toll et al., 2011). Further, domain-general cognitive mechanisms, including WM, have been found to predict mathematical achievement independently from basic math-specific abilities, such as counting sequence knowledge and digit comparison (Fuchs et al., 2010a; Fuchs et al., 2010b).

However, the specific relationship between mathematical skill development and WM is complex and depends on learning contexts, such as age, language of instruction, math ability level, the type of mathematical skill, and whether the skill is being newly learned, consolidated, or mastered (Raghubar et al., 2010). In addition, other cognitive skills influence the strength of the relationship between WM and math, as indicated by a wide range of variance of mathematics performances explained by WM, ranging from negligible (i.e., R^2 ranging from 0 to .02, Meyer et al., 2010) to robust (i.e., R^2 ranging from .50 to .70, Andersson & Lyxell, 2007) depending on whether examining visuospatial or phonological factors (Peng et al., 2016). Thus, whether WM is a causal predictor for mathematical development has been debated (Geary, et al., 2007; Raghubar et al., 2010).

Researchers have theorized that mathematical information, including numbers and arithmetic facts, are stored in WM as linguistic codes, rather than within a system separate from phonological knowledge (see De Smedt et al., 2010; Hecht et al., 2001; Kleemans et al., 2012; Kleemans et al., 2014; Simmons et al., 2008). Kleemans and colleagues (2014) found that although WM significantly predicted addition and subtraction skills, language-based skills (i.e., PA and grammatical ability) were also significant predictors for both native Dutch speakers and children learning Dutch as a second language. Additionally, Swanson and colleagues (2018) found that the relationship between WM and mathematic ability is influenced by language proficiency. Therefore, to understand the connection between WM and math, language skills, including PA, must be considered. WM ability may enable children to organize, store, and process mathematical knowledge, but the effects on actual math achievement may be altered depending on the child's phonological ability.

Fine Motor Skill. FMS is a known predictor for mathematics achievement throughout childhood (Gashaj et al., 2019b). The relationship between FMS and mathematic ability has been found to range from $r = .28$ (Michel et al., 2020) to $r \sim .15$ - $.42$ (Gashaj et al., 2019b) depending on the type of mathematic skill being tested and the age of the sample. Interacting motorically with one's physical environment throughout early development fosters the understanding of space, shape, and numeracy (Kim et al., 2018; Newcombe & Frick, 2010). Early numerical understanding stems from finger-counting (Andres et al., 2007; Penner-Wilger et al., 2007), and number processing shares cortical networks with fingers (Ardila et al., 2000). Further, FMS contributes to the finger-based representation of numerosity (Andres et al., 2007; Penner-Wilger et al., 2007) and remains correlated with mathematics skills through age 18 (Carlson et al., 2013; Grissmer et al., 2010; Roebers et al., 2014).

The overlap of functional networks involved in FMS and higher order abstract and cognitive processes may be responsible for the reciprocal relationship between FMS and mathematics skills in children (Kim et al., 2018). For example, visuomotor integration, a critical skill for mathematics learning, relies on fine motor coordination and its integration with attention (Carlson et al., 2013). Visuomotor integration is a skill involving visual-spatial processes, including the ability to see objects as a set of parts, to shift attention between those parts, and to create a mental image of the object (Carlson et al., 2013). To solve a math problem, an individual must be able to view a mathematic problem (i.e., the object), discriminate between the individual symbols within the problem (i.e., the parts of the object), and form mental representations of numerical information (Gunderson, et al., 2012). Thus, FMS may underlie higher order cognitive skill that are foundational for mathematic understanding.

There is evidence that FMS is indirectly related to mathematic achievement through WM in studies examining children between the ages of 4 and 8 (Gashaj et al., 2019a, 2019b;

Michel et al., 2020). FMS is thought to influence mathematic acquisition due to the role of finger representations in early numerical processing, which is evidenced on a behavioral and neural level (Andres et al., 2007). As a child's WM capacity increases, the need for FMS decreases in favor of WM (Noël et al., 2004). Empirical evidence indicates that beyond early childhood and infancy, the effect of motor skills on academic outcomes may be explained by the effects of higher-level cognitive functions, namely WM. For example, Cadoret and colleagues (2018) found that WM mediated the relationship between motor proficiency and academic outcomes (i.e., math and reading) for 7-year-old children. Taken together, it may be that motor development lays the foundation for early math acquisition, and, as WM improves, quantitative information that was represented externally becomes stored in WM.

Summary

When children first begin to write, FMS is necessary to develop handwriting skills and accurately form letters and shapes (Graham & Weintraub, 1996; Lê et al., 2021). As children age, writing becomes automatized, and the writing content demands greater WM to dissect and manipulate phonological information (Lê et al., 2021). Written expression is initiated by context-dependent planning, which must be encoded semantically (i.e., selecting words that convey intended meaning) and syntactically (i.e., within a particular language's grammatical rules). Language is then expressed externally through a motor component, controlled by FMS capacity, and each of these steps require WM (Deldar et al., 2020; Fromkin et al., 2018). Under a similar framework, Kim (2019) proposed a model of written expression, where domain-general abilities (including WM) influence language skills (including phonology), which in turn predict written composition quality (see also Kim & Park, 2019).

A similar relationship between PA and WM has been proposed for mathematic skill development (Krajewski & Schneider, 2009; Michalczyk et al., 2013). Similar to learning how to write, early numerical understanding stems from fine motor mechanisms (i.e., finger-counting, (Andres et al., 2007; Penner-Wilger et al., 2007) and then linguistic representations (Kleemans et al., 2012; Kleemans et al., 2014). As children age, numerical representations become represented as linguistic codes and are stored and manipulated in WM (Swanson et al., 2018). When first learning number words and number sequences, children rely on PA to express number words and connect those words to magnitudes (Krajewski & Schneider, 2009). However, as mathematic skills become more complex, the effects of PA are necessary, but not sufficient in enabling an individual to understand mathematics. For example, Michalczyk and colleagues (2013) found that the relationship between WM components and quantity-number competencies was fully mediated by PA.

Timed and Untimed Outcomes

As discussed above, automation of skills in question may influence achievement in writing and math. Therefore, the relative strength of the effects of predictor variables may vary depending on whether the academic measure is timed, where students rely more on automated skills, or untimed. When assessing writing skills, past research often considers untimed measures of spelling, but measures of word or letter writing fluency and untimed expressive writing have been examined as well (see Kim et al., 2011; Kim & Park, 2019). Across different aspects of writing, including spelling, writing composition, and word writing, PA has been implicated (Kim & Graham, 2022).

For WM, one study examined the effect of cognitive skills across a range of timed and untimed writing-related skills, such as spelling, handwriting fluency, and written composition among a cohort of first grader, and then re-administered some measures when the cohort entered third grade (Kim, 2020). WM was significantly but weakly to moderately correlated with all writing skills in first grade and with third grade. The researchers found that WM in grade one was directly related to writing quality and indirectly related to spelling in grade three. The relationship between WM and handwriting fluency was not assessed, however. A study by Adams and colleagues (2015) found that WM measured by a listening recall task and a digit recall task significantly predicted writing fluency for boys, but not girls (ages 5 to 8.5 years old).

The conceptual relevance of fine motor skills maps onto writing fluency tasks more directly than spelling or written expression tasks. Research has examined the effects of fine motor skills on both timed and untimed writing measures. One study examined the role of manual dexterity, measured as the average of time required to place ten pegs in a pegboard, switching between hands for six trials, on untimed real and nonword spelling and timed writing fluency (Doyen et al., 2017). Manual dexterity was significantly correlated with all writing tasks and was a significant predictor for real word spelling and writing fluency, but not nonword spelling.

Taken together, there is no extant evidence that timed versus untimed writing tasks have different relationships with phonological awareness, WM, or FMS. However, no known study to date has directly compared the effects of predictors between timed and untimed writing measures, so it is unclear whether differential prediction does or does not occur.

There is some evidence that PA exerts a more robust effect on untimed math compared to timed math. A meta-analysis on the role of PA on mathematic achievement (Yang et al., 2021) revealed that measures of both untimed (r = .30 - .37) and timed (r = .29 -

.37) math were significantly correlated with PA skills, but untimed measures were significantly more strongly related to PA than timed measures. Results from this meta-analysis suggest that PA may be a stronger predictor for untimed math compared to timed math.

There is no evidence, however, regarding the relative strength of the relationship between WM with either timed or untimed math. WM, measured by a listening recall task, was a significant predictor for timed math word problems, but not timed calculations in a study by Fuchs and colleagues (2010b). Although there is evidence that the relationship between WM and math is complex and depends on a variety of factors, including type of mathematical problem and skill under consideration (Raghubar et al., 2010), it is unclear whether math fluency differentially relies on WM in comparison to math computation. Like WM, the strength of the relationship of FMS with timed versus untimed math measures is unclear as this comparison has not been directly tested. Most studies examining the effects of FMS on math achievement have included only timed math measures (see Cadoret et al., 2018; Gashaj et al., 2019b; Michel et al., 2020).

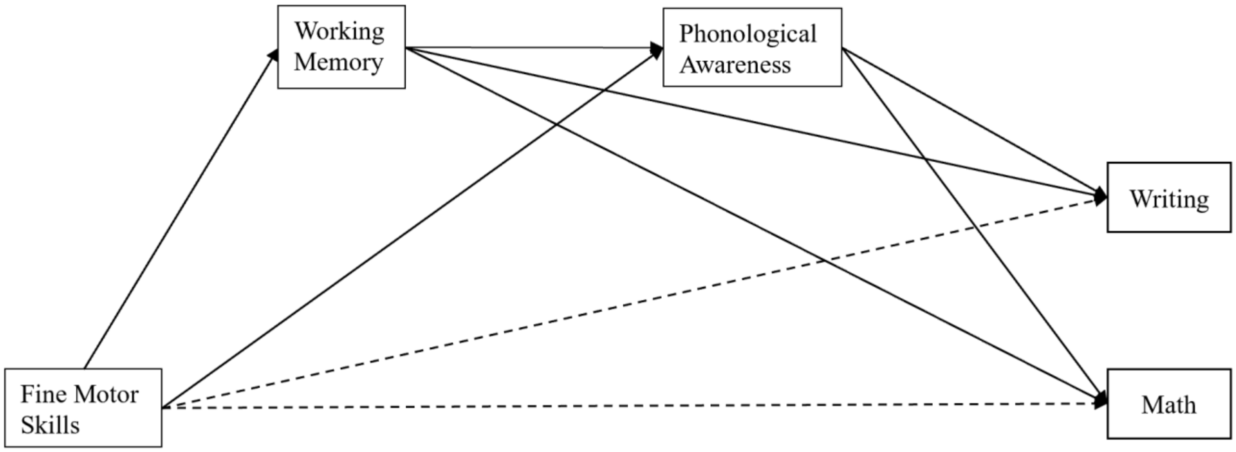
Present Study

The current study seeks to examine the overlap between writing and math skills and by extension, to better understand the relation between cognitive predictors of academic achievement. Given theoretical and empirical evidence of the overlap in cognitive predictors for writing and math achievement, we first hypothesize that, at the zero-order level, all variables (i.e., FMS, PA, WM, writing achievement, and math achievement) will relate to one another. Second, we hypothesize that the effect of the three predictors will vary based on outcome. Specifically, WM is hypothesized to have a stronger relationship with math measures than with writing measures, PA will have a stronger relationship with writing measures than with math measures. When considering just math measures, PA is hypothesized to have a stronger relationship with untimed math compared to timed math.

Third, we hypothesize that a path analysis will reveal significant direct relationships between WM and all academic outcomes, a significant direct relationship between PA and all academic outcomes, but no significant direct relationship between FMS and any academic outcome. Rather, we hypothesize that WM will fully mediate the relationship between FMS and all academic outcomes, and PA will partially mediate the relationship between WM and all academic outcomes.

We expect the above hypotheses to hold in context of covariates relevant to academic achievement, including age, gender, socioeconomic status (SES), nonverbal reasoning, special education status, and limited English proficiency status. For example, differences in FMS performance are evident depending on participant's gender (e.g., Goodway et al., 2010), and there is a well-established link between academic performance and SES (Hopson & Lee, 2011). Nonverbal reasoning was included as a covariate due to its established effects on language factors (Wilson & Bishop, 2022). Special education status is associated with weaker academic performance (Fuchs et al., 2010b) and was thus also considered. English language understanding and PA has been found to be influenced by limited English proficiency status (Zhang et al., 2020) and was thus also considered as a covariate. Finally, school district and timing of assessment were also considered.

Figure 1. Proposed Conceptual Model



METHODS

Participants

Third (*n* = 152), fourth (*n* = 380), and fifth grade students (*n* = 145) participated. The sample was divided between two schools in southwestern cities. This study was conducted in the context of larger project, which recruited 846 students; the sample used in the current study reflects participants who had data on the key measures focused on here. One component of the larger study was a 4th grade reading intervention (Vaughn, et al., 2016), which required that students struggling with reading (i.e., < 16th percentile on Gates MacGinitie Reading Test; MacGinitie, et al., 2007) be oversampled in that grade. This oversampling was taken into account through weighting, such that weighted reading performances matched the school populations as a whole. Treatment was less relevant; cognitive measures were administered prior to the intervention. The current dataset has been used for other studies. However, the aim of this study is substantially unique from the previous work, given the specific variables examined and research aims. Table 1 includes demographic characteristics for the sample, by grade, for the study sample.

Table 1. Demographic Information

	Third Grade	Fourth Grade	Fifth Grade	Total
Mean (SD)				
Age	9.01 (0.48)	9.79 (0.05)	11.24 (0.47)	9.93 (0.90)
Non-Verbal Intelligence	NA	98.23 (14.69)	NA	98.23 (14.69)
Frequency (%)				
Male	63 (41.5%)	205 (54.0%)	77 (53.1%)	345 (51.0%)
Low SES	112 (73.7%)	328 (86.3%)	107 (73.8%)	547 (80.8%)
Site (Houston)	78 (51.3%)	191 (50.3%)	73 (50.3%)	342 (50.5%)
Hispanic	32 (21.1%)	163 (42.9%)	42 (29.0%)	237 (35.0%)
Black and/or African American	61 (40.1%)	98 (25.8%)	45 (31.0%)	204 (30.1%)
White and Non-Hispanic	37 (24.3%)	39 (10.3%)	36 (24.8%)	112 (16.5%)
Other Ethnicity/Race	20 (13.2%)	77 (20.3%)	20 (13.8%)	117 (17.3%)
Limited English Proficiency	0	158 (41.6%)	0	158 (23.3%)
Special Education Status	11 (7.2%)	38 (10.0%)	26 (17.9%)	75 (27.1%)

Measures

We administered measures of phonological awareness (PA), working memory (WM), and fine motor skill (FMS) and academic achievement. Other measures were given, but not described here, as they are unrelated to the hypotheses of the current study. Measures were administered in a planned missingness fashion, ensuring sufficient covariance coverage, without having all participants receive every assessment, as the current study is part of a larger parent study. Students were randomly assigned to one of six measure patterns (see Cirino et al., 2019a). Given that the present study uses only specific measures, the analyses were carried out only on the sample that had data for most key measures, which was N = 677. Raw means and standard deviations for the used sample for each measure are indicated in Table 2.

Table 2. Descriptive Statistics for Measures

Variable	Measure	N	Mean	SD	Reliability	Skew	Kurtosis
PA	Elision Total	675	11.33	4.84	0.91	0.23	-1.29
	Elision Scaled	675	8.27	3.02		0.33	-0.56
WM	Listening Recall Total	285	11.20	3.66	0.84	-0.09	-0.02
	Listening Recall Standard	269	96.10	17.47		0.06	-0.39
FMS	Purdue Pegboard Total	677	12.56	1.99	*	0.01	0.51
	Purdue Pegboard Z-score	677	-0.99	1.17		-0.10	0.14
Untimed Writing	Spelling Total	670	30.48	6.20	0.90	0.13	-0.57
	Spelling Standard	668	94.01	13.63		-0.15	-0.41
	Spelling W-score	668	491.00	19.01		-0.20	-0.46
Untimed Math	Calculations Total	669	16.95	3.76	0.84	<0.01	0.52
	Calculations Standard	667	102.02	12.13		-0.61	1.53
	Calculations W-score	667	499.76	13.55		-0.52	1.97
Timed Writing	Wagner Letter Writing Total	667	22.38	12.74	*	0.80	0.75
Timed Math	Math Fluency Total	669	51.21	18.58	*	0.84	1.05
	Math Fluency Standard	667	92.92	14.54		0.17	0.24
	Math Fluency W-score	667	496.22	7.24		0.83	1.05

Note. PA = Phonological Awareness (CTOPP-3 Elision); WM = Working Memory (WMTB Listening Recall); FMS = Fine Motor Skills (Purdue Pegboard); Reliability calculated using Cronbach's alpha unless indicated; * indicates manual reliability

Phonological Awareness. The Elision task from the Comprehensive Test of Phonological Processing (CTOPP; Wagner et al., 1999) measures a participant's ability to segment words into smaller parts. The Elision subtest is untimed and involves 20 items. For the first two, the participant hears a compound word and says the word that remains after dropping one of the individual words comprising the original compound word (e.g., "Say airport without saying port"). For the remaining items, the participant listens to a word, repeats it, and then says the word without a specific sound (e.g., "Say sky without saying /k/"). In the current study, the raw total correct responses were used in analyses. Reliability, calculated using Cronbach's alpha from the sample data, was good (α = 0.91). CTOPP-2 subtests are regarded as nationally representative and valid measures of phonological processing (Dickens et al., 2015).

Working Memory. The Listening Recall subtest of the Working Memory Test Battery (Pickering & Gathercole, 2001) was used. Of the students in the current sample, 285 received the Listening Recall subtest due to the measure being administered in planned missingness fashion. Because students were randomly assigned into one of the six measure patterns, we do not expect that the subset of the current sample receiving the Listening Recall subtest would differ in any predictable way from the total sample. For this task, students were instructed to listen carefully to a sentence, and then to respond 'true' or 'false' if the sentence makes sense. Then, the student is asked to repeat the last word of the sentence. For example, if the experimenter says, 'all birds have four legs,' the student would say 'false' and 'legs.' As the trials progress, the students are then asked to listen to two sentences and respond with 'true' or 'false' for both sentences in addition to saying the last word of both the first and second sentences. In subsequent blocks, students are asked to listen to an increasing number of sentences until they incorrectly respond to three trials in a particular block. The Listening Recall task is considered a valid measure of WM and Planning (Pickering & Gathercole, 2001). The measure demonstrated good reliability in the present sample (α = 0.84).

Fine Motor Skill. The Purdue Pegboard (Lafeyette Instruments, 1999) involves placing as many small pegs as possible into holes on a wooden board in thirty seconds. Participants are assessed with their right and left hands separately and then using both hands simultaneously. Performance on the Purdue Pegboard is a commonly used measure for an individual's fine motor dexterity and speed (Sigirtmac et al., 2022). Tests of reliability of the Purdue Pegboard find that the task demonstrates adequate reliability (i.e., α ~ .60 – .79; Buddenberg & Davis, 2000; Tiffin & Asher, 1948) or better (i.e., Muller et al., 2011; Proud et al., 2019). Participants' performance on the trial using their dominant hand, measured by the total number of pegs placed within thirty seconds, determined their FMS in the current study. Dominant hand performance was selected because writing is a dominant hand activity and dominant hand dexterity is closely linked with motor function (Berninger et al., 1994; Cirino et al., 2019b).

Writing. Writing was assessed with one untimed and one timed measure. The untimed measure was the Woodcock-Johnson – Third Edition (WJ-III, Woodcock et al., 2001a) Spelling subtest. The WJ-III Spelling subtest assesses a participant's ability to spell orally presented words, and total scores are based on the number of correct words spelled. All WJ-III measures have demonstrated adequate validity and reliability (Woodcock et al., 2001b), and the median test reliability statistic for the Spelling subtest is .90 (Schrank & McGrew, 2001). For the current sample, 670 participants completed the subtest, and both a standard score and a w-score were calculated using the participant's age (n = 668). W-scores in WJ-III tests are derived by transforming ability and item scores obtained through fitting a Rasch model to test data (Benson et al., 2018). Reliability calculated from the current sample was good (α = 0.90).

The timed measure was the Wagner Writing Fluency Alphabet task adapted from a measure of Berninger (1999) (see Wagner et al., 2009). For the Alphabet task, students have one minute to legibly print every lowercase letter of the alphabet from memory. Scores were based on the total number of letters written legibly. Because there are no current established norms for this measure and it was not possible to calculate test-retest reliability, reliability of the test is not established, and unstandardized total number of letters correctly formed will be used in analyses. However, prior studies have used this measure (see Vaughn et al., 2020), and performance on this task requires foundational writing skills, such as handwriting, letter recognition and formation, and the ability to generate text quickly while maintaining legibility and accuracy. For the current study, 667 participants completed the Wagner Alphabet task.

Mathematics. Mathematics achievement was measured by untimed and timed measures from the WJ-III. The Calculations subtest is an untimed measure that requires participants to solve addition and subtraction problems in increasing difficulty. According to the WJ-III manual, the Calculations subtest has a reliability of $\alpha = 0.93$ (Woodcock et al., 2001b). For the current sample, 669 participants completed the task, and reliability was also good ($\alpha = 0.84$). Standard score and w-score were calculated based on subject's age (n = 667). Math Fluency is a timed measure allowing participants three minutes to solve as many addition, subtraction, and multiplication problems as possible. The total score for each is the number of correct responses (n = 669), and both standard score and W-score (n = 667) were calculated based on participant's age. Reliability is estimated to be 0.90 (McGrew & Woodcock, 2001).

Procedure

The Institutional Review Board of the University of Houston, along with the school and school district, reviewed and approved all procedures. The assessments took place in the students' schools at the school's preferred times, and participation was voluntary. Assessments lasted approximately four hours over multiple sessions (though this includes all assessments from the larger project). Students received gift cards for participating. To counteract order effects, approximately half of the sample received the battery in reverse order. All examiners received training and supervision to pass formal “check out” procedures prior to entering schools. On-site supervision was present at schools with numerous quality checks. After data collection was complete, data was subjected to additional quality control measures (e.g., score verification, basals/ceilings where relevant, range checks).

Analysis

The main hypothesis examining the relation of key predictors with both writing and math were tested within a path analytic framework, using MPLUS (Muthén & Muthén, 2017). A path analytic framework is an extension of the regression model and compares potential causal models with a sample covariance matrix (see Kline, 2015). The model establishes regression weights simultaneously, and for models with substantial degrees of freedom, calculates goodness of fit (which was less relevant for the present study). Path analysis can be conceptualized as a form of structural equation modelling (SEM) that employs only single indicators for variables in the proposed model. SEM assumptions include (1) normal distribution of all individual variables, (2) normal distribution of individual variables for the value of every other variable, and (3) each variable has a linear relationship with every other variable. Assumptions were checked by examining skew (i.e., asymmetric unimodal distribution about the mean) and kurtosis (i.e., tendency of data to cluster near the mean or away from the mean) of the data. Skewness and kurtosis were measured using the skew index and kurtosis index, respectively. In SEM, a skewness range of -1.5 to 1.5 and a kurtosis range of -3.25 to 3.25 indicates normality (Hau & Marsh, 2004).

We also examined the data for outliers and missing cases. Univariate outliers were identified as any score lying three or more standard deviations beyond the mean of a given variable, in addition to being half of a standard deviation from the next closest value. Such values were winsorized by substituting values just below the $|z| > 3.0$ threshold, which curbs extreme values but maintains rank ordering which is the essential requirement for correlational analyses (see Tabachnick & Fidell, 2001; Weston & Gore, 2006). Multivariate outliers (i.e., cases having a pattern of atypical scores) were detected by calculating the squared Mahalanobis distance, which is the distance between a score and the vector of sample means in variance units after intercorrelations are corrected for (Kline, 2015), and were similarly winsorized.

Regarding univariate outliers, one outlier was present for Purdue Pegboard, for both dominant hand total score and z-score, two outliers were present for Calculations total score, four outliers were present for Calculations standard score and w-score, one outlier was present for Writing Fluency, and one outlier was present for Math Fluency total score and w-score. These outliers were winsorized to the next extreme value. No multivariate outliers were found.

Cases with administration and scoring concerns were examined in detail. One subject was missing date of birth and thus had values only for total but not normative scores. Some participants exhibited reliability concerns due to language-related issues, which lead to two cases being removed from Listening Recall measures. Examiner errors, particularly with timing, were present for Purdue Pegboard ($n = 5$) and Writing Fluency ($n = 3$). Some additional cases were removed due to child engagement issues, which lead to four cases being removed from Writing Fluency.

Primary hypotheses examined the interrelations of the three predictors and four achievement outcomes using a mediated path analytic framework. Differential relations of each predictor to each outcome were evaluated as well, per hypotheses. Paths were constrained using the model constraint command in MPLUS to identify whether direct effects of prediction variables on outcomes were equivalent (Muthén & Muthén, 2017). While comparing pathways involves evaluating whether the effects of individual variables on outcomes are different, comparing models involves constraining aspects of the model to be equal and then comparing these models. Resulting beta values and zero-order correlations were used to determine size and direction of effects of individual variables on individual outcomes and thus addressed hypotheses regarding stronger effects depending on variable and outcome type. When constraints are applied, the constrained model may not perfectly match the observed data due to some relationships being forced to be equal. The path model also evaluated indirect effects, specifically, whether WM mediated the relationship between FMS and all academic outcomes and whether PA partially mediated the relationship between WM and all academic outcomes, per hypotheses. Goodness of fit was based on a chi-square distribution, but is less relevant in a path analytic model, which has few degrees of freedom, and so will not be emphasized here.

The primary path model was also interpreted in consideration of the effects of relevant covariates, including gender (i.e., male or female), ethnicity (i.e., Hispanic, white, Black/African American, or Other), grade (third, fourth, or fifth), economic disadvantage (free/reduced lunch or not), school district, special education status (yes or no), limited English proficiency (yes or no), nonverbal reasoning (i.e., scaled scores of Wechsler Abbreviated Scales of Intelligence, 2nd Edition (WASI-2) Matrix Reasoning), and timing of assessment. Due to a low number of subjects in the sample with data reported for nonverbal reasoning and special education status, these covariates were eliminated for consideration.

We followed a structured approach described by Tabachnick and Fidell (2013) for evaluating covariates. Specifically, after gauging which of the above variables had significant relations with the achievement outcomes, all those relevant covariates were included in a multiple regression analysis where potential covariates were treated as independent variables with each of the four outcomes acting as the dependent variables in individual regressions. For each outcome, the most parsimonious set of relevant covariates were selected based on the proportion of variance in the dependent variable uniquely explained by a particular covariate. Those with semi-partial eta squared values greater than 2% were selected to be included in the path analytic framework. For Spelling, these covariates were grade, age, timing of assessment, and limited English proficiency status (LEP). For Writing Fluency, selected covariates included grade, gender, SES, and LEP. For both Calculations and Math Fluency, grade and timing of assessment were selected.

The primary model is that with the three key predictors and four achievement outcomes, using raw or W scores. A series of supplemental models evaluated (a) covariates, (b) standard scores, (c) weighting (to account for the oversampling of fourth graders with reading difficulties), and (d) the fact that only a subsample had the WM measures. These models were each compared to baseline/primary model.

RESULTS

The first hypothesis was that the three predictors would relate to one another, as would outcomes, at the zero-order level. Predictors were also expected to relate to outcomes. All measures were significantly correlated at the zero-order level, as shown in Table 3.

Writing measures correlated with one another at $r = 0.55$ while math measures correlated at $r = 0.66$. The strength of the correlations between predictors was similar to what was expected based on prior research; however, the correlation of phonological awareness (PA) with fine motor skills (FMS) was notably low ($r = 0.09$). All predictors were significantly correlated with the outcomes, with variation in their effect sizes; PA values ranged from $r = 0.31 – 0.47$, working memory (WM) from $r = 0.32 – 0.43$, and FMS from $r = 0.13 – 0.28$.

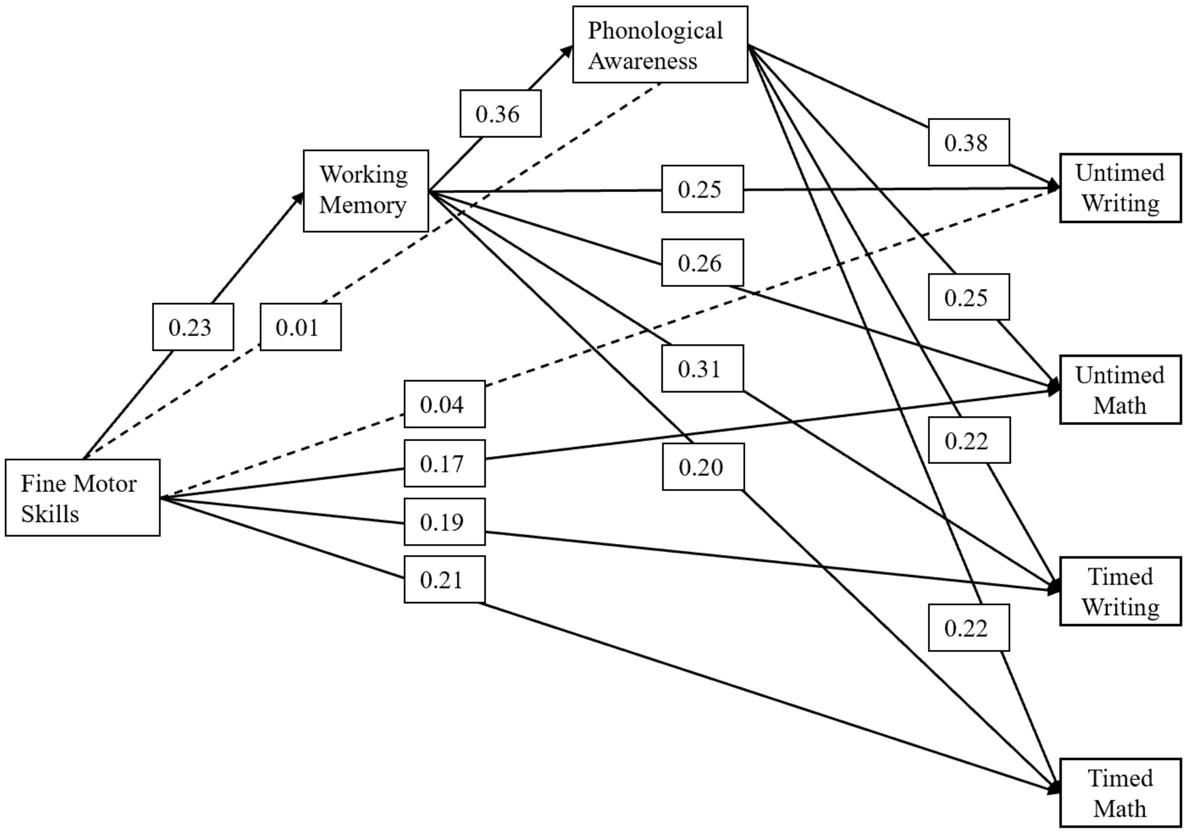
Table 3. Zero-Order Correlations

	1	2	3	4	5	6
1. PA						
2. WM	0.36**					
3. FMS	0.09*	0.23**				
4. Untimed Writing	0.47**	0.40**	0.13**			
5. Untimed Math	0.36**	0.39**	0.25**	0.55**		
6. Timed Writing	0.34**	0.43**	0.28**	0.55**	0.42**	
7. Timed Math	0.31**	0.32**	0.27**	0.52**	0.66**	0.46**

Note. PA = Phonological Awareness (CTOPP-3 Elision); WM = Working Memory (WMTB Listening Recall); FMS = Fine Motor Skills (Purdue Pegboard); Untimed Writing = Spelling (WJ-III); Untimed Math = Calculations (WJ-III); Timed Writing = Alphabet Task (Wagner Writing Fluency); Timed Math = Math Fluency (WJ-III). * indicates significant at $p < 0.05$ and ** indicates significant at $p < 0.001$

The second and third hypotheses, which involved the comparison of individual paths and mediational effects, were tested using path analysis. The standardized estimates indicated that all paths within the model (considered simultaneously, see Figure 2) were significant (at $p < 0.05$) except for the effect of FMS on PA ($p = 0.746$) and Untimed Writing ($p = 0.271$). Both PA ($\beta = 0.22$ to $\beta = 0.38$) and WM ($\beta = 0.20$ to $\beta = 0.31$) had significant unique path relations to all outcomes (all $p < 0.001$). Contrary to expectations, FMS also had direct relations to all outcomes ($\beta = 0.17$ to $\beta = 0.21$), except Untimed Writing ($\beta = 0.04$).

Figure 2. Model Results for Untimed and Timed Outcomes



For hypothesis two, WM and PA were expected to relate to all outcomes, but WM was expected to relate more strongly to math than writing, and PA was expected to exhibit the opposite pattern; PA was also expected to more strongly relate to untimed math compared to timed math. Only partial support was found for the hypotheses about the differential relation of two of the predictors (e.g., WM and PA) to achievement, when all predictors were considered simultaneously. For example, WM did not have stronger relationships with math relative to writing; for untimed outcomes, the effect of WM was similar, $p = .174$, but for timed outcomes, the effect of WM was actually *stronger* for writing than math ($p < .001$). On the other hand, PA was, as predicted, a stronger predictor for writing than math outcomes, whether untimed ($p < .001$) or timed ($p = .019$). Additionally, PA was a stronger predictor for untimed math compared to timed math (p < .001), in line with hypotheses. Table 4 contains details on model constraints.

Table 4. Differential Pathways

Factor	Outcome	Estimate	S.E.	t = Estimate / S.E.	p
WM	*UNTIMED*	*0.36*	*0.26*	*1.36*	*0.174*
PA	UNTIMED	0.79	0.14	5.50	<0.001
WM	TIMED	0.71	0.18	3.92	<0.001
PA	TIMED	0.24	0.10	2.36	0.019
PA	MATH	0.37	0.09	4.07	<0.001

Note: WM = Working Memory (WMTB Listening Recall); PA = Phonological Awareness (CTOPP-3 Elision); UNTIMED = untimed achievement measures (WJ-III Calculations and Spelling); TIMED = timed achievement measures (WJ-III Math Fluency and Wagner Writing Fluency); MATH = math measures (WJ-III Calculations and Math Fluency).

Our final hypothesis concerned the presence of mediators in the model. We expected that WM would fully mediate the relationship between FMS and all academic outcomes, and that PA would partially mediate the relationship between WM and all academic outcomes (see Table 5). As described above, each of the cognitive predictors had significant effects on all four of the academic outcomes at the zero-order level. When considering the *unique* effects of all variables, FMS, PA, and WM each still had a direct effect on each of the four academic outcomes, except for FMS and Untimed Writing. In this case, the effect of FMS was reduced from $\beta = 0.13$ to $\beta = 0.04$ when including the effects of WM and PA. Although the indirect effect of FMS on Untimed Writing via PA alone was not significant ($p = 0.746$), the indirect effect of WM alone ($p = 0.002$), and the path from FMS through WM and then PA to Untimed Writing ($p < 0.001$) were both significant. The result that WM fully mediated the pathway from FMS and Untimed Writing aligned with our third hypothesis, though this did not hold for the other three academic outcomes.

Table 5. Direct and Indirect Effects

Predictor	Mediator(s)	Outcome	t-Value	p-value
FMS	*PA*	Untimed Writing	*0.32*	*0.746*
FMS	WM		3.17	0.002
FMS	PA and WM		3.53	<0.001
FMS	Total Indirect		3.81	<0.001
FMS	*Direct*		*1.10*	*0.271*
WM	PA		5.11	<0.001
WM	Direct		4.93	<0.001
FMS	*PA*	Untimed Math	*0.32*	*0.746*
FMS	WM		3.17	0.002
FMS	PA and WM		3.25	0.001
FMS	Total Indirect		3.82	<0.001
FMS	Direct		4.60	<0.001
WM	PA		5.11	<0.001
WM	Direct		4.75	<0.001
FMS	*PA*	Timed Writing	*0.32*	*0.747*
FMS	WM		3.29	0.001
FMS	PA and WM		3.26	0.001
FMS	Total Indirect		3.85	<0.001
FMS	Direct		5.06	<0.001
WM	PA		4.87	<0.001
WM	Direct		6.12	<0.001
FMS	*PA*	Timed Math	*0.32*	*0.746*
FMS	WM		2.72	0.007
FMS	PA and WM		3.13	0.002
FMS	Total Indirect		3.49	<0.001
FMS	Direct		5.54	<0.001
WM	PA		4.58	<0.001
WM	Direct		3.68	<0.001

For Timed Writing, Untimed Math, and Timed Math, the indirect effects of FMS on academic skill were significant, via WM alone, or in combination with PA. However, for these outcomes, as noted, the direct effect of FMS on each of the three academic skills remained significant and thus, WM did not fully mediate the relationship between FMS and academic outcomes. However, where WM did mediate the relation of FMS and academic outcomes, this effect was partial rather than complete.

When considering the mediational effect of PA, results were consistent and in support of hypotheses. For each of the four outcomes, both the indirect effect of WM on achievement via PA, and the direct effects of WM, were each significant. Thus, results provided evidence that PA partially mediates the relationship between WM and timed and untimed writing and math measures.

Supplements

Sensitivity analyses were conducted to evaluate the robustness of the results and evaluated covariates, standard scores, weighting account for the oversampling of fourth graders with reading difficulties, and the subsample that had the WM measures. These results are generally consistent with the results described above. Exceptions are described below and in Supplemental Table 1 (see Appendix).

Inclusion of Covariates

The inclusion of covariates in the model generally led to similar results as when covariates were not considered. For example, including covariates did not alter zero-order correlations between the cognitive predictors and the academic outcomes. Compared to the base path analysis, relationships between predictors and academic outcomes when considering the effects of all variables were generally consistent. Most of the effects concerning whether the relation of FMS to achievement was mediated by WM and/or PA were also the same in the base versus covariate models. Similar to the base path analysis, PA was a partial mediator for the relationship between WM and all academic outcomes. Unlike the base path analysis, the direct relation between FMS and Untimed Math, was no longer significant (original $\beta = 0.17$, $p < 0.001$; covariate model $\beta = 0.06$, $p = 0.097$; see Supplemental Table 2). Further, with Untimed Math, the effect of FMS was now completely mediated. One other minor difference was that the effect of WM on timed outcomes was no longer differential (previous $\beta = 0.71$, $p < 0.001$; covariate $\beta = 0.40$, $p = 0.052$).

Weight

Path analyses which accounted for study design and sample weights to produce weighted population estimates were conducted. Results were generally consistent with unweighted results. Zero-order correlations were the same as the base model. In the path model incorporating the weight variable, relationships between predictors and academic outcomes were mostly consistent with the base path analysis. In terms of differential relations of WM and PA on outcomes, results from the path analysis incorporating the weight variable aligned with the base analysis. Consistent with the base path analysis, PA was a partial mediator for the relationship between WM and all academic outcomes. Unlike the base path analysis, the direct pathway between FMS and Untimed Writing was significant when including the weight variable (prior $\beta = 0.04$, $p = 0.271$; weighted $\beta = 0.13$, $p = 0.002$). Additionally, WM alone no longer had an indirect effect in the pathways from FMS to Untimed Math (prior $\beta = 0.06$, $p = 0.002$; weighted $\beta = 0.05$, $p = 0.055$) or to Timed Math ($\beta = 0.044$ to $\beta = 0.035$).

Standard Scores

When looking at standard scores rather than raw scores, results were generally consistent. Although values for zero-order correlations changed (see Supplemental Table 3), all zero-order relations between cognitive predictors and academic outcomes were significant. In the path analysis, results were consistent with the base path analysis; all paths within the model were significant apart from the effect of FMS on PA ($p = 0.500$) and Untimed Writing ($p = 0.692$). PA ($\beta = 0.19$ to $\beta = 0.46$) and WM ($\beta = 0.21$ to $\beta = 0.28$) both had significant effects on all outcomes, and FMS had significant effects on all outcomes (β = 0.10 to β = 0.13), apart from Untimed Writing (β = -0.01). In terms of differential relations of WM and PA on outcomes, results from the path analysis using standard scores, some results were consistent; WM did not affect writing or math differently for untimed outcomes while PA had a stronger effect on untimed writing compared to math ($\beta = 0.74$, $p < 0.001$). Mediation effects were consistent with the base path analysis; WM fully mediated the relationship between FMS and Untimed Writing and partially mediated the relationships between FMS and the other three academic outcomes, and PA partially mediated the relationship between WM and all four academic outcomes. However, unlike the base path analysis, the path where the effect of WM was compared between timed outcomes was no longer significant (prior $\beta = 0.71$, $p < 0.001$; standard score $\beta = 0.03$, $p = 0.556$), and the comparison of the effect of PA on both math outcomes was no longer significant (prior β = 0.37, $p < 0.001$; standard score $\beta = -0.03$, $p = 0.861$). Additionally, PA had a stronger effect on timed math compared to timed writing (prior $\beta = 0.24$, $p = 0.019$; standard score β = -0.52, $p < 0.001$).

Planned Missingness

Because of the disparity in the sample size of participants who received the Listening Recall WM measure ($n = 285$) compared to the total sample size ($n = 677$), additional sensitivity analyses examined only those participants who received the WM measure were conducted. Results of the smaller sample were generally the same. Zero-order correlations changed (see Appendix Table 3), but the relations among all cognitive predictors and academic outcomes remained significant. In the path model, relationships between predictors and academic outcomes were mostly consistent with the base path analysis. Other path comparisons were consistent with the base path analysis. When comparing mediation effects, results were consistent with the base path analysis; WM fully mediated the relationship between FMS and Untimed Writing and partially mediated the relationship between FMS and both math outcomes, and PA partially mediated the relationship between WM and all academic outcomes. Regarding differential effects, the differential effect of PA for timed outcomes was no longer significant (prior $\beta = 0.24$, $p = 0.019$; subsample $\beta = 0.16$, $p = 0.264$). Unlike the base path analysis, the direct pathway between FMS and Timed Writing was nonsignificant when looking at this subsample (prior $\beta = 0.19$, $p < 0.001$; subsample $\beta = 0.06$, $p = 0.260$). The effect of FMS was reduced from $\beta = 0.16$ to $\beta = 0.06$ when including the effects of WM and PA. Although the indirect effect of PA alone was not significant ($p = 0.326$), the indirect effect of WM alone ($p = 0.002$) and with PA ($p = 0.012$) were both significant.

Summary

Results from the sensitivity analyses revealed overall consistency with the main results of the base analyses. Results that did not change across all sensitivity analyses included the significant zero-order correlations between all variables, the finding that PA exerted a stronger effect on untimed writing compared to untimed math, and the finding that PA partially mediated the relationship between WM and all academic achievement outcomes. Most of the changes between the variety of sensitivity analyses involved a beta value changing modestly. The most substantive differences occurred with the standard/scaled score model. Whereas in the base model, WM had a differential effect on timed writing versus timed math (stronger for writing) and PA had a stronger effect on timed writing compared to math, in the model with standard scores, the differential effect of WM was no longer significant, and PA had a stronger effect on timed math rather than writing. For these, the beta values changed substantially.

DISCUSSION

The goal of the present study was to investigate the relationships between writing, math, and three plausible shared cognitive predictors of these achievement skills, namely fine motor skills (FMS), working memory (WM), and phonological awareness (PA). This work is important because understanding the shared cognitive skills between math and writing is crucial for assessing academic abilities in both research and clinical work. Exploring their overlap helps identify common challenges and sources of difficulty in academic achievement, which could eventually inform instruction and/or intervention for students who struggle in these domains. The strengths of this study include the direct comparison of math and writing, which is infrequently considered in the literature, despite relatively robust individual literatures. We also extend current literature by including both timed and untimed academic tasks, which is also rare. Finally, we also evaluate potential ways in which cognitive predictors work together to impact achievement in these domains. We expected all predictors and outcomes to relate to one another at the zero-order level, and we also expected differential effects. That is, we anticipated that WM would have a stronger effect on math than writing, while PA would exhibit the opposite pattern in addition to having a stronger effect on untimed math compared to timed math. Finally, we also expected mediational effects, such that the effect of FMS would be fully mediated by WM, and that PA would partially mediate the relationship between WM and all academic outcomes.

All predictors related to all outcomes, and we also demonstrated significant unique/direct effects of both PA and WM for each achievement outcome; contrary to expectation we also found unique effects of FMS to all outcomes except untimed writing. Also, unexpectedly, the effect of WM was not differential for untimed achievement, and though it was differential for timed achievement, this was in the opposite direction than anticipated (stronger for writing than for math). In line with expectation, PA was a stronger predictor of writing relative to math, for both timed and untimed tasks, and PA was a stronger predictor for untimed math relative to timed math. WM partially mediated the relationship between FMS and all academic outcomes; it only fully mediated the effect of FMS to untimed writing. However, as expected, PA did partially mediate the pathways from WM to each academic outcome. The key takeaways from this work are that cognitive mechanisms underlying math and writing achievement are overlapping and interconnected, even in the context of external factors.

Sensitivity analyses including covariates, weighting, standard scores, and planned missingness did not substantially alter the main findings. One exception was that the finding that the effect of WM differed for math versus writing outcomes for timed tasks did not remain when analyzing standard scores. Additionally, when using standard scores, the finding that the effect of PA was stronger for writing for timed tasks changed where the relative effect of PA on timed math was stronger than on timed writing.

Simple Relations of Predictors to Math and Writing

In alignment with hypotheses and prior research, all variables were significantly correlated at the zero-order level. FMS, WM and PA have been implicated in both writing and math achievement throughout development (see Friso-van den Bos et al., 2013; Kim & Graham, 2022; Kim & Park, 2019; Lê et al., 2021; Michalczyk et al., 2013; Michel et al., 2020; Peng et al., 2020), and academic skills are often related to one another (see Amland et al., 2021; Child et al., 2019; Cirino et al., 2018; Landerl & Moll, 2010; Peters & Ansari, 2019; Peterson et al., 2021; Willcutt et al., 2019), making this result unsurprising.

WM exhibited strong and direct relationships with both timed and untimed writing tasks and untimed math, corroborating its role as a fundamental skill for a wide range of academic abilities throughout development as shown by extant literature (Friso-van den Bos et al., 2013; Peng et al., 2016). The current findings contribute to the wealth of literature identifying WM as a crucial skill supporting each step of the writing process including planning, mentally representing ideas, applying grammatical and lexical knowledge, and executing physical expression of the message (see Bock & Levelt, 1994; Hayes & Grawdol-Nash, 1996; Olive, 2004). Likewise, WM is thought to have a multi-faceted role in math learning, including storing, organizing, and processing the linguistic and visual codes of mathematical information (De Smedt et al., 2010; Kleeman et al., 2014; Peng et al., 2016; Swanson et al., 2018).

PA similarly exhibited a robust effect on all academic outcomes, which is unsurprising considering prior research (Diamond et al., 2008; Kim et al., 2011; Kim & Graham, 2022; Yang et al., 2021). These findings corroborate extant evidence for the role of PA for both writing and math, the latter of which has been debated, especially for school-aged children (see Amland et al., 2021; Cirino et al., 2018; De Smedt et al., 2010). PA is widely acknowledged as a core building block for writing ability (Adams, 1990; Kim & Graham, 2022), and the current findings further highlight the importance of PA on writing skills during elementary school years, when writing often becomes more complex and relies more heavily on other higher-order cognitive skills (Berninger, 1999). While some researchers have found that early PA skills dictate the development of basic math concepts by enabling children to recite and mentally depict number words (Krajewski & Schneider, 2009; Yang et al., 2021), others have found conflicting evidence. For example, Amland and colleagues (2021) found that PA did not account for the development of arithmetic skills from kindergarten to first grade. The current study reinforces the importance of PA in math achievement even beyond early childhood.

When considering the effects of all variables, FMS no longer had a significant association with PA. While the lack of a unique relationship between these variables when considering all effects was not specifically hypothesized, the result was unsurprising. The connection between language and motor development has been discussed for decades, but much of that work has focused on infancy and early childhood (see Iverson, 2010). Research in later childhood rarely finds a direct connection between motor and language skills (see Oudgenoeg-Paz et al., 2016; Rhemtulla & Tucker-Drob, 2011). Therefore, our findings echo existing literature suggesting that the relationship between motor and language skills becomes less prominent in later stages of childhood, underscoring the evolving nature of these developmental connections.

Differential Effects of Predictors on Writing and Math

A novelty of the present study is in considering (timed and untimed) writing and math together and comparing effects of specific cognitive predictors on each. The strength of the effect of PA varied based on the academic subject (writing versus math) and the nature of the testing conditions (timed versus untimed). In line with literature which generally highlights the dominant role of language in writing (Juel, 1988; Juel, et al., 1986), the relative effect of PA on writing tasks was significantly greater compared to math tasks. Researchers have conceptualized spelling deficits as being reflective of poor PA, where improved PA leads to more accurate spelling (Caravolas et al., 2001; Treiman, 1993). The present study provides additional support for the essentiality of PA in writing even when separately considering different types of writing tests.

The finding that the relative effect of PA on untimed math was stronger than its effect on timed math aligns with findings from a recent meta-analysis by Yang and colleagues (2021) which similarly found that PA was more strongly related to untimed math measures compared to timed measures. Some researchers have posited that language becomes less relevant for math as problems become more abstract and complex (Michalczyk et al., 2013) or that language is only implicated in mathematic processing which directly involves verbal codes, such as word problems (Simmons & Singleton, 2008). However, the present study found that PA is significantly associated with math even when considering the effects of other robust predictors and is more closely linked with untimed math, which involves more complex problems such as long division, compared to timed math, which involves basic math facts. These results highlight the importance of language in math learning beyond early childhood and beyond phonological representations of math. Considering these findings in the context of theoretical accounts describing the relevance of language in math development (see Kleemans et al., 2014; Krajewski & Schneider, 2009; Swanson et al., 2018), more work must be done to understand which aspects of math are more closely tied to specific aspects of language.

Unexpectedly, our findings did not reveal differences in the way that WM relates to untimed academic skills – Untimed Math and Spelling. Moreover, the finding that WM had a stronger effect on timed writing (Writing Fluency) than on timed math was unexpected as well. Meta-analyses (Spiegel et al., 2021) and theoretical models of math (e.g., von Aster &

Shalev, 2007; Geary, 2004) have emphasized the importance of WM in math achievement, while models of writing have typically incorporated WM as an indirect indicator of writing achievement (e.g., Kim & Park, 2019; Olive, 2004). These findings call for further investigation of the role of WM in writing and math achievement. Future research on academic achievement should be sure to specify whether their tests highlight fluency versus untimed skills.

Mediational Effects of Predictors on Writing and Math

A novel finding of the current study is that the effect of FMS on achievement is only partially (rather than fully) mediated by WM.; this effect was only full for Spelling. The finding that WM did not have a mediational effect suggests that the influence of FMS capacity, which is typically a direct and robust effect especially at younger ages (Gandotra et al., 2021; Hudson et al., 2021), is not fully channeled through WM capacity for children in grades three through five. Our results suggest that in this diverse sample of third through fifth graders, FMS has a unique connection with academic achievement, timed and untimed.

The nature of the connection between FMS and WM in the context of academic achievement throughout childhood has been debated for decades. Some researchers conceptualize executive skills, including WM, as a mediator in the relationship between motor development and academic achievement (e.g., Michel et al., 2019; Oberer et al., 2018; Schmidt et al., 2017), while other researchers posit that WM development directly depends on the context of motor development (e.g., Diamond, 2000). Although the finding that WM did not fully mediate the relationship between FMS and all academic outcomes was surprising, these results do align with some prior studies. For example, Lê and colleagues’

(2021) found that executive function did not account for the link between motor skills and literacy.

We did find a full mediation of FMS to untimed writing, via WM. Complex skills such as spelling may depend moreso on a network of higher order cognitive skills rather than on motor-based skills (see Kim & Park, 2019). Furthermore, at the developmental stage represented in the current study, the motor movements integral to spelling are likely automated to some degree, allowing other cognitive domains, such as WM and PA, to assume greater prominence. Importantly, most prior research on the role of FMS in writing achievement focuses on fluency measures rather than untimed tasks (see Doyen et al., 2017) which aligns with the conceptual relevance of FMS in academic development where motor skills are typically associated with tasks that demand automated physical movement. Like writing, much of the literature on the effect of FMS on math achievement, especially beyond early childhood, focuses on timed measures (see Cadoret et al., 2018; Gashaj et al., 2019b; Michel et al., 2020). Compared to writing where much of the connection between FMS and achievement relates to the physical act of writing, the direct connection between FMS and math achievement may be explained by an embodied cognition framework, which suggests that abstract numerical processing relies on perception and the cortical motor system due to early experiences of finger-counting (Tschentscher et al., 2012). In line with the embodiment cognition framework, FMS may maintain a direct influence on math independent from the physical act of moving a pencil or perhaps visuomotor integration skills, which were not included in the current study, may be alternate explanations as well (Carlson et al., 2013). Future work on the interconnection between FMS and WM in the context of academic achievement should consider the effects of other factors, whether handwriting or visuomotor skills, and the involvement of executive functioning more broadly.

The present study found evidence that PA partially explains the pathway between WM and academic achievement, which aligns with current theories on writing and math development. For writing, the simple view focused on the interplay of ideation (idea generation and translation) and transcription (encoding ideas into print) (Berninger et al., 2002; Juel et al., 1986). The not-so-simple view of writing built off this model, incorporating WM as the mechanism by which an individual is able to activate both long-term memory to plan, compose, review, and revise and short-term memory to continuously revise and review the written output (Berninger & Winn, 2006). Kim and Park's (2019) direct and indirect effects model of writing (DIEW) views the writing process as consisting of various skills within a hierarchal relationship; foundational cognitive skills, including WM, support higher-order language skills, including PA, which in turn mediate their effects on writing. A longitudinal study of Korean-speaking children across grades one through three found WM in grade one was both directly and indirectly associated with writing quality in grade three, providing support for the DIEW model (Kim & Park, 2019). The current study provides further support for the DIEW model through the finding that WM directly and indirectly (through PA) impacted specific aspects of the writing process (timed writing fluency and untimed spelling accuracy). We extend prior research by specifically examining PA, which had not been considered in prior research on the DIEW model (Kim, 2019; Kim & Park, 2019). Additionally, through examining a sample of children in grades three through five rather than children in early grade school, the present study highlights the relevance of the DIEW model beyond early childhood.

Similar to writing, WM and PA have been linked with math across development (Krajewski & Schneider, 2009). Our finding that PA partially mediates the relationship between WM and math provides support for the theory that WM allows children to process and organize mathematical information which is stored as linguistic information (Simmons et al., 2008; Swanson et al., 2018). The finding that WM's effect on math is altered depending on phonological ability for third through fifth grade children further calls into question whether PA's relevance in math declines with age, as previously proposed (Michalczyk et al., 2013). Compared to the research on literacy, math has not been investigated in depth; thus, theoretical understanding of math development and achievement is lacking. The present study contributes to math learning literature by highlighting the interconnection between WM and PA in both timed and untimed math testing.

Theoretical Implications and Practical Applications

The current study shows that FMS, PA, and WM each directly impact writing and math in third through fifth grade. The most unexpected finding was that of a continued role of FMS for achievement at this developmental period. Compared to WM and PA, the relevance of FMS for academic achievement in school-aged children is more uncertain. In early childhood, motor development is considered a marker for school readiness, which has influenced the development of academic interventions that promote motor development with the expectation of indirectly improving cognitive and academic performance (see Ericsson, 2008). However, as children age, the connection between FMS, cognitive development, and academic skill acquisition become more complex and whether motor skills directly influence cognition and academic ability becomes nonsignificant (Houwen et al., 2017). Our findings, which highlight the direct impact of FMS on academic performance, align with some prior work with younger school aged children. For instance, a longitudinal study of kindergarteners conducted by Grissmer and colleagues (2010) found that FMS, along with attention and general knowledge, were robust predictors of future achievement, surpassing the significance of socioemotional variables. Similarly, Geertsen and colleagues (2016) found that motor skills have a positive relationship with cognitive testing and academic achievement for pre-adolescent children. Future work on the role of FMS in math achievement especially should consider the indirect effects of visuomotor integration and handwriting to verify whether FMS is indeed a direct predictor for math achievement or whether the connection is better explained by the embodied cognition framework or through physical automation of written math.

The study further emphasizes the multifaceted role of WM in different aspects of writing, and math, underscoring the importance of WM in orchestrating complex cognitive tasks essential for academic success. The finding that WM did not consistently have a differential effect on writing versus math highlights the domain-general nature of the skill. The consistent finding that PA mediated the relationship between WM with both writing and math suggests a common cognitive system supporting both math and writing competency. One explanation is that both written language and math are drawn from linguistic codes stored in WM (see De Smedt et al., 2010; Hecht et al., 2001; Kleemans et al., 2012; Kleemans et al., 2014; Simmons et al., 2008).

Further, results of the present study challenge prior assumptions about the (lack of a) role of PA in math, especially in more complex and abstract mathematical problems. Our findings demonstrate that PA continues to play a significant role in math achievement beyond early childhood, highlighting the importance of language-related skills in math learning. Finally, the differential impact of cognitive predictors, particularly PA, depending on the nature of the assessment (timed versus untimed) and subject (writing versus math) emphasizes the need for detailed analysis of what specific aspects of academic achievement map onto the functional impact of various cognitive abilities.

Limitations and Future Directions

The current study had several limitations that may warrant consideration when interpreting the results. First and foremost, aspects of the study design may limit the generalizability of the findings. These aspects include (1) oversampling of fourth graders who are struggling to read, (2) random missingness of particular measures, and (3) the cross-sectional design. Weighting based on the proportion of struggling readers in the oversampled group compared to the total sample was applied to account for the effects of oversampling. Participants from the oversampled subgroup were given lower weights, compensating for their higher likelihood of being included in the study due to oversampling. Comparing the output of analyses both with and without the weighting variable allowed us to transparently display the effects of oversampling. Additionally, the study design purposefully incorporated random missingness to minimize the time each student spent testing to maximize their effort and motivation. Nonetheless, the planned missingness aspect of the study protocol led to a smaller proportion of the present sample receiving the WM measure. Conducting sensitivity analyses where we looked specifically at the subsample that received the WM measure allowed us to directly compare results with the overall sample, and we found that these two analyses led to comparable findings.

Finally, the sample characteristics are another limitation of the current study; in particular, the large number of students denoted as limited English proficiency (LEP) status may introduce some bias in interpretation of the results. All the students with LEP status were fourth graders as well, in addition to being struggling readers. Because the tests described in the current study were conducted in English only, actual abilities of students with LEP status may have been under-estimated due to difficulty understanding instructions or due to limited familiarity with words presented during language-focused tasks (especially Spelling and Elision). To address the potential effects of LEP status on results, this variable was controlled for when relevant. However, future research should directly examine the role of English learning status on writing and math abilities, and more work should be done integrating research on assessments conducted in a myriad of languages to capture the unique effects of cognitive mechanisms underlying academic skills independent of a child's LEP status.

Further, the cross-sectional design of the study prohibits causal interpretation of findings. Because causality cannot be inferred from the mediation analyses, assumptions of the specific pathways may not hold true in real life or in longitudinal research. Future research should employ longitudinal study designs to answer the question of causality in cognitive and academic development literature.

Conclusions

The current study imparts significant contributions to the understanding of the cognitive skills associated with academic achievement. The results highlight the direct impact of FMS, WM, and PA on both writing and math achievement, emphasizing the continued significance of motor skills in academic success during this developmental period. The study provides evidence that challenges assumptions that PA does not directly impact math achievement outside of learning number words and solving word problems. Moreover, our findings provide a unique perspective on FMS by incorporating untimed measures and examining a sample of school-aged children. Our findings demonstrate that, although math and writing are not typically compared in research, these disparate academic skills rely on similar cognitive systems which may relate to the high levels of comorbidity between specific learning disabilities. Overall, this study enriches the academic literature by providing valuable insights into the complex interplay between executive functioning, language, motor skills and academic performance, paving the way for future investigations in the field of cognitive and academic development.

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Appendix A

A1. Summary of Supplement Analyses

Analysis	Covariates	Weight	Standard Scores	Subsample
Zero Order	-	-	-	-
Differential	The effect of WM on timed outcomes was no longer differential	-	The effect of WM on timed outcomes was no longer differential; The effect of PA on math outcomes was no longer differential; PA had a stronger effect on timed math compared to timed writing	The effect of PA on timed outcomes was no longer differential
Direct/Mediational FMS	The direct effect of FMS on Untimed Math was fully mediated by WM	The direct effect of FMS on Untimed Writing was significant when considering indirect effects; WM alone no longer had an indirect effect in the pathways from FMS to Untimed Math or to Timed Math	-	The direct effect of FMS on Timed Writing was fully mediated by WM
Direct/Mediational WM	-	-	-	-

Note. Note. WM = Working Memory (WMTB Listening Recall); PA = Phonological Awareness (CTOPP-3 Elision); FMS = Fine Motor Skills (Purdue Pegboard)

Appendix B

A2. Direct and Indirect Effects After Including Covariates

Predictor	Mediator(s)	Outcome	t-Value	p-value
FMS	*PA*		*0.37*	*0.713*
FMS	WM		2.06	0.040
FMS	PA and WM		2.99	0.003
FMS	Total Indirect	Untimed Writing	2.88	0.004
FMS	*Direct*		*-0.50*	*0.618*
WM	PA		3.99	<0.001
WM	Direct		2.34	0.019
FMS	*PA*		*0.37*	*0.714*
FMS	WM		2.77	0.006
FMS	PA and WM		2.84	0.005
FMS	Total Indirect	Untimed Math	3.37	0.001
FMS	*Direct*		*1.66*	*0.097*
WM	PA		3.66	<0.001
WM	Direct		3.54	<0.001
FMS	*PA*		*0.37*	*0.715*
FMS	WM		2.53	0.011
FMS	PA and WM		2.79	0.005
FMS	Total Indirect	Timed Writing	3.12	0.002
FMS	Direct		3.92	<0.001
WM	PA		3.48	<0.001
WM	Direct		3.33	0.001
FMS	*PA*		*0.37*	*0.714*
FMS	WM		2.19	0.029
FMS	PA and WM		2.64	0.008
FMS	Total Indirect	Timed Math	2.86	0.004
FMS	Direct		3.05	0.002
WM	PA		3.23	0.001
WM	Direct		2.59	0.010

Appendix C

A3. Zero-Order Correlations for Standard Scores

	1	2	3	4	5	6
1. Elision						
2. Listening Recall	0.31**					
3. Purdue Pegboard	0.12*	0.20*				
4. Spelling	0.52**	0.30**	0.09*			
5. Calculations	0.30**	0.32**	0.20**	0.57**		
6. Wagner Letter Writing	0.30**	0.29**	0.19**	0.50**	0.36**	
7. Math Fluency	0.36**	0.26**	0.22**	0.54**	0.64**	0.41**

Note. * indicates significant at $p < 0.05$ and ** indicates significant at $p < 0.001$

Appendix D

A4. Zero-Order Correlations for Working Memory Subsample

	1	2	3	4	5	6
1. Elision						
2. Listening Recall	0.39**					
3. Purdue Pegboard	0.13*	0.21*				
4. Spelling	0.51**	0.41**	0.13*			
5. Calculations	0.43**	0.41**	0.26**	0.56**		
6. Wagner Letter Writing	0.36**	0.43**	0.16**	0.56**	0.43**	
7. Math Fluency	0.37**	0.34**	0.23**	0.54**	0.70**	0.45**

Note. * indicates significant at $p < 0.05$ and ** indicates significant at $p < 0.001$