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Domain-specific skills, but not fine-motor or executive function, predict later arithmetic and reading in children☆

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ABSTRACT

Fine motor skills and executive function are two examples of domain-general skills. Both are correlates of arithmetic and reading ability, and have been identified as predictors of school readiness. Little research has simultaneously assessed the influence of both these skills as predictors of academic abilities. Current evidence suggests their role as predictors lessens once children enter school. Importantly this limited research often disregards the role of well-established domain-specific predictors. In this large-scale longitudinal study ($N = 569$) we evaluate the role of fine motor skills, executive function, and domain-specific skills at 5-years as predictors of arithmetic and reading skills at 6-years. Fine motor skills and executive function at school entry correlate strongly with each other, with the longitudinal association between fine motor skills and performance in reading and arithmetic completely accounted for by variance shared with executive function skills. However, neither executive function nor fine motor skills account for variance in reading or arithmetic after controlling for more proximal predictors of these skills. If either fine motor or executive function skills promote learning in school, it seems their effects on reading and arithmetic development may be mediated by more proximal skills. From an applied perspective, this study casts doubt on the usefulness of motor skills as a target for intervention to support academic performance, at least after school entry. It also highlights the need to examine more closely the relations between domain-general and domain-specific skills in early development.

1. Introduction

Fine motor and executive function skills are among the domain-general abilities that are related to school readiness and early academic achievement (for reviews, see Macdonald et al., 2018; McClelland & Cameron, 2019, Ober et al., 2020, Peng et al., 2016). Although their association with academic performance has typically been modeled separately (e.g., Child et al., 2018; Cirino, 2011; Halverson et al., 2021) there is evidence to suggest that fine motor skills and executive function, while correlated, are independent predictors of school readiness and early academic performance in mathematics and reading (Cameron et al., 2019; Duran et al., 2018; Oberer et al., 2018). To date, however, research that has examined *concurrently* the influence of these two domain-general abilities on children's academic performance (Cameron et al., 2019; Duran et al., 2018; Oberer et al., 2018; Pitchford et al., 2016; Roebers et al., 2014) has not typically evaluated the contribution of domain-specific predictors (e.g., phonological awareness for reading, numerosity discrimination for arithmetic). For the purposes of this research, the term domain-specific refers to skills that are more proximally related to the academic outcome (e.g., number knowledge or phonologically awareness as they relate to mathematics and reading, respectively), while domain-general relates to those general cognitive and motor skills that may be implicated across a range of academic outcomes (i.e., not specific to mathematics or reading).

When the known domain-specific predictors of either reading or mathematics have been considered alongside domain-general skills in preschool or school-aged children, focus tends to be on either fine motor skills or executive function alone (e.g., Cirino et al., 2018; Cragg et al., 2017; Fuchs et al., 2016; Geary, 2011). Moreover, studies evaluating the contribution of these domain-general skills rely on statistical techniques

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that do not incorporate a latent variable modelling approach, despite the advantages of doing so for executive function given the 'task impurity problem' (see Cassidy, 2016). That is, executive function skills are multifactorial, drawing upon a range of lower order executive and nonexecutive processes for completion. This means there is no single "pure" measure of executive function and, therefore, this construct may be better represented as a latent variable. Given the lack of research that has incorporated this latent variable approach, it is not yet clear how fine motor skills and executive function operate in the context of well-established domain-specific predictors of reading and mathematics.

To address these issues, we examine the extent to which unique variance in reading and arithmetic is captured by latent variable measures of executive function and fine motor skills when assessed alongside domain-specific indicators in a large sample of children unselected for ability at school-entry. Gaining a better understanding of these relations will highlight more definitively the skills that should be targeted during the transition to formal schooling. It should be noted we use two terms when discussing mathematics performance: 'mathematics' is used when referring to studies that report measures of mathematical ability assessing multiple constructs (e.g., measurement, time, and arithmetic); 'arithmetic' is reserved for those that report assessments of basic calculation skills such as addition and subtraction (see Göbel et al., 2014). Our mathematics related focus in the current study is on measures of arithmetic ability.

1.1. Fine motor skills

It is common to distinguish between fine (hand and finger movements) and gross (large body movements including the arms and legs) motor skills (Cameron et al., 2016). These skills correlate moderately with each other (e.g., rs = 0.32 to 0.50; Cameron et al., 2012; Rhemtulla & Tucker-Drob, 2011), but fine motor skills are the stronger correlate of early academic achievement (Cameron et al., 2012; Grissmer et al., 2010; Rhemtulla & Tucker-Drob, 2011). Fine motor skills are often defined as those that integrate small muscle movements requiring close hand-eye coordination, including skills such as manipulating small objects (e.g., bead threading) and drawing (e.g., Luo et al., 2007). Some research (e.g., Martzog et al., 2019) also argues for the role of speeded fine motor skills (e.g., tapping), but these are less frequently included in research examining academic development as they often have weaker associations with cognitive skills (see Suggate et al., 2017).

A considerable body of research indicates that fine motor skills are predictors of early mathematics and reading ability (e.g., Macdonald et al., 2020; McClelland & Cameron, 2019; Suggate et al., 2017; Suggate et al., 2019), with this relationship appearing stronger for mathematics (Pitchford et al., 2016; Son & Meisels, 2006). These links have been observed both concurrently (e.g., Duran et al., 2018; Geersten et al., 2016; Kim & Cameron, 2016) and longitudinally (e.g., Cameron et al., 2012; Duran et al., 2018; Miller et al., 2017). As such, fine-motor skills in pre-school have been identified as an indicator of school readiness. Fine motor skills are also considered a foundational skill to support academic development (Grissmer et al., 2010), therefore suggesting it may be an important component of interventions targeting early academic development (e.g., Pitchford et al., 2016).

Fine motor skills may relate to the development of early mathematical skills because when learning to count children often engage in finger counting (Baroody & Wilkins, 1999), which in turn has long-standing implications for how numbers are mentally represented (Fischer, 2008; Klein et al., 2011). Fingers are also used as an early arithmetic strategy with children using their fingers to represent sets of numbers (Baroody, 1987). Less is known about why fine motor skills are associated with reading. Cameron et al. (2012), however, found that better fine motor skills in kindergarteners predicted improvement in several domain-specific indictors of reading (i.e., letter-word identification, print knowledge, and phonological awareness). From a practical standpoint, fine motor skills are implicated in reading as children often engage in finger pointing to support the association between speech sounds and printed text (Invernizzi, 2017; Morris, 1983; Rawlins & Invernizzi, 2018). Moreover, fine motor skills are a critical component of the associated literacy skill of writing across both logographic and orthographic systems (Lam & McBride, 2018; Suggate et al., 2016).

1.2. Executive function

Executive function is typically described as a set of higher-order cognitive processes important for planning and problem solving (Garon et al., 2008). These skills include working memory, cognitive flexibility, attention, and inhibitory control (e.g., Diamond, 2013; Miyake et al., 2000). Executive function is considered a foundational skill that plays a role in acquiring academic skills (McClelland & Cameron, 2019). Extensive research shows that executive function is a predictor of reading and mathematical ability (Cirino, 2011; Halverson et al., 2021, Nesbitt et al., 2015; see Cragg & Gilmore, 2014, for a review), and an indicator of school readiness (Grissmer et al., 2010). When reading, executive function is argued to facilitate integration of many elements of reading including word sounds, semantics, and word order, therefore supporting reading comprehension (Cartwright, 2012). For mathematics, executive function supports the manipulation of information in mind, suppression of distractions and engagement in flexible thinking (Cragg & Gilmore, 2014).

1.3. The link between fine motor, executive function and academic performance

Both fine motor skills and executive function are considered to be intertwined during infancy and early childhood (see Kim et al., 2018), with studies showing modest associations between these skills in typically (e.g., Becker et al., 2014; Cameron et al., 2015; Wassenberg et al., 2005) and differently (e.g., Wilson et al., 2012; cf. Molitor et al., 2015) developing children. Additionally, the neural networks associated with the development of fine motor skills overlap with those involved in aspects of executive function (Floyer-Lea & Matthews, 2004), aligning with Anderson's (2007) thesis that brain areas can be utilized by many different diverse tasks.

There are two possible accounts of the relation between fine motor skills, executive function and academic performance. The automaticity account suggests that there may be an indirect causal relationship between the development of fine motor skills and academic performance that is mediated via executive function (see also Schmidt et al., 2017). In this view if the fine motor skills needed to complete basic classroom tasks become automated with practice (e.g., writing), attention and other executive function skills can be then focused on more complex concepts and academic skill development (e.g., arithmetic, comprehension; see Cameron et al., 2015; Kim et al., 2018; automatization of fine motor skills ➔ freeing of executive function resources ➔ improvements in academic outcomes). In contrast, the reciprocity theory suggests these skills develop alongside each other. Therefore, both fine motor skills and executive function are reciprocally related to each other and to development in academic domains.

Of these two approaches, the automaticity account seems more relevant to children in the early years of formal education. Schmitt et al. (2017) found that while executive function and mathematics have a bidirectional relationship for 4- to 5-year-olds (indicating reciprocity), by school age (5- to 6-years) this relationship becomes unidirectional with EF predicting mathematics but not vice versa (see also Fuhs et al., 2014 for similar results). Possible reciprocal relationships between fine motor skills and academic achievement have been less studied, yet there is some evidence to suggest that bidirectional relations also attenuate after the preschool period so that only motor skills predict academic performance (e.g., Kim et al., 2018). As our study uses a school-aged sample of children, we focus on understanding the nature of directional rather than reciprocal relations between fine motor skills, executive function, and academic performance.

Of the few studies that have simultaneously examined the relation between executive function and fine motor skills on early academic performance, most have found both skills function as unique predictors of reading and/or mathematics (Cameron et al., 2019; Duran et al., 2018; Oberer et al., 2018). This has been observed for children of preschool age (e.g., 3- to 4-years; Cameron et al., 2019) and those in the early years of formal education (e.g., 5.5- to 6.6-years; Duran et al., 2018). Some research, however, indicates that the influence of fine motor skills on academic performance may be more fragile during the early school years than that of executive function (e.g., Pitchford et al., 2016). When the relations between fine motor skills and academic performance were assessed in isolation during the first two years of school, fine motor skills were found to be a unique predictor of mathematics and reading. However, once verbal short-term memory was taken into consideration, only executive function (and not fine motor skills) predicted reading performance (Pitchford et al., 2016). This finding is echoed by Roebers et al. (2014) who found executive function, but not fine motor skills, predicted unique variance in academic outcomes (measured as a latent variable including spelling, reading and mathematics) in 5- to 6-year-old children. Additionally, there also seems to be a trend for domain-general skills to become less influential as children develop and move towards the transition to formal schooling. For example, in a sample of 100 children assessed over a year period from preschool to kindergarten, Chu et al. (2016) found a trend for domain-specific skills to be more strongly related to achievement in reading and mathematics at the end of preschool than at the beginning of preschool, with these correlations tending to be stronger than those for either executive function or intelligence (i.e., domain-general skills).

Given the limited research addressing the simultaneous influence of both fine motor and executive function skills on academic performance during the early years of formal schooling, it is difficult to draw firm conclusions about the relative importance of these skills. However, executive function typically explains a larger proportion of variance in academic performance than fine motor skills (Cameron et al., 2012; Cameron et al., 2015; Cameron et al., 2019; Duran et al., 2018; Grissmer et al., 2010; Oberer et al., 2018). It is possible that fine motor skills depend in part on executive function skills for their development, and that fine motor skills only relate to academic performance because they act as a proxy for executive function skills. This proposition is consistent with the view that the development of fine motor skills is facilitated by executive function skills (e.g., see Becker et al., 2014; Maurer & Roebers, 2019, 2020; McClelland & Cameron, 2019). In this view, the automatization of fine motor skills and school performance may both depend upon executive function skills. As highlighted above, however, evidence for this is mixed, with some studies showing that executive function and motor skills both capture unique variance in academic performance (e.g., Duran et al., 2018).

To date, the few studies which examine the simultaneous contributions of fine motor skills and executive function to academic achievement in school-aged children rarely focus on more than one academic skill (e.g., Duran et al., 2018). Others rely on a latent factor capturing multiple academic domains (e.g., Oberer et al., 2018; Roebers et al., 2014). Even fewer studies incorporate executive function, fine motor skills, and domain-specific indicators of both reading (e.g., phonological awareness) and arithmetic (e.g., numerosity discrimination) when assessing relations with academic performance. To understand the importance of fine motor skills and executive function to the development of early academic skills, it is important to examine these relations for both reading and arithmetic as these are considered two of the key outcomes for early education across many Western countries (e.g., UK, USA, New Zealand, and Australia).

1.4. Domain-specific predictors of academic performance

It is well established that rapid automatized naming (RAN; Koponen et al., 2016; Norton & Wolf, 2012), phoneme awareness (e.g., Malone, Heron-Delaney, et al., 2019) and letter-sound knowledge (Foorman et al., 1991) are powerful predictors of word-reading (decoding) ability in English and other alphabetic orthographies (e.g., Caravolas et al., 2013). These predictors are in line with theories of reading including the Simple View of Reading (e.g., Gough & Tunmer, 1986; Hoover & Gough, 1990) and its extensions (Joshi & Aaron, 2000). Less is known about the predictors of arithmetic, but there is a general consensus that understanding of quantity (e.g., Malone, Pritchard, et al., 2019; Schneider et al., 2017), knowledge of Arabic numerals (e.g., Göbel et al., 2014; Malone et al., 2021) and counting (Koponen et al., 2016) predict arithmetic development. Importantly, research evaluating such indictors alongside either executive function or fine motor skills show these typically account for more variance in mathematics (e.g., numerosity judgment: $R^2 = 0.15$, Malone, Heron-Delaney, et al., 2019; number identification: $R^2 = 0.49$, Göbel et al., 2014) and reading performance (e.g., phonological awareness: $R^2 = 0.52$; Malone, Heron-Delaney, et al., 2019) than executive function (e.g., reading: $R^2 = 0.06$–0.10, Cameron et al., 2012; arithmetic: $R^2 = 0.04$, Viterbori et al., 2017) or fine motor skills (e.g., $R^2 = 0.03$–0.12; Cameron et al., 2012). It is therefore important to assess whether measures of executive function and fine motor skills remain predictors of reading and arithmetic ability once the influence of well-established domain-specific predictors is controlled. This will provide a more holistic understanding of the skills contributing to proficiency in arithmetic and reading during the early school years, while also clarifying the optimal targets for interventions designed to improve reading and arithmetic in these early school years.

When examining the simultaneous association between fine motor skills, executive function and academic performance, few longitudinal studies have included measures of known domain-specific predictors. Three exceptions are Pinto et al. (2016), Gashaj et al. (2019) and Suggate et al. (2019). Pinto et al. (2016) measured aspects of executive function (working memory, selective attention) and fine motor skills (oculomotor coordination) alongside a range of domain-specific skills (i.e., phoneme related abilities, counting, number reading, number recognition and seriation). They found only domain-specific skills (number recognition and phonological skills) at 5.6 years were significant predictors of reading and mathematics at 6.7 years. In contrast, Gashaj et al. (2019) found a significant relation between an element of executive function (updating) assessed in preschool (*M* age = 6.45 years) and mathematics in second grade (*M* age = 7.95 years), although the domain-specific skill of numerosity understanding remained the stronger predictor. One potential explanation for the difference in findings between Pinto et al. (2016) and Gashaj et al. (2019) is the domain-specific skills considered. That is, the numerical skill assessed by Gashaj et al. – numerosity understanding – is known to be a weaker predictor of mathematics than other relevant indictors such as knowledge of Arabic numerals (e.g., Malone et al., 2020; Malone et al., 2021). As such, it may capture less variance in mathematics performance than other relevant numerical skills.

Finally, Suggate et al. (2019) assessed children's reading performance at 7.2-years of age in relation to fine motor skills (coin posting, bead threading and maze tracing), executive function (attention and inhibitory control) and domain-specific predictors of reading (phoneme awareness and nonword repetition) assessed at 6.2-years. They found that only fine motor skills (entered as a latent variable), and not the individual executive function or domain-specific skills (entered as observed variables), predicted reading ability approximately one year later. This result contrasts with that of Pinto et al. (2016) in that Suggate et al. (2019) found domain-specific skills were not predictive of later reading ability. Indeed, phoneme awareness and nonword repetition are known to be robust predictors of reading ability for this age group (e.g., Burgoyne, Lervåg, et al., 2019; Cunningham et al., 2020). The different finding obtained by Suggate et al. (2019) could be explained by how they entered these skills into the model: fine motor – the focus of their research – was entered as a latent factor derived from four observed variables, while executive function and domain-specific predictors were entered as individual observed variables. While latent factors control for measurement error; observed variables, when entered directly into the model as predictors, do not (see Cole & Preacher, 2014). It is therefore possible that measurement error may account for why Suggate et al. (2019) did not find a significant relation between domain-specific skills and reading.

The results of these three studies reveal that while a combination of domain-general and domain-specific abilities predict variations in the development of children's early mathematics and reading skills, domain-specific factors tend to be the stronger predictors of mathematics achievement than domain-general factors (cf. Suggate et al., 2019). Particular doubt, however, has been cast on the predictive value of fine motor skills as Suggate et al. (2019), but neither Gashaj et al. (2019) nor Pinto et al. (2016), found them to be a predictor of performance once domain-specific skills were considered.

1.5. Research aims and hypotheses

Previous research is unclear about the importance of fine motor skills and executive function as predictors of variations in reading and arithmetic skills in the first few years of formal education. Even less is known about the extent of relations between domain-general versus domain-specific indictors of academic performance. Here we use data from a large-scale longitudinal study of children in the first two years of formal education to clarify this picture. Previous publications from this longitudinal dataset have informed the selection of domain-specific factors that influence the development of arithmetic and reading during the early years of formal education (e.g., Burgoyne, Malone, et al., 2019; Malone et al., 2021; Pritchard et al., 2021). However, these previous studies did not contrast the relations between fine motor skills and executive function on arithmetic or reading ability, and therefore did not directly inform the current hypotheses.

In an advance on previous research, the current study uses multiple measures of key domain-general (fine motor skills, executive function) and domain-specific (number knowledge, counting, non-symbolic numerosity judgment, phoneme awareness, letter-sound knowledge and RAN) predictors of reading and arithmetic, along with multiple measures of performance in both reading and arithmetic. Moreover, we use latent variable models to account for measurement error (Cole & Preacher, 2014). This research builds on previous studies by assessing a comprehensive range of well-established predictors relevant to mathematics and reading to clarify which skills are critical predictors of later academic performance during the early years of formal education. As such, this study makes a novel contribution by allowing the relative importance of domain-specific and domain-general factors on two key academic skills (i.e., reading and arithmetic) in a school aged sample to be elucidated.

In line with previous literature examining the relative strength of relations between executive function, fine motor and academic performance (e.g., Duran et al., 2018; Pitchford et al., 2016; Roebers et al., 2014), we predict that executive function and fine motor skills assessed at school entry will correlate with reading and arithmetic, with executive function being the stronger correlate. To determine the relative contributions of fine motor, executive function and domain-specific correlates of academic performance, three models will be considered. Given the potential fragility of the fine motor-academic performance relation (e.g., Gashaj et al., 2019; Pinto et al., 2016), fine motor skills will be entered as a single predictor of academic performance before adding executive function and finally the domain-specific predictors. We predict that when entered alone, fine motor skills will account for unique variance in later academic performance, yet we do not expect fine motor skills to account for unique variance in reading or arithmetic performance after controlling for the effects of executive function (e.g., Pitchford et al., 2016; Roebers et al., 2014). Finally, given the strength of the associations between domain-specific skills and reading/arithmetic observed in previous research (e.g., Gashaj et al., 2019; Göbel et al., 2014; Malone et al., 2021; Pinto et al., 2016), we expect that well-established, proximal predictors of reading and arithmetic (for word reading – phoneme awareness, letter-sound knowledge and RAN; for arithmetic – number knowledge, counting and non-symbolic numerosity judgment) will be the strongest predictors of these skills. We will also explore whether executive function remains a unique predictor of reading or arithmetic skills after controlling for well-established proximal predictors.

2. Method

2.1. Participants

Children from 11 schools in Brisbane, Australia participated; eight served students with an average level of educational advantage (Index of Community Socio-Educational Advantage (ICSEA) values between 997 and 1090), and three with relatively higher levels of advantage (ICSEA values between 1112 and 1153). These scores reflect variables such as family background (parent occupation and education) and school characteristics (e.g., percentage of indigenous Australian pupils and geographical location; Australian Curriculum, Assessment and Reporting Authority, 2013). The mean ICSEA value is 1000 (average range: 900 to 1100). Ten percent of the participating schools had an indigenous population of 6% or greater.

Children were assessed within 4-months of school entry (preparatory year) when their average age was 5-years ($n = 569$; 274 boys; mean age $= 63.86$ months, $SD = 4.36$, range 54–82 months) and again during latter half of their second school year (year 1) when the average age was 6-years ($n = 496$; 241 boys; mean age $= 81.23$ months, $SD = 4.25$, range 71–99 months). Preparatory year and year 1 in Australia are equivalent to years 1 and 2 in the United Kingdom, and to kindergarten and grade 1 in the United States. The age range at each time point is greater than expected as a minority of children were repeating the first school year at the start of the study. Ethical approval for research with human participants was provided by the Australian Catholic University research ethics committee, with the research conducted in accordance with the Declaration of Helskini. Schools provided informed consent for children to take part, and parents were able to opt-out of the research. Children provided their assent and were able to withdraw at any point.

2.2. Measures and procedure

Children completed measures at two time points: school entry (prep) whereby they completed motor, executive function, arithmetic and reading-related tasks, with follow-up assessments of arithmetic and reading at the end of the following school year (Year 1). These were administered individually, except for drawing trails, numerosity judgment, number writing, and number identification which were completed in a whole class format. These tasks form part of a larger longitudinal study (e.g., Malone et al., 2021; Pritchard et al., 2019), but only measures relevant to this paper are reported here.

2.3. School entry assessments (5-years-old)

2.3.1. Fine motor skills

Fine motor performance was assessed using two fine motor tasks from the Movement ABC (Henderson et al., 2007). *Bead Threading* involved children being asked to thread 12 beads (one at a time) onto a lace as quickly as possible. Children completed a practice trial, followed by two test trials. The time taken (in seconds) to thread all 12 beads was recorded, with faster performance indicating greater fine motor skills. For *Drawing Trials*, children traced a pattern between two lines without lifting their pen from the page or crossing the boundary lines. A practice trial was followed by two test trials. As per manualised instructions, error marks were awarded for crossing the boundary and for discontinuous or overlapping lines, as such a higher score indicated more errors and therefore poorer fine motor skills.

2.3.2. Executive function

Three components of executive function were assessed: inhibition, visual-spatial working memory and visual selective attention. These measures capture the core constructs of executive function (Diamond, 2013) as well as those strongly associated with reading and arithmetic (i.e., inhibition, working memory) at early school age (Cameron et al., 2009; Roebers et al., 2014).

The Head-Toes-Shoulders-Knees task (HTSK; Burrage et al., 2008) was used to assess behavioral inhibition. The HTSK shows good construct validity, demonstrating significant relations with cognitive flexibility, working memory, and inhibitory control in prekindergarten and kindergarten children (McClelland et al., 2014). This task consisted of two parts: 1) "touch your head/toes" (10 trials); and 2) "touch your head/toes" and "shoulders/knees" (10 trials). For each trial the child was asked to touch a body part (e.g., head), and the child was to inhibit this response and touch the alternative body part instead (e.g., toes). Four training and feedback trials were provided before each Part. If the child completed five trials were completed correctly in Part 1, they continued to Part 2; otherwise, the task was discontinued. For each trial, two points were awarded if the child touched the correct body part, one point for self-corrections (e.g., an initial movement to the incorrect part), and zero points for an incorrect response. This scoring procedure is one that has been reported previously (Malone et al., 2020).

The visual search efficiency task assessed selective visual attention (Breckenridge, 2008). Children were asked to find as many red apples ($n = 30$) as possible in a 15 × 20 matrix within 1 min, while ignoring distractor items (white apples and red strawberries). An efficiency score was generated: (number of correct items − number of errors) / 60.

The dot locations task from the Children's Memory Scale (Cohen, 1997) assessed visual-spatial working member. Children were presented for 5 s with a 4 × 3 grid depicting a pattern using 6 red dots. They were then asked to replicate the pattern on a blank grid using 6 plastic tokens (trial 1). This was repeated for a further two trials (trials 2 and 3). A distractor yellow pattern (6 dots on a 4 × 3 grid) was then presented and replicated by the child, before they were asked to recreate the red pattern from memory (trial 4). One point was awarded for the correct placement of each red token, with the score summed across the four trials.

2.4. Domain-specific predictors of arithmetic

2.4.1. Non-symbolic numerosity judgment

Children's ability to discriminate between numerosities was assessed using a paper-and-pencil method, similar to Nosworthy et al. (2013). Children were presented with booklets (21 cm × 14.5 cm) containing three conditions: Ratio 0.86 (most difficult), Ratio 0.66, and Ratio 0.57 (easiest), with the ratio dictating the difference in numerosity between the stimulus pairs (e.g., 6 vs. 7; 24 vs. 36; and 7 vs. 12, respectively). These were completed in order of difficulty (most difficult to easiest), therefore reducing task frustration and possible attrition. Each condition consisted of 36 trials (6 trials per page); with each trial presenting two 2.2 cm^2 boxes containing arrays of small squares. The total surface area of the small squares was matched across arrays, with the number of squares ranging from 6 to 11 in the 0.86 condition, 21 to 45 in the 0.66 condition and 5 to 13 in the 0.57 condition. For each condition, children were asked to tick the most numerous array in each stimulus pair. As this was a speeded task, children were informed not to count the squares as this would be too slow. The number of correctly identified arrays was recorded, thus providing a measure of approximate number system efficiency (cf. Göbel et al., 2014). To correct for guessing, any score on an individual subtest that reflected 50% or less correct was scored as missing since this level of performance (at or below chance) indicates that a child was not able to perform the task.

2.4.2. Number knowledge

The *number identification* task assessed recognition of Arabic numerals using three practice trials and 14 test trials. Each trial required children to identify the printed target number (from an array of four) spoken by the researcher. The numbers ranged from single digits to triple digits. Each correctly identified test item was provided a score of 1. *Number writing* assessed children's ability to hand-write Arabic numerals which corresponded to numbers spoken by the researcher. Six trials were completed (2, 7, 13, 28, 69, and 145). A score of 1 was provided for each correctly written number that was identifiable out of context (reversals of digits were scored as errors).

2.4.3. Counting

Counting ability was assessed with two tests. In *Rote Counting,* children were asked to count to 40 and were stopped once they made an error. The last correct number was recorded. In *Object Counting,* children were presented with presented with six object arrays (1 practice and 5 test trials), which increased in numerosity as the assessment progressed (9, 14, 23, 36 and 42). Children counted the number of items in each array, and the final number in their count sequence recorded. They were then asked, "how many are there?" Up to two points were awarded per trial; one for the correct final number in the sequence and one for their response to the "how many" question.

2.4.4. Addition

Two practice problems (with feedback) and ten written addition problems which summed below 10 were used. As children had only recently been introduced to the concept of addition, counting objects were available to assist them in solving the problems allowing children who were yet to develop more advanced strategies (e.g., fact recall) to demonstrate their addition skills. Three minutes were provided to answer verbally as many test problems as possible. One point was awarded for each correct response.

2.5. Domain-specific predictors of reading

2.5.1. Phoneme awareness

This was measured using the *Phoneme Deletion* task from the York Assessment of Reading for Comprehension – Australian edition (YARC: Hulme et al., 2012). For each of the seven teaching items and 12 test items, children were asked to delete a phoneme from a spoken word paired with a picture (e.g., say "sheep" without the "p"). Testing was discontinued after four consecutive incorrect responses. One point was awarded for each correct response.

2.5.2. Letter-sound knowledge

This was measured using a subtest from the YARC (Hulme et al., 2012). Children were asked to say the sounds associated with 17 individual letters and digraphs. If the children provided the letter name, they were asked to give the letter sound. Testing was discontinued after four consecutive incorrect responses. One point was awarded for each correct response.

2.5.3. Rapid automatized naming

Four trials were completed (2 × colour; 2 × object) to assess processing speed. Children first named the five stimuli (colours: brown, blue, black, red and green; objects: dog, eye, key, lion, table). Following this they were presented with an 8 × 5 item matrix, displaying 8 iterations of the items in a random order. The time taken for children to name each item (moving left to right, along each row) was recorded. Testing was discontinued if three consecutive errors were made. An efficiency score was calculated for each trial: number correct/time in seconds.

2.5.4. Reading

Children's reading ability was assessed using the Early Word Reading subtest from the YARC (Hulme et al., 2012). A list of 30 single words which increased in difficulty was provided. After five consecutive errors, the child was asked if they could read any further words in the list. If they correctly read a later word, testing was continued from this item until a further five consecutive errors were made. When the child was not able to read any further words, testing was discontinued. One point was assigned for each correct response.

2.5.5. *Academic outcomes (6-years-old)*

To assess children's academic performance at the end of year 1 (second year of formal schooling), children completed two measures for each outcome.

2.5.6. *Arithmetic*

These skills were measured using the addition (single digits with a sum less than 11) and subtraction (minuend from 2 to 9; subtrahends from 1 to 8) subtests of the Test of Basic Arithmetic and Number Scale (Brigstocke et al., 2016). For each subtest, children were presented with 90 questions, and provided with 1 min to answer verbally as many problems as possible. The questions were displayed in two columns per page, with 15 problems per column. Children were instructed to work down the columns, with the examiner redirecting the children to the correct problem if needed. One point was awarded per correct response. This assessment was deemed appropriate for our age group as one of the mathematics goals of year 1 is to develop a range of mental strategies to represent and solve simple addition and subtraction problems (Queensland Curriculum and Assessment Authority, 2021).

2.5.7. *Reading*

Two measures assessed word-level decoding. *Single Word Reading* (Hulme et al., 2012) asked children to read as many of 60 words (increasing in difficulty) as they could. This assessment was administered and scored in the same way as early word reading. *Nonword Reading*, using the phonemic decoding subtest from the Test of Word Reading Efficiency (Torgesen et al., 1999), provided children with 45 s to read as many non-words as possible. The list increased in difficulty from two-letter, single syllable nonwords (e.g., ip) to four syllable nonwords (e.g., emulbatate). Prior to the test proper, children were shown eight practice nonwords. If they were unable to decode a minimum of one nonword, testing was discontinued. One point was awarded per correct response to the test items. This assessment was considered appropriate for our participants as a goal in year 1 is to read decodable texts (Queensland Curriculum and Assessment Authority, 2021).

3. Results

The means, standard deviations and reliabilities for all measures are shown in Table 1. Correlations between measures are shown in Table 2, in which missing data were handled by pairwise deletion. Both fine motor tasks were negatively scored: Poor performance was indicated by a larger number of errors (drawing trails) or amount of time taken to complete a task (bead threading). Children's fine motor performance at 5-years (bead threading and drawing trails) correlated weakly with arithmetic (addition and subtraction; $rs = -0.14$ to -0.21) and reading ability ($rs = -0.15$ to -0.30) at 6-years. The strength of these correlations is somewhat weaker than the correlations between academic performance at 6-years and the other domain-general executive function skills (arithmetic: $rs = 0.14$–0.32; reading: $rs = 0.13$–0.30). As expected, domain-specific skills were often the strongest correlates of academic ability (arithmetic: $rs = 0.09$–0.40; reading: $rs = 0.39$–0.53). Notably, there were weak correlations between individual measures of fine motor skills and executive function ($rs = -0.18$ to -0.30), and the correlations

Table 1
Descriptive statistics (means, standard deviations, and range) and reliabilities.

Variables (maximum)	*N*	Mean (*SD*)	Reliability	Range	95% CI
Fine motor skills (5-years)					
Bead threading trial 1 (150)	542	54.19 (13.96)	0.67[3]	28.09–143.50	[53.01–55.37]
Bead threading trial 2 (150)	537	50.82 (13.49)		28.56–121.97	[49.68–51.97]
Drawing trails 1	531	3.46 (2.86)	0.70[2]	0–20	[3.21–3.70]
Drawing trails 2	532	4.39 (3.47)		0–22	[4.10–4.69]
Executive function (5-years)					
Dot location (24)	485	17.46 (3.86)	–	7–24	[17.01–17.70]
Heads toes knees shoulders (40)	547	21.34 (10.06)	0.79	0–39	[20.49–22.18]
Visual search efficiency	531	0.18 (0.10)	–	−0.63–0.40	[0.17–0.19]
Mathematics (5-years)					
Addition (10)	552	4.40 (2.82)	0.90	0–10	[4.17–4.64]
Non-symbolic numerosity judgment			0.72[1]		
Ratio 0.86 (36)	301	7.31 (3.42)	–	0–23	[6.92–7.70]
Ratio 0.66 (36)	364	11.24 (5.61)	–	0–36	[13.52–14.76]
Ratio 0.57 (36)	364	14.15 (5.98)	–	0–35	[10.67–11.82]
Number identification (14)	537	8.53 (2.33)	0.60	0–14	[8.33–8.72]
Number writing (6)	449	2.43 (1.61)	0.64	0–6	[2.28–2.57]
Object counting (10)	486	3.09 (1.69)	0.71	0–8	[2.94–3.25]
Count sequence (40)	554	28.01 (11.08)	–	2–40	[27.08–28.93]
Reading (5-years)					
Early word reading (30)	553	6.60 (6.81)	0.95	0–30	[6.03–7.17]
Letter-sound knowledge (17)	557	10.40 (3.83)	0.91	0–17	[10.08–10.72]
Phoneme awareness (12)	541	3.56 (2.30)	0.78	0–11	[3.37–3.76]
RAN	553	0.72 (0.18)	0.86[3]	0.31–1.61	[0.70–0.73]
Arithmetic (6-years)					
Addition (90)	474	12.32 (7.42)	0.92[2]	0–58	[11.65–12.99]
Subtraction (90)	469	7.32 (4.33)	0.88[2]	0–33	[6.92–7.71]
Word reading (6-years)					
Single word reading (60)	479	23.10 (10.57)	0.96	0–52	[22.15–24.05]
Non-word reading (66)	463	17.59 (10.36)	0.84[4]	0–48	[16.64–18.54]

Note. All reliabilities unless noted are Cronbach's alpha.
[1] Composite reliability (omega).
[2] Test–retest values reported in the manual (*r*).
[3] Alternate forms (*r*).
[4] Test–retest (*r*).

Table 2
Correlations between measures of fine motor, executive function, mathematics and reading.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Five-years-old																							
1. Bead threading 1	–	0.68**	0.21**	0.16**	−0.11*	−0.16**	−0.16**	−0.17**	−0.15*	−0.12*	−0.20**	−0.13**	−0.14**	−0.13**	−0.15**	−0.13**	−0.23**	−0.20**	−0.26**	−0.16**	−0.20**	−0.17**	−0.11*
2. Bead threading 2	0.69**	–	0.19**	0.16**	−0.11*	−0.17**	−0.20**	−0.14**	−0.20**	−0.14**	−0.26**	−0.10*	−0.10*	−0.12*	−0.16**	−0.15**	−0.19**	−0.19**	−0.24**	−0.17**	−0.19**	−0.16**	−0.13**
3. Drawing 1	0.23**	0.20**	–	0.50**	−0.15**	−0.18**	−0.29**	−0.23**	−0.06	−0.14**	−0.10	−0.18**	−0.23**	−0.13**	−0.13**	−0.18**	−0.23**	−0.18**	−0.20**	−0.17**	−0.16**	−0.29**	−0.25**
4. Drawing 2	0.19**	0.19**	0.51**	–	−0.13**	−0.20**	−0.16**	−0.16**	−0.10	−0.14**	−0.10	−0.14**	−0.17**	−0.16**	−0.13**	−0.12**	−0.22**	−0.16**	−0.17**	−0.13*	−0.14**	−0.16**	−0.15**
5. Dot location	−0.15**	−0.14**	−0.16**	−0.15**	–	0.21**	0.14**	0.26**	0.16**	0.16**	0.09	0.16**	0.18**	0.11*	0.13**	0.13**	0.19**	0.19**	0.20**	0.13*	0.13**	0.17**	0.10*
6. HTKS	−0.20**	−0.20**	−0.20**	−0.22**	0.23**	–	0.21**	0.44**	0.22**	0.28**	0.22**	0.29**	0.17**	0.17**	0.32**	0.36**	0.42**	0.38**	0.29**	0.30**	0.31**	0.33**	0.24**
7. Visual search	−0.19**	−0.22**	−0.30**	−0.18**	0.16**	0.23**	–	0.22**	0.11	0.17**	0.17**	0.14**	0.18**	0.17**	0.12**	0.17**	0.26**	0.16**	0.29**	0.22**	0.18**	0.25**	0.22**
8. Addition	−0.22**	−0.18**	−0.25**	−0.18**	0.28**	0.46**	0.24**	–	0.21**	0.35**	0.25**	0.33**	0.25**	0.20**	0.37**	0.46**	0.44**	0.39**	0.33**	0.42**	0.42**	0.35**	0.31**
9. Ratio 0.86	−0.20**	−0.25**	−0.08	−0.13*	0.19**	0.25**	0.13*	0.26**	–	0.49**	0.51**	0.19**	0.12*	0.14*	0.25**	0.10**	0.17**	0.16**	0.28**	0.27**	0.26**	0.27**	0.28**
10. Ratio 0.66	−0.15**	−0.17**	−0.15**	−0.16**	0.19**	0.30**	0.18**	0.37**	0.50**	–	0.51**	0.22**	0.23**	0.23**	0.30**	0.21**	0.24**	0.24**	0.30**	0.39**	0.38**	0.27**	0.24**
11. Ratio 0.57	−0.23**	−0.28**	−0.12*	−0.12*	0.11*	0.24**	0.19**	0.27**	0.53**	0.52**	–	0.20**	0.18**	0.18**	0.25**	0.19**	0.24**	0.20**	0.22**	0.30**	0.33**	0.25**	0.20**
12. Number ID	−0.16**	−0.12**	−0.19**	−0.15**	0.17**	. 31**	0.15**	0.35**	0.21**	0.23**	0.22**	–	0.32**	0.12*	0.29**	0.43**	0.42**	0.33**	0.31**	0.34**	0.26**	0.38**	0.33**
13. Number writing	−0.15**	−0.11*	−0.23**	−0.18**	0.18**	0.18**	0.19**	0.25**	0.13*	0.24**	0.19**	0.33**	–	0.17**	0.21**	0.36**	0.37**	0.28**	0.26**	0.25**	0.23**	0.38**	0.35**
14. Object counting	−0.15**	−0.13**	−0.13**	−0.17**	0.12*	0.18**	0.18**	0.21**	0.15*	0.24**	0.19**	0.13**	0.17**	–	0.25**	0.21**	0.21**	0.21**	0.22**	0.12*	0.09	0.24**	0.16**
15. Count sequence	−0.16**	−0.16**	−0.14**	−0.13**	0.13**	0.32**	0.13**	0.37**	0.25**	0.30**	0.26**	0.30**	0.21**	0.26**	–	0.40**	0.42**	0.32**	0.31**	0.24**	0.26**	0.42**	0.37**
16. Early word	−0.19**	−0.20**	−0.20**	−0.15**	0.17**	0.39**	0.19**	0.49**	0.16**	0.24**	0.23**	0.44**	0.36**	0.22**	0.40**	–	0.69**	0.50**	0.37**	0.37**	0.36**	0.56**	0.49**
17. LSK	−0.27**	−0.23**	−0.24**	−0.25**	0.22**	0.44**	0.28**	0.47**	0.21**	0.26**	0.27**	0.44**	0.38**	0.22**	0.42**	0.71**	–	0.50**	0.38**	0.31**	0.30**	0.52**	0.42**
18. Phoneme awareness	−0.24**	−0.23**	−0.20**	−0.19**	0.22**	0.40**	0.18**	0.42**	0.21**	0.26**	0.23**	0.35**	0.29**	0.22**	0.32**	0.53**	0.52**	–	0.30**	0.25**	0.23**	0.45**	0.38**
19. RAN	−0.29**	−0.27**	−0.22**	−0.19**	0.22**	0.32**	0.31**	0.36**	0.31**	0.32**	0.25**	0.32**	0.27**	0.23**	0.31**	0.40**	0.40**	0.32**	–	0.43**	0.35**	0.45**	0.47**
Six-years-old																							
20. Addition	−0.19**	−0.19**	−0.18**	−0.14**	0.14**	0.31**	0.23**	0.44**	0.29**	0.40**	0.32**	0.35**	0.26**	0.13*	0.24**	0.39**	0.33**	0.27**	0.45**	–	0.74**	0.40**	0.39**
21. Subtraction	−0.21**	−0.20**	−0.16**	−0.15**	0.14**	0.32**	0.18**	0.42**	0.27**	0.39**	0.34**	0.27**	0.24**	0.09	0.26**	0.36**	0.30**	0.23**	0.35**	0.74**	–	0.42**	0.38**
22. Single word	−0.20**	−0.18**	−0.30**	−0.18**	0.19**	0.34**	0.27**	0.37**	0.30**	0.28**	0.27**	0.39**	0.38**	0.25**	0.42**	0.57**	0.53**	0.46**	0.46**	0.41**	0.43**	–	0.87**
23. Non-word	−0.13**	−0.15**	−0.26**	−0.16**	0.12**	0.26**	0.23**	0.32**	0.30**	0.25**	0.21**	0.34**	0.35**	0.16**	0.37**	0.50**	0.42**	0.39**	0.47**	0.39**	0.38**	0.87**	–
24. Age	−0.25**	−0.21**	−0.11*	−0.14**	0.17*	0.18**	0.12**	0.21**	0.25**	0.15**	0.17**	0.13**	0.07	0.07	0.04	0.27**	0.21**	0.22**	0.17**	0.12**	0.06	0.13**	0.09*

Note. Zero order correlations below the diagonal; partial correlations controlling for age above the diagonal; Drawing = drawing trails; BWS = backwards word span; HTKS = head toes knees shoulders; Early word = early word reading; LSK = letter sound knowledge; RAN = rapid automatized naming; Single word = single word reading; Non-word = non-word reading.

** $p < .01$.

* $p < .05$.

between the HTKS measure and fine motor measures were comparable in strength (rs = −0.20 to −0.22) to that reported by Cameron et al. (2012; r = 0.17).

Preliminary analyses revealed that measures of fine motor skills and executive function showed linear relationships with both reading and arithmetic. We assessed the longitudinal relations between academic outcomes at age 6-years (arithmetic and reading) and their predictors assessed at age 5-years (fine motor, executive function and domain-specific skills) using latent variable path models using MPlus 8.0 (Muthén & Muthén, 1998-2017). Missing values were handled using Full Information Maximum Likelihood estimation. All constructs in the models were represented by latent variables. At school entry (5-years-old), four latent variables were defined using multiple indicators (fine motor, executive function, number knowledge, and counting), two using item-parcelling (numerosity judgment and RAN), and four by a single indicator constrained by the error variance of the indicator (1-reliability of the measure; reading, addition, letter-sound knowledge and sound deletion). At 6-years, academic outcomes were defined by latent variables using item-parcelling for arithmetic and multiple indicators for reading.

We modeled the data using a series of autoregressive path models in which performance at 6-years (reading or arithmetic) was predicted from the same skill assessed at school entry (5-years with reading assessed by Early Word Reading or arithmetic assessed by a simple addition task), together with a range of other possibly important predictors. Autoregressive models assess the extent to which change in an outcome variable (reading or arithmetic) after controlling for initial levels on that variable (the autoregressor) can be predicted from other measures. We developed these models sequentially, in a theoretically prespecified way. In the models described below, all observed variables were regressed on age (though these regressions are not shown in the figures). These models therefore represent the relations between variables that are independent of the shared variance attributable to chronological age. To determine the fit of these models, a range of fit indices were consulted. A model is considered a good fit to the data if the comparative fit index (CFI) ≥ 0.95 (although ≥0.90 is an acceptable fit; Brown, 2006), standardized root mean square (SRMR) ≤ 0.08, and root mean square error of approximation (RMSEA) ≤ 0.06 (Hu & Bentler, 1999).

The first pair of path models assessed the role of fine motor skills alone as a predictor of the growth in arithmetic (Fig. 1a) and word reading (Fig. 1b) respectively. The models revealed that for both arithmetic and reading, fine motor skills at school entry are a significant predictor of performance. Both models provided a good fit to the data: Arithmetic, χ^2 (11) = 22.98, p = .02; Root Mean Square Error of Approximation (RMSEA) = 0.05; Comparative Fit Indices (CFI) = 0.99; Standardized Root Mean Square Residual (SRMR) = 0.05; missing values n = 30); and reading, χ^2 (11) = 35.41, p < .01; RMSEA = 0.06; CFI = 0.98; SRMR = 0.06; missing values n = 28. The correlations between latent variables in these models can be seen in Tables 3 and 4. In these models the correlation between the fine motor skills latent variable and later performance were: arithmetic r = −0.25; reading r =

Table 3
Correlations among the latent variables for the arithmetic model (a) shown in Fig. 1.

	1.	2.	3.
Five-years-old			
1. Fine motor	–		
2. Addition	−0.21**	–	
Six-years-old			
3. Arithmetic	−0.25**	0.51**	–

** p < .01.

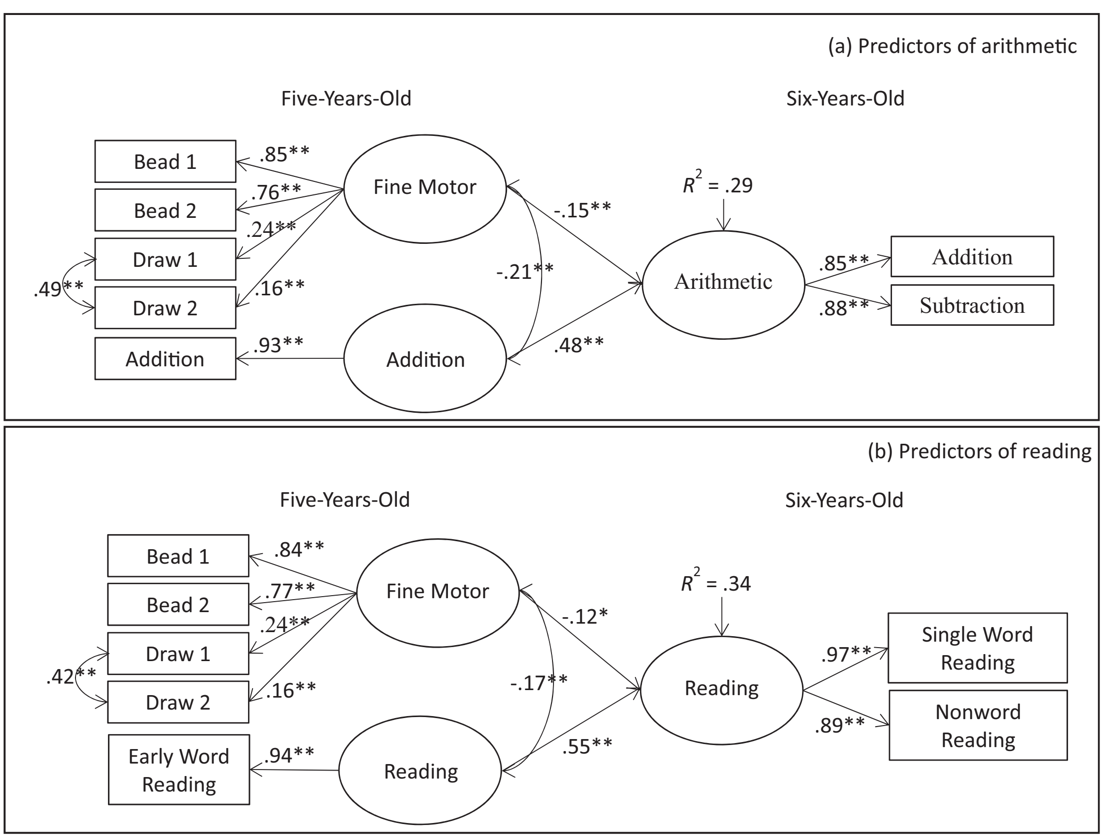

Fig. 1. Latent variable path model showing the relation between fine motor, corresponding autogressor and academic outcome in children. Two headed arrows represent correlations. Bead = bead threading; Draw = drawing trails; * p < .05; ** p < .01.

Table 4
Correlations among the latent variables for the reading model (b) shown in Fig. 1.

	1.	2.	3.
Five-years-old			
1. Fine motor	–		
2. Reading	−0.17*	–	
Six-years-old			
3. Reading	−0.22**	0.57**	–

* $p = .01$.
** $p < .01$.

−0.22. The pattern here provides support for the findings of Cameron et al. (2012) and confirms that fine motor skills is a significant though relatively weak longitudinal predictor of both reading and arithmetic.

Next, we examined whether fine motor skills remains a significant direct predictor of later academic skills after executive function is included as an additional predictor (see Fig. 2). The initial saturated models with all regression paths included provided an acceptable fit to the data (arithmetic: χ^2 (29) = 79.50, $p < .001$; RMSEA = 0.06; CFI = 0.96; SRMR = 0.06; missing values $n = 51$; reading: χ^2 (29) = 92.72, $p < .001$; RMSEA = 0.06; CFI = 0.96; SRMR = 0.07; missing values $n = 49$). For each model the non-significant paths were trimmed iteratively until the most parsimonious model was obtained (arithmetic: χ^2 (31) = 80.18, $p < .001$; RMSEA = 0.05; CFI = 0.96 SRMR = 0.06; reading: χ^2 (30) = 92.75, $p < .001$; RMSEA = 0.06; CFI = 0.96; SRMR = 0.07). This caused no appreciable loss of fit for either the arithmetic or reading model (arithmetic: χ^2 (2) = 0.68, p = .71; reading: χ^2 (2) = 0.04, p = .98). Correlations between the latent variables can be seen in Tables 5 and 6. In both models there is a substantial correlation between the fine motor and executive function latent variables (rs = −0.42 to −0.43). However, the correlations between the executive function latent variable and later arithmetic (r = 0.64) and reading (r = 0.59) were higher than the corresponding correlations with fine motor skills latent variable (r = −0.27

Table 5
Correlations among the latent variables for the arithmetic model (a) shown in Fig. 2.

	1.	2.	3.	4.
Five-years-old				
1. Fine motor	–			
2. Executive function	−0.42**	–		
3. Addition	−0.21**	0.79**	–	
Six-years-old				
4. Arithmetic	−0.27**	0.64**	0.51**	–

** $p < .01$.

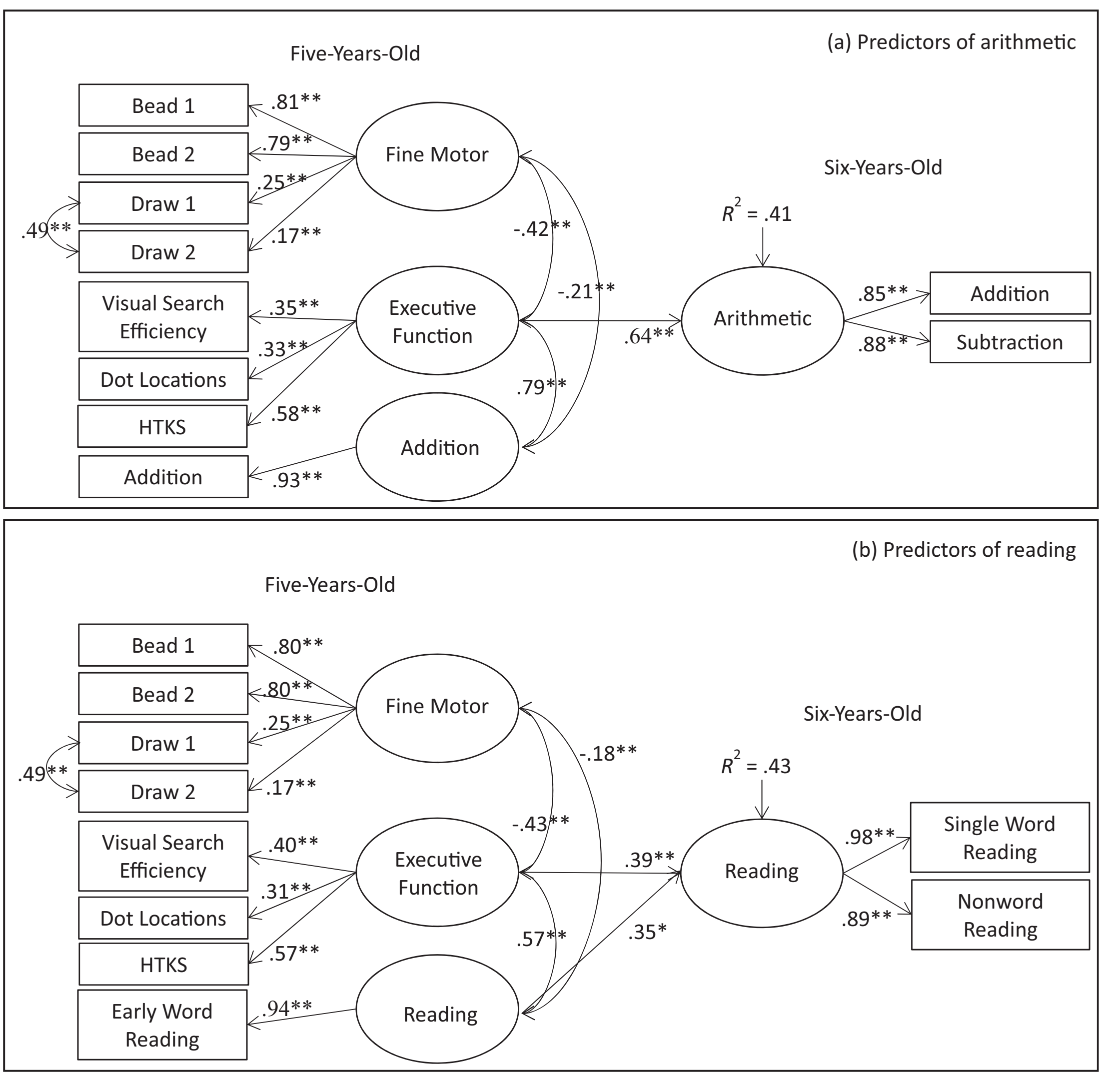

Fig. 2. Latent variable path model showing the relation between fine motor, EF, corresponding autoregressor and academic outcome in children. Two headed arrows represent correlations. Bead = bead threading; Draw = drawing trails; HTKS = head, toes, knees, shoulders; * $p < .05$; ** $p < .01$.

Table 6
Correlations among the latent variables for the reading model (b) shown in Fig. 2.

	1.	2.	3.	4.
Five-years-old				
1. Fine motor	–			
2. Executive function	−0.43**	–		
3. Reading	−0.18**	0.57**	–	
Six-years-old				
4. Reading	−0.23**	0.59**	0.57**	–

** $p < .01$.

and −0.23 respectively). In line with the findings of Roebers et al. (2014), only executive function (and not fine motor skills) accounted for significant variance in later academic performance in these models.

Finally, to address the relative roles of domain-general and domain-specific predictors of academic performance, we added the respective domain-specific predictors to each model. For arithmetic we added latent variables reflecting number knowledge, counting and numerosity judgment; for reading we included latent variables reflecting letter-sound knowledge, phoneme awareness, and RAN. As our previous models (see Fig. 2) showed that fine motor skills was not a predictor of academic performance over and above executive function and the relevant autoregressor, it was omitted from these more complex models. The final models with the nonsignificant paths deleted are shown in Fig. 3 and provide a very good fit to the data (arithmetic: χ^2 (53) = 47.76, $p = .68$, RMSEA = 0.00, CFI = 1.00; reading: χ^2 (43) = 64.45, $p = .19$, RMSEA = 0.03, CFI = 0.99). Dropping the nonsignificant paths caused no appreciable loss in fit to either model (arithmetic: χ^2 (2) = 0.62, $p = .73$; reading: χ^2 (2) = 3.76, $p = .15$). Overall, these final models account for 42% of the variance in arithmetic performance and 47% of the variance in word reading ability. It is notable that if we retained the path from executive function to arithmetic in the model shown in Fig. 3a there was no additional variance accounted for in arithmetic (change in $R^2 = 0.00$), similarly if we retained the path from executive function to reading in the model shown in Fig. 3b the increase in the variance accounted for in reading was tiny and nonsignificant (change in $R^2 = 0.01$). These models therefore demonstrate very clearly that once domain-specific predictors are included in our models, executive function accounts for no appreciable variance in arithmetic or reading skills.

The pattern of correlations between the latent variables are informative (see Tables 7 and 8). Arithmetic has a stronger correlation with executive function ($r = 0.57$) than any of the established domain-specific predictors (*rs* = 0.48 to 0.53; see Table 7). Executive function, however, also shows very strong correlations with the domain-specific predictors (number knowledge, numerosity judgment, counting and addition). Only number knowledge and numerosity judgments accounted for unique variance in arithmetic performance in the final model. Similarly, executive function and the domain-specific predictors correlated moderately with reading (*rs* = 0.51 to 0.58; see Table 8), and executive function also showed strong correlations with the domain-specific predictors (letter-sound knowledge, phoneme awareness, RAN, and reading). Once again in the final model only domain-specific skills (sound deletion, RAN and reading) accounted for unique variance in later reading ability, as in the model for arithmetic.

4. Discussion

This large-scale longitudinal study compared the relative role of domain-specific and domain-general predictors of later performance in arithmetic and reading ability during the first two years of formal schooling. The main aim of the study was to provide a clearer picture of the predictive power of domain-general and domain-specific competencies measured at early school age on formal learning. Our study extends previous research (e.g., Gashaj et al., 2019; Pinto et al., 2016; Suggate et al., 2019) by focusing on a school-aged sample and using multiple measures of performance in each domain coupled with latent variable models to control for measurement error. Although fine motor skills were weak predictors of later reading and arithmetic skills when considered in isolation, their role was essentially subsumed by our measure of executive function. Furthermore, executive function did not account for significant variance in arithmetic or reading when entered alongside well-established domain-specific predictors of each skill. For arithmetic, number knowledge and numerosity judgment were the only significant unique predictors and for reading, phoneme awareness and RAN were the only significant unique predictors. It must be noted, however, that while this highlights the importance of these skills to academic development, this study does not establish causality.

4.1. The Role of Domain-General Predictors of Arithmetic and Reading

We found that fine motor skills correlated with both arithmetic ($r = -0.25$) and reading performance ($r = -0.22$) and were a significant predictor of both when considered in isolation. This finding is in line with much previous research (e.g., Campos et al., 2000; Grissmer et al., 2010; Miller et al., 2017). One notable difference, however, between the current findings and earlier ones is that we observed comparable associations between fine motor skills and both arithmetic and reading whereas previous studies have typically reported stronger correlations between mathematical knowledge and motor skills than with reading (e.g., Pitchford et al., 2016; Rhemtulla & Tucker-Drob, 2011; but see Cameron et al., 2012). This discrepancy may simply be due to the measures used to assess reading and mathematical knowledge. We used tasks that assessed specific aspects of these abilities: word-level decoding (reading) and arithmetic. Much previous research has adopted a broader definition of these academic skills. For example, Campos et al. (2000) and Pitchford et al. (2016) included abilities in their outcome measures that we considered domain-specific predictors (e.g., letter-sound knowledge, recognizing numbers and digits, and counting).

Fine motor skills correlated moderately with our executive function latent variable (*rs* = −0.42 and −0.43). This supports the idea that the development of these skills is related in young children (e.g., Adolph, 2005; Adolph & Berger, 2006). Given the degree of shared variance between these abilities it is not surprising that, when entered into the analysis simultaneously, only executive function was an independent predictor or arithmetic or reading. Although this finding is at odds with Grissmer et al. (2010) and Cameron et al. (2012) who identified both fine motor and executive function as independent contributors to academic ability, these findings are consistent with those of Roebers et al. (2014). A key difference between these studies is that Grissmer et al. and Cameron et al. assessed only a single facet of executive function (attention and inhibition, respectively), while the current study and Roebers et al. used multiple measures of executive function. A further difference is age. The current study and that of Roebers et al. related fine motor skills in 5- to 6-year-old children to academic performance approximately one year later. Cameron et al. (2012) related fine motor skills at an earlier age (3- to 4-years) to academic performance assessed at 5.4 years of age. It is possible that very early variations in motor skills predict initial levels of academic performance at the beginning of school. Further studies are required to test this idea. If it is true, our findings suggest such effects are short-lived. Finally, effects may be task dependent. For example, in a study of the relation between fine motor skills and reading at early school age, Pritchard et al. (2021) found that handwriting was a stronger predictor of reading than other fine motor skills (i.e., drawing trials, shape copying). This was true even in the context of the best-established longitudinal predictors of reading. As such, and in line with the research by Pritchard et al., it may be that a continued emphasis on children's handwriting skills is more important than interventions focused on more general measures of fine motor skills.

Nevertheless, our findings clearly indicate that executive function is a stronger predictor of academic performance than fine motor skills.

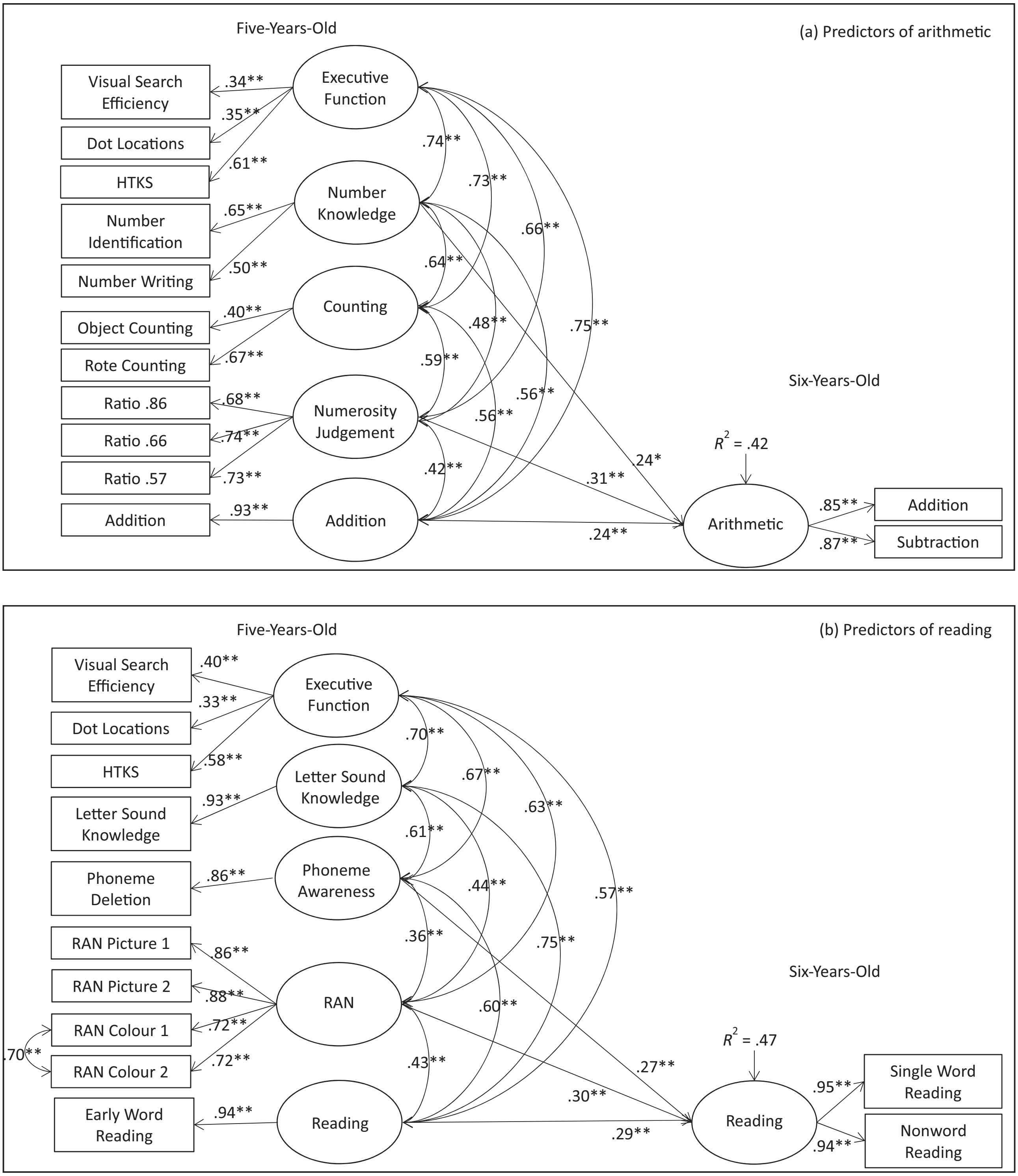

Fig. 3. Latent variable path model showing the relation between predictors at school entry and later arithmetic (a) and reading (b) ability in children. Two headed arrows represent correlations. HTKS = head, toes, knees, shoulders RAN = rapid automatized naming; * $p < .05$; ** $p < .01$.

However, neither executive function nor fine motor skills predicted either arithmetic or reading skills once better-established predictors of these skills were included. However, modest correlations were observed between the domain specific indicators and executive function, particularly for HSTK task ($rs = 0.18$ to 0.44). Thus, executive function may have some role in the development of these foundational skills. Certainly, our findings fail to provide any support for idea that motor proficiency frees up attentional resources that can then be allocated to learning other skills (Cameron et al., 2015). But as noted above it is possible that such effects operate earlier in development than the age considered here.

4.2. *The Role of Domain-Specific Predictors of Arithmetic and Reading*

Our findings largely confirm previous research concerning the domain-specific predictors of early variations in reading and arithmetic.

Table 7
Correlations among the latent variables for the arithmetic model (a) shown in Fig. 3.

	1.	2.	3.	4.	5.
Five-years-old					
1. Executive function	–				
2. Number knowledge	0.74**	–			
3. Numerosity judgment	0.66**	0.48**	–		
4. Counting	0.73**	0.64**	0.59**	–	
5. Addition	0.75**	0.56**	0.42**	0.56**	–
Six-years-old					
6. Arithmetic	0.57**	0.53**	0.53**	0.48**	0.51**

** $p < .01$.

Table 8
Correlations among the latent variables for the reading model (b) shown in Fig. 3.

	1.	2.	3.	4.	5.
Five-years-old					
1. Executive function	–				
2. Letter sound knowledge	0.70**	–			
3. Phoneme awareness	0.67**	0.61**	–		
4. Rapid automatized naming	0.63**	0.44**	0.36**	–	
5. Reading	0.57**	0.75**	0.60**	0.43**	–
Six-years-old					
6. Reading	0.53**	0.51**	0.55**	0.52**	0.58**

** $p < .01$.

We found that phoneme awareness and RAN were powerful predictors of variations in early reading skills. Letter-sound knowledge was strongly correlated with reading ability, but due to its shared variance with phoneme deletion was not a unique predictor of reading. The role of phoneme awareness and RAN as predictors of early reading skills replicates a number of earlier findings (Caravolas et al., 2013; Clayton et al., 2019).

As expected, we found that number knowledge was a predictor of arithmetic skills (see Göbel et al., 2014). In addition, numerosity judgment was a powerful correlate of arithmetic in this study ($r = 0.53$); more powerful than in most previous studies that have examined this relation (rs = 0.20 to 0.24: Chen & Li, 2014; Fazio et al., 2014; Schneider et al., 2017). This may reflect the fact that we used a latent variable to assess numerosity judgments (eliminating measurement error) and that numerosity judgments were assessed earlier here than in most other studies in this area.

These domain-specific findings align well with earlier research (cf. Suggate et al., 2019). Pinto et al. (2016) found that number recognition was a predictor of mathematics, and phonological awareness a predictor of reading. Gashaj et al. (2019) found that numerosity understanding was an independent predictor of mathematics. Importantly, while Pinto et al. and the current study found domain-general skills to be non-significant once domain-specific abilities are accounted for, Suggate et al. (2019) found fine motor skills to predict reading and Gashaj et al. found evidence for working memory (i.e., updating) being a predictor of mathematics. This may simply be because Suggate et al. used a latent variable to represent their fine motor skills assessments, meaning that measurement error was controlled, while this was not the case for their measures of executive function or domain-specific skills which were instead entered as individual skills into their models. Gashaj et al. only assessed one domain-specific predictor: numerosity understanding. Had they assessed multiple domain-specific skills (as in the current study), working memory may have no longer accounted for unique variance in performance. Alternatively, it may be that working memory is a predictor of performance in arithmetic over and above general executive function ability. To address this issue, further research is needed to assess working memory as a predictor of arithmetic when considered alongside a wide variety of domain-specific skills such as those in the current study.

4.3. Limitations

In this study we have looked at the relative contribution of domain-specific skills and domain-general skills on later academic performance in the early years of formal schooling. In assessing fine motor skills, we used tasks taken from the Movement-ABC which is a standardized assessment of movement (Henderson et al., 2007). It is worth noting that the tasks selected allowed us to measure dexterity (i.e., bead threading) and grapho-motor skills (i.e., drawing trails), both of which capture small muscle movements associated with fine motor skills (Luo et al., 2007). However, the factor loadings of the drawing trails task on the fine motor latent variable were much lower than those of bead threading. This limitation of the drawing trails task has been observed in earlier research (e.g., Schulz et al., 2011). Future research may benefit from considering other measures of grapho-motor performance that may load more strongly onto the fine motor latent variable.

While this study has focused on elucidating the role of general fine motor skills on later academic performance, some research (e.g., Martzog et al., 2019) has suggested that fine motor skills in fact have a three-factor structure: dexterity (e.g., bead threading), grapho-motor (e.g., drawing trails) and speed (e.g., tapping). To clarify further the role of fine motor skills (and executive function) in the development of reading and arithmetic, future research could look at the relative contributions of each facet of this three-factor structure using latent variables represented by multiple tasks assessing the same construct. Specific tasks or subdomains of fine motor skills may also be differentially related to domain-specific skills. Of final note, although we refer to RAN as a domain-specific skill, it may be argued to be reflective of a domain-general skill given evidence to suggest it correlates with both reading and mathematics. It may therefore also be regarded as a general predictor of arithmetic and reading (e.g., see Koponen et al., 2016; Korpipää et al., 2020).

5. Conclusions and future directions

It has been suggested that the domain-general skills of fine motor skills and executive function are key predictors of school readiness (e.g., see McClelland & Cameron, 2019). Although fine motor skills show a weak correlation with later reading ($r = -0.22$) and arithmetic skills ($r = -0.25$), and executive function shows moderate correlations (reading: $r = -0.59$; arithmetic: $r = -0.64$), our findings show that they are much less powerful predictors than well-established domain-specific skills (i.e., number knowledge and numerosity judgments as predictors of arithmetic and phoneme awareness and RAN as predictors of reading). These findings suggest that measures of domain-specific skills should be considered in assessments of early academic achievement alongside measures of domain-general skills. It also indicates that it is domain-specific skills that may be the most advantageous targets of interventions to enhance academic performance in the early years of schooling. Although there was no direct relation between executive function and arithmetic or reading in our study, there was a large amount of overlap between the most comprehensive of our executive function tasks (i.e., the HTSK task) and measures of domain-specific skills. Thus, our study is also important in highlighting a need for future research to assess the extent to which very early variations in executive function may be related to the development of skills that are foundational for reading (e.g., phoneme awareness) and arithmetic (e.g., number knowledge) and vice-versa.

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