Cognitive and home predictors of precocious reading and math before formal education

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Abstract

Children start formal schooling with substantial individual differences in their early literacy and numeracy abilities, but little is known about predictors of precocious (i.e. early advanced) reading and math. In this study, we investigated contributions from a range of cognitive and home-related predictors to early reading, arithmetic and applied math in 224 Dutch kindergartners (M_{age}=5;5). Our results showed that precocious reading and math were differentially predicted by specific combinations of domain-specific, domain-general and cross-domain cognitive skills. For reading, we primarily observed contributions from literacy-specific skills, especially letter knowledge. For mathematics, we observed contributions from various domain-specific, domain-general and cross-domain cognitive skills. Predictors of 'basic' arithmetic skills differed from predictors of 'precocious' arithmetic fluency, suggesting qualitative differences between typical and precocious learners. Contributions from children's home environments (parental education levels, parent-child activities) provided small, yet notable results. Together, our results provide novel insights into the (co-)development of precocious reading and math in preschool-aged children.

Keywords: Early reading, Early math, Precocious, Co-development, Home environment

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Children enter the formal school setting with substantial individual differences in their early academic abilities, particularly with regards to early literacy and numeracy (Napoli & Purpura, 2018). Researchers have attempted to explain these individual differences by assessing the roles of children's early cognitive abilities and characteristics of their home environments (e.g. parental education levels and parent-child activities). To date, most studies have focused on typical populations, or on children at risk of developing specific learning disabilities such as dyslexia and dyscalculia (Peters et al., 2020; Viesel-Nordmeyer et al., 2023). As a result, much less is known about the contributions of cognitive and home-related factors within the population of precocious learners. Precocious learners can be defined as children who demonstrate advanced reading and/or math abilities beyond what is typically expected for their age, for instance before the start of formal education. As studies on precocious reading and/or math have been scarce, it is not well known how precocious abilities are predicted by children's home environments and/or their early cognitive skills. Moreover, it is uncertain whether differences between precocious and typical learners are solely quantitative (i.e. differences *in degree*), with precocious learners representing the higher end of the ability spectrum, or if these differences are qualitative, indicating differences *in kind* between precocious learners and their peers (Bakker, Torbeyns, et al., 2023; Peters & Ansari, 2019).

In the current study, we investigated the cognitive and home-related predictors of early reading and math precocity in kindergarten. By assessing reading and math concurrently within the same sample, we systematically examined the contributions from a wide range of cognitive and home-related predictors across both domains. The cognitive predictors were divided into domain-specific skills (which relate specifically to one particular domain, i.e. reading or math) and domain-general skills, which support learning in a broader sense and are applicable across different domains (Coolen et al., 2021; De Smedt, 2022; Zhang & Peng, 2023). Cross-domain influences between literacy- and numeracy-related skills were also studied, in order to assess the patterns of co-development of early reading and math.

1.1: Early Reading: Domain-Specific Cognitive Predictors

Throughout the years, researchers have identified several linguistic and language-related skills that are fundamental for early reading development. Chief among these domain-specific predictors are phonological awareness, letter knowledge, vocabulary and naming speed (e.g. Blachman, 2000; Kirby et al., 2003; Snel et al., 2016). Phonological awareness refers to a child's ability to recognize and manipulate the phonemic structure of spoken language (Blachman, 2000; Gillon, 2005). Phonological awareness comprises a range of interrelated skills, including the ability to combine a sequence of phonemes to form a word (*phoneme blending*), the ability to split words into separate phonemes (*phoneme segmentation)*, or other skills such as alliteration and rhyming (Blachman, 2000; Gillon, 2005; Olson et al., 2006). Various studies have highlighted the importance of phonological awareness in early reading in general (Blachman, 2000; Clayton et al., 2020; Liberman, 1973; Mann & Liberman, 1984), and in precocious readers in particular (Briggs & Elkind, 1977; Olson et al., 2006; Stainthorp & Hughes, 1998).

A second foundational skill for the development of early reading is letter knowledge (i.e. letter-sound knowledge), which refers to children's knowledge of letter symbols and their corresponding sounds. Prior research has identified letter knowledge as one of the strongest precursors of reading development in alphabetic orthographies such as English and Dutch (Blaiklock, 2004; Gijsel et al., 2006). Furthermore, superior phonological awareness and letter knowledge have both been identified as the main communalities between precocious readers across different languages (Bergman Deitcher et al., 2021; Silvén et al., 2004; Tafa & Manolitsis, 2008).

Next to phonological awareness and letter knowledge, children's vocabulary size is regarded as an important predictor of individual differences in early reading. Children's receptive vocabulary has been found to predict both phonological and word decoding skills, both cross-sectionally and longitudinally (Hansen & Broekhuizen, 2021; Van Goch et al., 2014). Some studies have also reported larger expressive and/or receptive vocabularies in precocious readers compared to their peers (Silvén et al., 2004; Stainthorp & Hughes, 2000), while other studies have not (Bergman Deitcher et al., 2021).

Lastly, another cognitive skill associated with early reading is naming speed, typically assessed using rapid automatized naming (RAN) tasks. RAN tasks assess the speed by which children can name continuous lists of familiarized objects, colors, letters or digits. RAN has been established as a longitudinal predictor of reading skills, even when controlling for e.g. phonological awareness, letter knowledge, vocabulary and (verbal) STM (Clayton et al., 2020; Kirby et al., 2003; Snel et al., 2016). Although the exact mechanism(s) underlying the association between RAN and reading are not precisely understood, it is commonly believed that RAN and reading both tap orthographic processing speed, articulation fluency and the speed by which phonological representations can be retrieved from long-term memory (Hjetland et al., 2019; Lervåg & Hulme, 2009).

1.2: Early Reading: Domain-General Cognitive Predictors

Several domain-general cognitive skills have been associated with early reading in general, and precocious reading in particular. Chief among these cognitive skills are fluid intelligence and verbal short-term memory. Fluid intelligence refers to a person's capacity of abstract reasoning and novel problem solving. In young children, fluid intelligence (i.e. non-verbal reasoning) has been found to interact with (and/or support) the acquisition of letter-sound correspondence rules (Levy, 2011; Peng et al., 2019).

Verbal short-term memory (STM), a concept related to verbal working memory (WM), has also been linked to early reading development. In the literature, it is commonly accepted that tasks which merely require the 'passive' short-term storage and retrieval of verbal information (e.g. forward word span tasks) address the phonological loop component of working memory. These tasks are often referred to as verbal STM tasks (De Smedt, 2022; Gathercole et al., 2006; Swanson, 2006). By contrast, complex span tasks, which involve both the storage and 'active' manipulation of verbal information (e.g. backward word span tasks) are often considered to tap both the phonological loop *and* central executive components of working memory, and are often referred to as verbal working memory (WM) tasks (Gathercole et al., 2006; Swanson, 2006).

In prior studies, pre-school measures of verbal STM (or WM) have been found to predict reading abilities in subsequent years, even when controlling for other cognitive and environmental factors (Dufva et al., 2001; Mann & Liberman, 1984). Furthermore, verbal STM deficits are frequently reported in children facing developmental reading difficulties such as dyslexia (Kramer et al., 2000; Tijms, 2004). However, to date, the literature regarding the role of verbal STM in precocious reading remains limited. Earlier studies have found only moderate associations between verbal STM and precocious reading (Jackson et al., 1988; Jackson & Myers, 1982). Moreover, in children aged 13 to 14, high verbal abilities were found to be associated with high verbal STM performance, while high math abilities were more strongly associated with visuospatial STM. This suggests that the role of STM is different for different domains of academic precocity (Benbow & Minor, 1990; Dark & Benbow, 1991).

1.3: Early Math: Domain-Specific Cognitive Predictors

In the literature, various numeracy-specific skills have been associated with individual differences in early mathematical abilities (De Smedt, 2022; Schneider et al., 2017). These numeracy-specific skills encompass various domains of numerical cognition, including counting, symbolic and non-symbolic magnitude processing, mapping between quantities and numerical symbols, ordering and estimation (De Smedt et al., 2013; Friso-van den Bos et al., 2015; Kolkman et al., 2013; Koponen et al., 2019; Merkley & Ansari, 2016).

Numerical magnitude processing skills are typically assessed through symbolic or non-symbolic comparison tasks, in which participants are presented with pairs of numerical symbols or non-symbolic quantities (e.g. dot arrays), and are asked to indicate which one represents a larger magnitude (Hawes et al., 2019; Lyons et al., 2014). While both symbolic and non-symbolic comparison skills have been shown to predict mathematical abilities in kindergarten and subsequent years, symbolic comparison skills are typically reported as the strongest predictor (De Smedt et al., 2013; Hawes et al., 2019; Schneider et al., 2017).

Symbolic number line estimation tasks are frequently used to assess children's understanding of numerical magnitudes and the relationships between numbers. In these tasks, children are asked to place specific written numbers at their appropriate positions along an empty line, with the endpoints labeled (for example) 0 and 100. In young children, accuracy on this task is associated with various numerical and mathematical abilities, such as counting, symbolic comparisons and arithmetic (Booth & Siegler, 2006; Geary, 2011; Schneider et al., 2018). Although the precise mechanism(s) underlying its relationship to mathematics is still debated, it is believed that number line estimation assesses the ability to map numbers onto space (number-to-space mapping), which in turn is considered a building block for math proficiency (Booth & Siegler, 2006; Schneider et al., 2018; van 't Noordende et al., 2021).

A large body of research has demonstrated the role of symbolic comparison and number line estimation skills in typical numerical development (De Smedt et al., 2013; Schneider et al., 2017) and in children with mathematical learning difficulties such as dyscalculia (Landerl et al., 2004; Schwenk et al., 2017). However, it remains uncertain whether above-average (or precocious) symbolic processing skills are also associated with precocious math abilities, and whether this association remains significant when controlling for other cognitive skills. In a study by Hoard et al. (2008), a group of 46 'intellectually precocious' children (mean age: 6) showed superior performance on both a number line estimation task and an arithmetic task (*addition*), compared to age-matched peers. However, these precocious children also outperformed their peers across various WM tasks, making it difficult to determine whether their superior numerical and arithmetic abilities reflect a domain-specific or domain-general advantage (Hoard et al., 2008). Furthermore, in a study in slightly older children (aged 8-10), Bakker and colleagues found that high-achieving math learners excelled in symbolic order processing but not symbolic comparison, compared to their peers. Precocious math learners also showed superior spatial visualization skills, whereas verbal and visuospatial WM did not significantly differ between the groups. When considering all predictors simultaneously, only spatial visualization skills emerged as a significant predictor of precocious math abilities (Bakker, Pelgrims, et al., 2023).

1.4: Early Math: Domain-General Cognitive Predictors

Various domain-general cognitive skills have been associated with early numerical and mathematical development. Most notably, fluid intelligence and (verbal and visuospatial) STM and WM have been identified as significant predictors of early math development in general (Coolen et al., 2021; De Smedt, 2022; Peng et al., 2016) and math precocity in particular (Bakker, Pelgrims, et al., 2023; Swanson, 2006).

In a study by De Smedt et al. (2009), children's non-verbal (fluid) reasoning skills significantly predicted their math achievement throughout the first two years of primary school, after controlling for various components of STM and WM. Relatedly, in a study by Kleemans et al. (2012), non-verbal intelligence predicted numeracy skills in kindergartners (after controlling for WM), but this effect was diminished when early literacy skills and home numeracy factors were entered into the model. In a study in slightly older children, Kroesbergen and Schoevers (2017) reported that high math achieving fourth graders (aged 8-10) did not outperform their peers on a symbolic comparison and a number line estimation task, but they did perform significantly better in two domain-general cognitive skills, namely visuospatial WM and creativity (Kroesbergen & Schoevers, 2017).

Taken together, research on the cognitive factors underlying reading and math precocity in kindergarten (i.e. before formal education) remains limited. While several studies have explored specific combinations of domain-specific and domain-general cognitive predictors in typically developing populations, a comprehensive and systematic investigation of the cognitive predictors of early reading and math precocity is still lacking.

1.5: Co-development of Early Reading and Math

In addition to studying the predictors of early reading and math in isolation, there is a growing body of research dedicated to studying their co-development. Across various age groups (including the earliest primary school years), high correlations have been found between children's reading and math performance (Jöbstl et al., 2023; van Bergen et al., 2014; Vanbinst et al., 2016, 2020). Furthermore, high comorbidities are also reported between learning disabilities across both domains, such as dyslexia and dyscalculia (Jöbstl et al., 2023; Landerl & Moll, 2010; Vanbinst et al., 2020). Crucially, however, the co-occurence of reading and math has not yet been investigated in the context of precocious learners (Bergman Deitcher et al., 2021), making this a relevant domain for further study.

Earlier studies have often investigated the co-development of reading and math by studying their shared cognitive foundations (Collins & Laski, 2019; Peng et al., 2020). For instance, verbal and visuospatial STM (and WM) have been associated with both reading and math. Specifically, reading abilities have generally been more strongly associated with verbal

STM, whereas math has been linked to both verbal and visuospatial STM (De Smedt et al., 2009; Friso-van den Bos et al., 2013; Peng et al., 2016, 2018). Fluid intelligence has also been linked to both domains, but its association appears to be strongest for math (Peng et al., 2019).

In addition to studying the shared cognitive foundations of reading and math, there has also been a growing focus on the (bi)directional (i.e. cross-domain) influences between both domains in early development (Peng et al., 2020; Zhang et al., 2023; Zhang & Peng, 2023). For instance, earlier studies have found that phonological awareness not only predicts children's reading but also arithmetic development, even when controlling for various other skills (De Smedt et al., 2010; Vanbinst et al., 2020). Moreover, various skills that are generally regarded as literacy-specific (e.g. vocabulary) have also been associated with numerical and mathematical development (Kleemans et al., 2011, 2012; LeFevre et al., 2010; Purpura et al., 2011). A theoretical framework for these cross-domain associations was provided by LeFevre et al. (2010), who argued that one of the key 'pathways' in early numerical development is a general linguistic pathway, in which children rely on both phonology and vocabulary when learning to connect written numerals with numerical magnitude representations (LeFevre et al., 2010; Purpura & Napoli, 2015).

Although the association between numeracy-related skills and early reading has received less attention, Vanbinst et al. (2020) showed that kindergartners' number recognition skills predicted not only arithmetic abilities but also letter knowledge, even after controlling for age, general intelligence and phonological awareness. In line with this, several studies have reported strong correlations between number and letter knowledge in kindergartners, suggesting that symbolic knowledge across both domains is significantly associated during early development (Austin et al., 2011; Bergman Deitcher et al., 2021; Piasta et al., 2010).

Lastly, it should be noted that although RAN has typically been associated with early reading, recent studies have also shown a relationship between RAN and mathematics (Jöbstl et al., 2023; Koponen et al., 2013, 2017). This relationship is strongest for math tasks that tap the automatic retrieval of math facts from long-term memory, such as (single-digit) arithmetic fluency tasks (Jöbstl et al., 2023; Koponen et al., 2017; Peng et al., 2020).

1.6: Home Environment

In addition to the literature on the cognitive predictors of early reading and math, there has been a growing interest in studying the role of children's home learning environment (Napoli & Purpura, 2018; Skwarchuk et al., 2014). Prior research has investigated various aspects of children's home learning environment, including parental demographic characteristics (e.g. socioeconomic status; SES), parent-child activities and various types of parental beliefs, attitudes and expectations.

For both literacy and numeracy, parent-child activities are commonly categorized into informal and formal activities. Informal (i.e. 'indirect') activities can be defined as casual, everyday interactions that may implicitly stimulate children's literacy or numeracy skills, without the parents' deliberate intention (Sénéchal & LeFevre, 2002). Examples of informal literacy-related activities include shared storybook reading or storytelling, and informal numeracy-related activities may include playing board games or doing groceries together (Purpura et al., 2020; Sénéchal & LeFevre, 2002). In contrast, formal (i.e. 'direct') parent-child activities involve more intentional and explicit efforts to promote children's literacy or numeracy abilities. Examples of formal literacy-related activities include reading 'letter books' together (Sénéchal & LeFevre, 2002), while formal numeracy-related activities may include practicing calculations or reading age-appropriate 'math books' together (Daucourt et al., 2021; Mutaf-Yıldız et al., 2020).

Although the literature is not unanimous, most studies have reported that early word reading abilities are more strongly associated with formal literacy-related activities (compared to informal activities), whereas phonological awareness, vocabulary and broader language skills appear to be more strongly related to informal activities (Khanolainen et al., 2020; Sénéchal & LeFevre, 2002; Skwarchuk et al., 2014; Torppa et al., 2022). With regards to numeracy, most studies have reported that formal activities are a stronger predictor of symbolic numerical skills compared to informal activities (LeFevre et al., 2010; Purpura et al., 2020), although a few exceptions should be noted (De Keyser et al., 2020; Dunst et al., 2017; Trickett et al., 2022). In general, it should be noted that research on the role of the home numeracy environment has been limited compared to the home literacy environment, and results have been less consistent and conclusive for home numeracy compared to home literacy (James-Brabham et al., 2023; Khanolainen et al., 2020; Skwarchuk et al., 2014).

Despite the growing body of research in this field, several important questions still remain unanswered. For instance, it is unclear to what extent the relationships between parental activities and children's literacy/numeracy abilities might be influenced by demographic or cultural factors, or by parents' beliefs and attitudes towards reading and math. Various studies have shown that parental education level (often used as a proxy of SES) is positively related to the frequency of home activities (Dunst et al., 2017; Segers et al., 2016). Also, parents who hold higher expectations for their children's academic development also report higher frequencies of (formal) literacy or numeracy activities (Daucourt et al., 2021; Skwarchuk et al., 2014).

Since the majority of studies within this field have concentrated on typical populations or children at risk of developing specific learning difficulties, it remains to be determined to what extent home-related factors are associated with precocious reading and/or math. It has been reported that parents of precocious readers tend to show higher levels of reading enjoyment themselves, and a higher responsiveness and encouragement towards their child's early interest in reading (Olson et al., 2006). Moreover, some studies found that precocious readers were read to more regularly by their parents or older siblings (Briggs & Elkind, 1977;

Durkin, 1966; Stainthorp & Hughes, 2004), while others found no differences between precocious and non-precocious readers (Hood et al., 2008; Stainthorp & Hughes, 2000).

With regards to math precocity, a latent profile analysis by Bakker et al. (2023) showed that precocious math achievement (at age 4-6) was not significantly associated with parental activities and expectations, and only weakly associated with parental SES and parents' appraisal of the importance of numeracy. Furthermore, a systematic review by Mutaf-Yildiz et al. (2020) indicated that only 'advanced' numeracy interactions (e.g. practicing with larger numbers or arithmetic operations) but not 'basic' interactions were associated with children's (advanced) math skills. However, this observation may be explained by the notion that formal (or 'advanced') math activities may be most beneficial if children already have a basic understanding of number symbols and the relations between numbers (Silver et al., 2024), or by the notion that parents might only engage in such activities if they believe their child has mastered these elementary numerical skills. Furthermore, as noted by Daucourt et al. (2021), parents who are more comfortable with mathematics might engage in numeracy-related interactions more frequently, or in ways that might enhance the quality of these interactions.

Lastly, the role of digital media represents an underinvestigated area within the home environment literature. In recent years, digital media have become an increasingly important part of young children's ecosystem at home (Hutton et al., 2020; Sundqvist et al., 2023), but only very few studies have investigated the associations between screen-based media use (e.g. educational videos or games) and children's reading and math abilities (Hutton et al., 2020; Madigan et al., 2020). Therefore, the current study will also examine the role of 'digital activities' in early reading and math development.

1.7: The current study

In this study, we aimed to address three main goals. First, we assessed the contributions from a wide range of home-related and cognitive predictors to early (precocious) reading. The home-related predictors included measures of literacy-related parent-child activities (formal, informal and digital), as well as parental education levels, parental literacy-related expectations, parents' own reading enjoyment and their appraisal of literacy importance. The cognitive predictors consisted of a wide range of domain-specific, domain-general and cross-domain cognitive skills. Specifically, this selection included: phonological awareness, letter knowledge, vocabulary, verbal STM, visuospatial STM, non-verbal reasoning, RAN, rote counting, number line estimation and symbolic comparisons. In line with previous literature, we expected that parental education levels and formal literacy-related activities would show the strongest home-related contributions. With regards to the cognitive predictors, we expected to find the strongest contributions for letter knowledge and phonological awareness (*literacy-specific*) and verbal STM (*domain-general*).

Second, using a similar approach, we assessed the contributions from a wide range of home-related and cognitive predictors to early (precocious) arithmetic abilities. The selection of home-related predictors was similar to the selection described above, but specific to numeracy instead of literacy. The selection of cognitive predictors was identical to the selection described above, in order to systematically compare the cognitive predictors for reading versus arithmetic. In line with previous literature, we expected parental education levels and formal numeracy-related activities to show the strongest home-related contributions for arithmetic. With regards to the cognitive predictors, we expected to find the strongest contributions for symbolic comparisons and number line estimation (*numeracy-specific*), visuospatial STM (*domain-general*), and letter knowledge (*cross-domain*).

Third, we examined the home-related and cognitive predictors of children's 'applied math' abilities. In this task, children had to apply their knowledge of the number system and basic mathematical principles to various fictional situations. This task was used alongside the arithmetic task in order to assess children's mathematical abilities independently of knowledge or experience with written arithmetic problems. We hypothesized that the predictors of applied math abilities would be roughly similar to the predictors of arithmetic, but we expected a slightly stronger contribution from non-symbolic and language-related skills such as phonological awareness, vocabulary and verbal STM.

2. Methods

2.1: Participants

The initial sample included 224 Dutch children in the early months of their second (i.e. last) year of kindergarten. The children were native Dutch speakers, recruited from 12 different schools in the Netherlands. Two children were excluded from our initial sample because they were one year older than their peers, resulting in a final sample of 222 kindergartners (115 girls, 107 boys). The ages ranged between 4;9 and 6;2 years (mean age: 5;5 years). In the Netherlands, children start in the first year of kindergarten when they turn 4 years old. During kindergarten, children are offered play-based preparatory learning activities. Formal literacy and numeracy instruction only starts one year later, in first grade. In our study, all children from the participating kindergarten classes were eligible to participate, but parents/caregivers had to give active consent for their child's participation.

2.2: Materials

Parental questionnaire

Parental questionnaires were digitally distributed one month before the start of the behavioral sessions. Questionnaires were filled in by one parent/caregiver per child. In total, 204 out of 222 parent dyads (91.9%) completed the questionnaire in full, and 10 questionnaires were completed partially. Out of the 204 complete questionnaires, 162 (79.4%)

were completed by the mother. For 181 out of 204 children (88.7%), both parents (if applicable) had Dutch as their native language, and 194 out of 204 children (95.1%) had at least one parent with Dutch as their native language.

Parental education level: Parents were asked to indicate their highest educational degree, both for themselves and for their co-parent (if applicable). Education levels were then coded on a six-point scale, and an average was calculated for each parent dyad. The distribution of parental education levels is shown in section S1 of the Supplementary Materials.

Parent-child activities were assessed using a set of twenty items. These items were constructed based on prior studies (Kleemans et al., 2012; LeFevre et al., 2009; Segers et al., 2016; Sénéchal & LeFevre, 2002). The twenty items included sixteen (formal and informal) parent-child activities; eight for literacy and eight for numeracy. In addition, four digital activity items were included, pertaining to educational videos and games related to literacy and numeracy, respectively. For all twenty items, parents were asked to rate the frequency of these activities on a five-point scale, ranging from 'Almost never' to 'Multiple times per day'. Two principal component analyses (PCAs) confirmed that the hypothesized factor structure ('formal', 'informal' and 'digital' activities) was indeed observed, and we constructed six scale scores: formal literacy activities, informal literacy activities, digital literacy activities, formal numeracy activities, informal numeracy activities, and digital numeracy activities. The results of the PCAs and the reliability of the scale scores are described in section S2 of the Supplementary Materials.

Parental expectations, parental appraisal of importance, and parental enjoyment of reading and math were assessed using six items. Parental expectations were assessed using the statement: "I expect that my child will show good reading (/math) abilities in the upcoming years of primary school". Parent's appraisal of importance was assessed using the statement: "I find it very important for my child to develop good reading (/math) abilities". Parent's reading/math enjoyment was assessed with the statement: “When I was a child, I much enjoyed reading (/math) in school”. All six statements were answered on a 10-point Likert scale, ranging from ‘totally disagree’ to ‘totally agree’. A complete overview of the questionnaire items is included in section S5 of the Supplementary Materials.

Behavioral Sessions: Literacy-Specific Skills

Phonological awareness: the Audisynt task from the Dutch ‘Diagnostiek van Technisch Lezen en Aanvankelijk Spellen’ (DTLAS; Struiksma et al., 2009) was used to assess children’s ability to perform phoneme blending, a subdomain of phonological awareness. In this task, the experimenter pronounced a series of isolated phonemes (i.e. consonant or vowel sounds), and the child was asked to combine these phonemes to form a word. The outcome measure was the number of correctly solved items (between 0 and 15).

Vocabulary: the Dutch version of the Peabody Picture Vocabulary Task (PPVT-III-NL) (Schlichting, 2005) was used to assess children's receptive vocabulary. Words were orally presented, and the child was asked to choose the correct image from four alternatives. The official starting rules and stopping rules were applied. Outcome measures were calculated by subtracting the total number of errors from the ceiling item. Reliability (lambda-2 coefficient) for this task is reported to be between .93 and .97 for young children (Schlichting, 2005).

Letter knowledge: a productive letter naming task from the DTLAS (Struiksma et al., 2009) was used to assess children’s letter-sound-correspondence knowledge. Children were asked to pronounce 34 letters (including common Dutch diphthongs) from a printed card. They were asked to produce the sounds associated with the letters (i.e. not the letter names). The outcome measure was the number of correctly pronounced items (between 0 and 34).

Word decoding (i.e. reading) was assessed using an adaptive procedure. All children were presented with a ‘pre-task’, in which they were asked to decode (i.e. read aloud) a list of five monosyllabic Dutch words (VC or CVC). Children who could correctly decode two or more words were included in the 'reading group', and presented with the actual reading task, which consisted of 'list 1' of the 'Drie-Minuten-Toets' (DMT; Verhoeven, 1995). In this reading fluency task, children were asked to read aloud (as quickly as they could) from a pseudo-random list of words that gradually increased in length and difficulty. The outcome measure was the number of correctly pronounced words within one minute. The reliability of this task is reported to be >.90 in first grade (Moelands et al., 2003).

Numeracy-Specific Skills

Counting: counting skills were assessed using a rote counting task, in which children were asked to recite the number sequence (as far as they could) in the correct order, starting at 1. The task was ended by the experimenter if the child reached 101. Children were allowed to make maximally one skipping error (or other type of error), meaning that if they counted to 100 but skipped 67, we would use 100 as their counting score. If children counted to 79 but skipped 55 and 67, we would use 66 as their counting score.

Number line estimation: a symbolic number line estimation task was administered digitally, on a touchscreen device. Children were asked to place specific written numbers at their appropriate positions along an empty horizontal line, with the endpoints labeled 0 and 10. After giving extensive instructions, six items (numbers 2, 3, 4, 6, 7 and 8) were presented in a random order. For each item, the percentage of absolute errors (PAE) was calculated using the following formula: ([response - target number]) / number line range (10) * 100%). Since PAE is an error score, the average PAE (averaged across the six items) was subtracted from 100 to obtain the accuracy score (i.e. our outcome score), in which higher scores reflect higher accuracy (Lomas et al., 2011; Siegler & Booth, 2004).

Symbolic number comparison was assessed using the Numeracy Screener (Hawes et al., 2019). Children were presented with pairs of single digits (on paper) and asked to mark the one that represented the larger magnitude in each pair. After an explanation and four practice items, children were given one minute to solve as many items as they could. The outcome measure was an adjusted score, calculated as the number of correct items – the number of incorrect/skipped items (Lyons et al., 2018).

Applied math: the "Applying knowledge of the number system" subtask of the Early Numeracy Test - Revised (ENT-R) (van Luit & van de Rijt, 2009) was used to assess math abilities independently of knowledge/experience with written arithmetic problems. In this untimed task, children had to apply their knowledge of the number system and basic mathematical principles to various daily situations. Each item consisted of an orally presented problem, illustrated with a schematic picture. For example, children were asked: "I have twelve cakes and I eat seven of them. How many cakes are left? Point to the picture that depicts the right answer". The children received nine items in a fixed order, and the outcome measure was the number of correctly solved items. The reliability of the entire ENT-R battery is reported to be .93 (van Luit & van de Rijt, 2009). In our current study, the split-half reliability (Spearman-Brown coefficient) for this task was .72.

Arithmetic abilities were assessed using an adaptive procedure, similar to the reading task. All children were presented with a 'pre-task', in which they were asked to solve two addition problems (*2+1* and *4+2*) and two subtraction problems (*3-1* and *5-2*). If children were not familiar with the addition or subtraction signs, they were told that these signs meant "adding the numbers" and "subtracting the numbers". Children were asked to write down the answer using a pencil. Only children who correctly solved all four items were included in the 'arithmetic group', and they were given the actual arithmetic task. Here, they were presented with the addition and subtraction cards from the 'TempoTest Automatiseren' (TTA) (De Vos, 2010), a timed arithmetic fluency task. The split-half reliability is reported to be high for both the addition (0.96) and subtraction (0.95) cards (De Vos, 2010). In our current study, the arithmetic scores within this subgroup were defined as the number of correctly solved items for addition and subtraction (each within one minute), added together into one score.

Domain-General Cognitive Skills

Verbal STM was assessed using a forward word list recall task (Geary, 2011; Hoard et al., 2008). Children were asked to reproduce random sequences of spoken words, presented by the experimenter. The task started with a sequence of two words; i.e. a span length of two. Two sequences of the same length were presented sequentially for each span length. The span length gradually increased, until the child incorrectly reproduced both sequences within the same span length. To match our outcome measure for the visuospatial STM task, the outcome measure was defined as the product (i.e. multiplication) of the number of correctly reproduced sequences and the longest span length in which a correct response was given. Children were also given a backward version of this task (to assess verbal working memory (WM)), but this task was excluded from our current analyses due to floor effects.

Visuospatial STM was assessed using a digital version of the forward Corsi block tapping task (Kessels et al., 2000), presented on a touch screen device. Children were asked to memorize the sequence in which a number of blocks were automatically ‘tapped’ on the tablet screen. Then, children were asked to reproduce this sequence by tapping the blocks in the same order. Similarly to the verbal STM task, the sequences gradually increased in length until the child incorrectly reproduced both sequences of the same span length. The outcome measure was defined as the product of the number of correctly solved items and the longest span length in which a correct response was given, as described by Kessels et al. (2008). Children were also given a backward Corsi block tapping task (assessing visuospatial WM), but this task was excluded from our analyses due to floor effects.

Non-verbal reasoning (i.e. fluid intelligence) was assessed using subsets A and C from the Raven's Standard Progressive Matrices battery (SPM; Raven et al., 1992). Both sets consist of a series of matrices, each showing an abstract pattern with a missing element. Children were asked to identify the missing piece from a set of multiple-choice options. After an explanation and three practice items, children were presented with 24 test items. There was no time limit for this task. The outcome measure was the total number of correct responses, summed over both subsets (maximum score: 24).

Naming speed was assessed using a Rapid Automatized Naming (RAN) task. After a training and familiarization period, children were asked to quickly name a continuous list of objects from a printed card. The objects were presented as black drawings on white paper (5 vertical rows of 15 items). All five objects represented common monosyllabic words. The outcome measure was the number of correctly named items within one minute.

2.3: Procedure

The current data were obtained from the first wave of data collection of the Radboud Early Academic Development Inquiry (READI); a longitudinal project on early literacy and numeracy. The behavioral sessions took place from late September through early December 2022, in the early months of the second (i.e. last) year of kindergarten. Children were tested individually by a trained experimenter, in a quiet room at the child's school. The sessions were divided into two blocks, administered on the same day with minimally 2 hours in between or on adjacent days. The duration of each block was around 35 minutes, resulting in approximately 60 to 70 minutes of testing per child. The tasks were always administered in the same order (Block 1: counting, literacy-specific tasks (except vocabulary), numeracy-specific tasks. Block 2: domain-general tasks, vocabulary). Children were rewarded for their effort with stamps and stickers. The research was independently reviewed by the Ethics Committee Social Sciences of Radboud University, and there was no formal objection.

2.4: Analyses

As described above, we used an adaptive procedure to assess children's reading (i.e. word decoding) and arithmetic abilities. Children were first presented with a 'pre-task', consisting of a small selection of basic items. Children who performed above the cut-off score on these pre-tasks were included in the 'reading group' or 'arithmetic group' (respectively), and they were presented with the actual reading task (DMT) or arithmetic task (TTA).

First, we calculated the descriptive statistics and the correlations between all variables. We then used independent samples *t*-tests (for each variable separately) to examine whether the 'reading group' significantly differed from the 'non-reading group' across the entire range of cognitive and home variables. The same was done to compare the 'arithmetic group' versus the 'non-arithmetic group' across all cognitive and home variables.

Research Question 1: Predictors of Reading Ability

To assess the predictors of early (precocious) reading ability, we first fitted a logistic mixed-effects model to examine which combination of home variables significantly predicted membership in the 'reading group'. This 'home model' was a logistic mixed-effects model, because the dependent variable was dichotomous ('1' for membership, '0' for non-membership). In such models, the maximum number of predictors that can be included is limited by the sample size of the smallest group, and minimally ten observations are required per predictor (Bujang et al., 2018; Ranganathan et al., 2017). Hence, given the size of our 'reading group' (n = 66), the 'home model' included a selection of the six most relevant home predictors, based on the group comparisons (see Table 1) and prior literature.

Next, the 'home model' was followed by a 'cognitive model', where we fitted a logistic mixed-effects model to examine which (combination of) cognitive skills significantly predicted 'reading group' membership. Due to the model constraints described above, the ‘cognitive model’ only contained the six most relevant literacy-specific and domain-general cognitive skills, based on the group comparisons (Table 1) and prior literature.

After fitting the ‘home model’ and ‘cognitive model’, we used a step-wise regression technique (using backward elimination) to investigate which cognitive *and* home variables most strongly predicted ‘reading group’ membership, when assessing all predictors simultaneously. The cross-domain cognitive variables (i.e., the numeracy-specific skills) were also included in this model (see model specification below).

The three logistic regression models described above were only used to examine the predictors of membership in the ‘reading group’. In a next step, we specifically focused on the children who were included in this group (n = 66). Specifically, we investigated which variables significantly predicted higher scores on the actual reading task (DMT) within this subgroup. Similarly to the approach described above, we first fitted a ‘home model’, following by a ‘cognitive model’, which was then followed by a backwards elimination model where all predictors were included simultaneously. Since the scores on the DMT represent a continuous variable, these models were fitted as linear regression models.

Research Question 2: Predictors of Arithmetic Ability

To assess the predictors of early (precocious) arithmetic ability, we used an approach that was very similar to our approach with regards to reading. First, we fitted a ‘home model’ to examine which home-related variables significantly predicted membership in the ‘arithmetic group’ (n = 60). This ‘home model’ contained the same predictors as the ‘home model’ for reading, but now the variables were specific to numeracy instead of literacy. Next, we fitted a ‘cognitive model’, which included a selection of the six most relevant numeracy-specific and domain-general cognitive skills, based on the group comparisons (Table 2) and prior literature. Then, we used a backward elimination regression to investigate which cognitive and home variables most strongly predicted ‘arithmetic group’ membership, when assessing all predictors simultaneously. Again, the cross-domain cognitive variables (i.e., the literacy-specific skills) were also included in this model. Again, all of these models were logistic regression models, because the dependent variable was dichotomous (‘1’ for arithmetic group membership, ‘0’ for non-membership).

In a next step, we specifically focused on the children who were included in the ‘arithmetic group’. Similarly to our approach for reading, we investigated which variables significantly predicted higher scores on the actual arithmetic task (TTA) within this subgroup. Again, we first fitted a ‘home model’, followed by a ‘cognitive model’, which was then followed by a backwards elimination model where all predictors were included simultaneously. Since the scores on the TTA represent a continuous variable, these models were fitted as linear regression models.

On a general note, it can be argued that the logistic regression models (assessing the predictors of ‘reading/arithmetic group’ membership) examined the predictors of ‘basic’ reading and arithmetic abilities. Subsequently, the regression analyses *within* these respective subgroups can be argued to assess the predictors of ‘advanced’ (i.e. precocious) reading and arithmetic abilities. Moreover, it should be noted that by fitting these separate ‘home’ and ‘cognitive’ models, we were able to compare the amount of variance explained by the child’s home environment versus the child’s cognitive skills, and we could assess to what extent this was different for reading versus arithmetic.

Research Question 3: Predictors of Applied Math Ability

Lastly, we assessed the predictors of applied math abilities using a three-step procedure. First, we fitted a ‘home model’ featuring the numeracy-related home variables, followed by a ‘cognitive model’ featuring numeracy-specific and domain-general cognitive skills. These models were followed by a backward elimination model, in which all predictors were included simultaneously. Unlike reading and arithmetic, children's applied math abilities were not measured using an adaptive procedure. In other words, there was no 'pre-task' and no subgroup for applied math. Therefore, these analyses were done on the entire sample (n = 222), which means that we could include more than six predictors in each step.

Model specification

All statistical analyses were conducted in R (R Core Team, 2021). All logistic and linear regression models were mixed-effects models, in which 'school ID' was included as a random intercept. This was done to account for potential differences between schools, e.g. in terms of their curriculum and/or socio-economical characteristics. Children's precise age (in days) was included as a control predictor in the 'home models' and in the step-wise regression models. The continuous predictors were scaled and centered in all models. In the logistic mixed-effects models, the estimates (B) represent the unstandardized regression coefficients. These are unstandardized log odds (on the logit scale), which can be interpreted in terms of the change in log-odds for a one-unit change in the predictor, holding other variables constant. In typical logistic regression models (without random effects), odds ratios and/or probabilities are typically reported as well. However, in mixed-effects models, odds ratios and/or probabilities cannot be reliably reported due to the inclusion of random effects. Similarly, we could not report McFadden's or Nagelkerke R^2 values, due to the inclusion of a random intercept. Instead, we calculated conditional R^2 values, which is a pseudo-R^2 measure suitable for generalized mixed-effect models. This measure estimates the total variance explained by both fixed and random factors together (Nakagawa & Schielzeth, 2013). Importantly, these conditional R^2 measures can be estimated for both linear and logistic mixed-effects models, which allowed us to compare R^2 measures across all models reported in the current study.

In the backwards elimination models, the initial models were not limited to six predictors. Therefore, each of these models started with an initial model that contained *all* variables from the preceding ‘home’ and ‘cognitive’ models, as well as the cross-domain cognitive skills. Hence, these were the only models that included the cross-domain cognitive skills. After the initial model had been fitted, we iteratively removed the predictor with the *highest* p-value in a step-by-step procedure (one predictor at a time), and checked whether this removal resulted in a lower (i.e. improved) AIC value. If it resulted in a higher (i.e. worse) AIC value, we removed the predictor with the next highest p-value. This step was repeated, until we obtained a final model composed of only predictors with a p-value <0.1. The specification of these models was similar to other recent papers (Marcoux et al., 2022; Mulder et al., 2021; Zee et al., 2021).

Model diagnostics were assessed using the ‘performance’ package (Lüdecke et al., 2021) and ‘DHARMa’ package (Hartig, 2022) in R. VIF values were below 3 in all models, indicating no issues with multicollinearity. Excluding outliers and influential cases did not result in different findings, so we report the results from the full sample. There were no significant random slopes in any of the models, indicating that the relationships between the independent and dependent variables did not vary significantly between the schools. The full model diagnostics can be found in section S4 of the Supplementary Materials.

3. Results

3.1: Descriptive Statistics and Group Comparisons

Table 1 shows the descriptive statistics for all literacy-related measures. A total of 66 children (29.7% of our sample) passed the pre-task for reading (i.e. word decoding), and were thus included in the ‘reading group’. Table 1 also reports a series of independent-samples *t*-tests, comparing the ‘reading group’ versus the ‘non-reading group’ across all variables. We observed that children in the ‘reading group’ were slightly older than their peers. With regards to the home environment, children in this group showed higher parental education levels, parental literacy expectations and formal literacy-related home activities. With regards to the cognitive skills, children in the ‘reading group’ showed higher performance across all domain-specific, domain-general and even numeracy-specific (i.e. cross-domain) cognitive skills.

Table 1

Descriptive Statistics and Group Comparisons for Literacy-Related Measures

		Full sample (n = 222)				Non-reading group (n = 156)		Reading group (n = 66)		Group comparison:	
		Min	*Max*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*t*	*p*
Home variables	Age	4.74	6.19	5.41	0.32	5.38	0.32	5.48	0.31	2.21	0.029*
	Parental education	1.00	6.00	3.56	1.22	3.38	1.19	3.98	1.17	3.44	0.001**
	Literacy expectations	0.00	10.00	7.48	1.65	7.12	1.66	8.29	1.31	5.38	<0.001***
	Literacy importance	3.00	10.00	8.71	1.31	8.63	1.40	8.87	1.05	1.36	0.176
	Literacy enjoyment	0.00	10.00	7.70	2.22	7.65	2.27	7.81	2.12	0.48	0.634
	Literacy activities formal	1.00	5.00	2.72	0.58	2.63	0.54	2.92	0.61	3.30	0.001**
	Literacy activities informal	2.00	4.60	3.33	0.54	3.36	0.53	3.28	0.58	0.93	0.354
	Literacy activities digital	1.00	4.50	2.43	0.86	2.42	0.89	2.44	0.79	0.18	0.857
General	Verbal STM	4.00	48.00	19.16	7.85	17.55	6.81	23.05	8.79	4.54	<0.001***
	Visuospatial STM	0.00	48.00	16.25	9.68	15.00	9.08	19.14	10.52	2.75	0.007**
	Non-verbal reasoning	4.00	21.00	10.21	3.00	9.81	2.85	11.18	3.17	3.01	0.003**
	RAN	6.00	65.00	42.10	8.88	40.39	8.74	46.41	7.77	5.02	<0.001***
Specific	Vocabulary	52.00	106.00	78.82	9.57	76.59	9.34	84.34	7.77	6.34	<0.001***
	Phonological awareness	0.00	15.00	5.60	5.34	3.10	3.83	11.42	3.56	15.58	<0.001***
	Letter knowledge	0.00	34.00	14.49	9.50	9.64	6.27	26.02	4.69	21.42	<0.001***
Cross	Rote counting	8.00	101.00	52.48	30.75	41.81	25.35	78.17	27.18	9.29	<0.001***
	Number line estimation	50.33	96.67	82.36	8.18	81.52	8.06	84.33	8.19	2.35	0.021*
	Symbolic comparisons	0.00	40.00	17.14	8.45	14.69	8.11	22.86	6.18	8.17	<0.001***
	Applied math	1.00	9.00	5.08	1.97	4.49	1.89	6.45	1.42	8.53	<0.001***

Note. * p < .05, ** p < .01, *** p < .001

Table 2 shows the descriptive statistics and group comparisons for all numeracy-related measures. A total of 60 children (27.0% of our sample) passed the arithmetic pre-task, and were thus included in the ‘arithmetic group’. Children in the ‘arithmetic group’ were slightly older than their peers. There were significant home-related differences for parental numeracy expectations and informal activities, but not formal activities or parental education levels. Moreover, the two groups differed significantly across all domain-specific, domain-general and literacy-specific (i.e. cross-domain) skills. Thus, similarly to 'readers' vs. 'non-readers', the children in the 'arithmetic group' significantly outperformed their peers across all cognitive tasks. It should be noted here that there was only a modest degree of overlap between the 'reading' and 'arithmetic' group: approx. 50% of children in the 'reading group' were also included in the 'arithmetic group', and vice versa (34 children were included in both subgroups).

Table 2

Descriptive Statistics and Group Comparisons for Numeracy-Related Measures

		Full sample (n = 222)				Non-arith. group (n = 162)		Arithmetic group (n = 60)		Group comparison:	
		Min	*Max*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*t*	*p*
Home variables	Age	4.74	6.19	5.41	0.32	5.37	0.33	5.52	0.28	3.37	0.001**
	Parental education	1.00	6.00	3.56	1.22	3.47	1.16	3.81	1.34	1.68	0.097
	Numeracy expectations	0.00	10.00	7.10	1.58	6.95	1.66	7.47	1.30	2.38	0.019*
	Numeracy importance	1.00	10.00	7.86	1.56	7.91	1.49	7.72	1.72	-0.75	0.454
	Numeracy enjoyment	0.00	10.00	6.59	2.56	6.53	2.60	6.75	2.48	0.58	0.562
	Numeracy activities formal	1.00	4.33	2.58	0.68	2.58	0.66	2.60	0.74	0.24	0.812
	Numeracy activities infor.	1.00	4.00	2.13	0.50	2.07	0.51	2.30	0.46	3.14	0.002**
	Numeracy activities digital	1.00	5.00	2.36	0.85	2.30	0.85	2.52	0.83	1.69	0.093
General	Verbal STM	4.00	48.00	19.19	7.85	18.17	7.54	21.93	8.06	3.14	0.002**
	Visuospatial STM	0.00	48.00	16.21	9.68	14.71	9.05	20.36	10.23	3.71	<0.001***
	Non-verbal reasoning	4.00	21.00	10.22	3.01	9.84	2.75	11.24	3.44	2.80	0.006**
	RAN	6.00	65.00	42.15	8.88	41.19	9.03	44.81	7.97	2.87	0.005**
Specific	Rote counting	8.00	101.00	52.62	30.75	45.62	27.91	71.52	30.30	5.77	<0.001***
	Number line estimation	50.33	96.67	82.36	8.18	81.44	8.41	84.81	7.02	3.01	0.003**
	Symbolic comparisons	0.00	40.00	17.12	8.45	15.09	8.06	22.60	6.92	6.85	<0.001***
	Applied math	1.00	9.00	5.07	1.97	4.51	1.86	6.58	1.41	8.89	<0.001***
Cross	Vocabulary	52.00	106.00	78.88	9.57	77.82	9.57	81.78	9.04	2.83	0.005**
	Phonological awareness	0.00	15.00	5.57	5.34	4.30	4.75	9.00	5.39	5.94	<0.001***
	Letter knowledge	0.00	34.00	14.51	9.50	12.04	8.63	21.17	8.56	7.04	<0.001***

Note. * $p < .05$, ** $p < .01$, *** $p < .001$

Figure 1

Histograms of the Frequencies of DMT and TTA Scores within the Subgroups

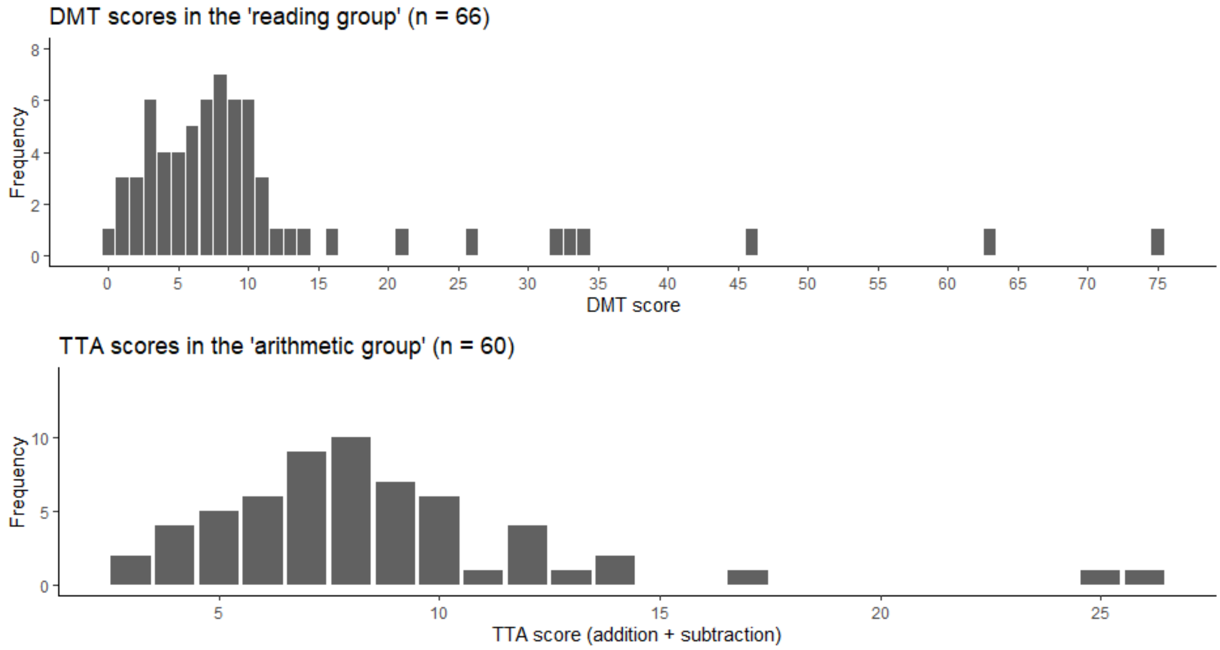
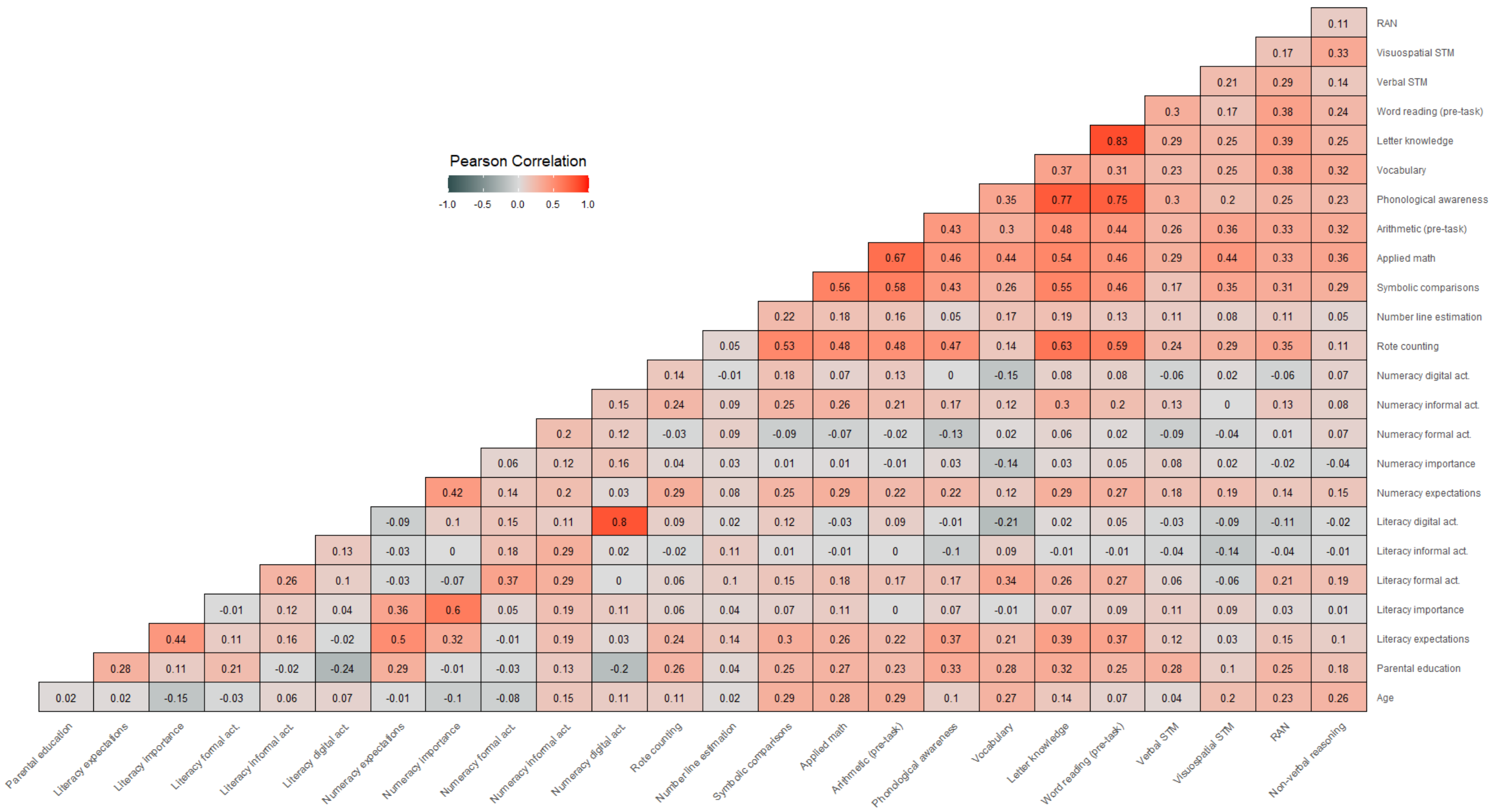


Figure 2

Correlation Heatmap for All Cognitive and Home Variables



3.2: Reading Ability

First, we fitted a logistic mixed-effects model containing the home-related predictors of 'reading group' membership (i.e., the 'home model'), followed by the 'cognitive model'. To achieve a selection of six predictors per model, we excluded parental enjoyment and digital activities from the 'home model', and visuospatial STM from the 'cognitive model'.

Table 3

Results of the Logistic and Linear (Mixed-Effects) Regression for Reading

	Membership in reading group (logistic reg.) *n* = 222 (66 yes, 156 no)				DMT scores within reading group (linear reg.) *n* = 66			
Predictor	B	SE (B)	*z*	*p*	B	SE (B)	*t*	*p*
Home model								
(Intercept)	-1.122	0.235	-4.781	<0.001***	7.728	2.411	3.206	0.005**
Age	0.431	0.190	2.275	0.023*	-1.429	1.723	-0.829	0.411
Parental education level	0.240	0.187	1.286	0.198	-0.944	1.802	-0.524	0.602
Literacy expectations	1.002	0.258	3.883	<0.001***	5.422	2.296	2.362	0.022*
Literacy importance	-0.128	0.237	-0.542	0.588	-0.755	2.311	-0.327	0.745
Literacy activities formal	0.642	0.202	3.170	0.002**	2.239	1.694	1.322	0.191
Literacy activities informal	-0.501	0.195	-2.563	0.010*	0.251	1.712	0.147	0.884
	Conditional R^2 = .375				*Conditional* R^2 = .216			
Cognitive model								
(Intercept)	-3.765	0.984	-3.824	<0.001***	-10.872	3.779	-2.877	0.006**
Verbal STM	0.225	0.362	0.622	0.534	1.984	1.222	1.624	0.110
Non-verbal reasoning	-0.261	0.479	-0.545	0.585	-0.859	1.384	-0.621	0.537
RAN	0.312	0.412	0.758	0.448	-1.035	1.654	-0.626	0.534
Vocabulary	0.838	0.473	1.773	0.076 .	0.260	1.692	0.154	0.878
Phonological awareness	0.936	0.572	1.636	0.102	-1.569	2.446	-0.642	0.524
Letter knowledge	4.559	1.148	3.970	<0.001***	18.699	3.731	5.012	<0.001***
	Conditional R^2 = .913				*Conditional* R^2 = .449			
Backward step-wise model								
(Intercept)	-4.454	1.445	-3.083	0.002**	-9.778	3.422	-2.858	0.006**
Rote counting	0.927	0.499	1.854	0.064 .				
Vocabulary	1.046	0.493	2.121	0.034*				
Phonological awareness	1.389	0.708	1.962	0.049*				
Letter knowledge	4.776	1.528	3.125	0.002**	16.567	2.517	6.582	<0.001***
	Conditional R^2 = .939				*Conditional* R^2 = .441			

Note. * p < .05, ** p < .01, *** p < .001

The results in Table 3 show that, in the ‘home model’, membership in the ‘reading group’ was significantly predicted by children’s age, parental literacy expectations and formal literacy activities. Informal parental activities showed a negative effect, even though the correlation between informal activities and reading pre-task scores was almost zero (-0.01; see Figure 2). Next, in the ‘cognitive model’, we found a substantial contribution from letter knowledge, and a weak contribution from vocabulary. We observed that the ‘cognitive model’ had a considerably higher conditional R^2 value than the ‘home model’.

In the step-wise regression model, we found significant contributions from three domain-specific cognitive skills, namely: vocabulary, phonological awareness and letter knowledge. We found no significant contributions from any of the home variables or any of the domain-general cognitive skills in this model, but we did find a weak positive contribution from counting skills (i.e. a numeracy-specific skill).

Subsequently, we examined which variables predicted higher scores on the actual reading fluency task (DMT) within the ‘reading group’. As shown in the right columns of Table 3, we only observed a significant contribution from parental expectations in the ‘home model’, and from letter knowledge in the ‘cognitive model’. Again, the ‘cognitive model’ showed a considerably higher conditional R^2 value. When examining all variables simultaneously, only letter knowledge emerged as a significant predictor of DMT scores. Taken together, we found that letter knowledge serves as the strongest predictor of differentiating between ‘readers’ and ‘non-readers’, while it is also the strongest predictor of reading fluency within the ‘reading group’, over and above all other variables.

3.3: Arithmetic Ability

To address our research questions regarding arithmetic, we first fitted a logistic mixed-effects model containing the home predictors of ‘arithmetic group’ membership (i.e., the ‘home model’), followed by the ‘cognitive model’. Again, parental enjoyment and digital activities were excluded from the ‘home model’. In the ‘cognitive model’, we excluded non-verbal reasoning, which yielded the smallest between-group difference.

Table 4

Results of the Logistic and Linear (Mixed-Effects) Regression for Arithmetic

	Membership in arithmetic group (logistic reg.) *n* = 222 (60 yes, 162 no)				TTA scores within arithmetic group (linear reg.) *n* = 60			
Predictor	B	SE (B)	*z*	*p*	B	SE (B)	*t*	*p*
Home model								
(Intercept)	-1.086	0.172	-6.318	<0.001***	7.302	0.695	10.513	<0.001***
Age	0.412	0.172	2.395	0.017*	1.325	0.572	2.319	0.025*
Parental education level	0.143	0.175	0.819	0.413	0.428	0.573	0.747	0.459
Numeracy expectations	0.311	0.204	1.525	0.127	1.771	0.802	2.208	0.032*
Numeracy importance	-0.190	0.183	-1.041	0.298	-0.493	0.515	-0.958	0.343
Numeracy activities formal	-0.053	0.172	-0.307	0.759	0.667	0.540	1.235	0.223
Numeracy activities informal	0.359	0.182	1.973	0.049*	0.470	0.581	0.809	0.423
	Conditional R^2 = .144				*Conditional* R^2 = .355			
Cognitive model								
(Intercept)	-1.369	0.202	-6.780	<0.001***	5.785	0.574	10.070	<0.001***
Verbal STM	0.235	0.194	1.215	0.224	0.019	0.426	0.044	0.965
Visuospatial STM	0.311	0.181	1.716	0.086 .	1.091	0.410	2.660	0.011*
RAN	-0.004	0.196	-0.019	0.985	0.551	0.512	1.078	0.287
Rote counting	0.495	0.195	2.544	0.011*	0.666	0.459	1.453	0.153
Number line estimation	0.384	0.212	1.814	0.070 .	1.167	0.485	2.406	0.020*
Symbolic comparisons	0.668	0.237	2.813	0.005**	2.095	0.549	3.818	<0.001***
	Conditional R^2 = .369				*Conditional* R^2 = .542			
Backward step-wise model								
(Intercept)	-1.408	0.208	-6.784	<0.001***	6.087	0.503	12.103	<0.001***
Numeracy expectations					0.937	0.527	1.779	0.081 .
Numeracy activities formal					0.727	0.387	1.804	0.077 .
Visuospatial STM	0.329	0.187	1.763	0.078 .	1.264	0.392	3.222	0.002**
Rote counting	0.379	0.201	1.883	0.059 .				
Number line estimation	0.406	0.213	1.909	0.056 .	1.072	0.476	2.251	0.029*
Symbolic comparisons	0.555	0.240	2.310	0.021*	2.243	0.512	4.385	<0.001***
Phonological awareness	0.547	0.194	2.814	0.005**				
	Conditional R^2 = .395				*Conditional* R^2 = .576			

Note. * p < .05, ** p < .01, *** p < .001

The results in Table 4 demonstrate that only age and informal (but not formal) numeracy activities significantly predicted ‘arithmetic group’ membership in the ‘home model’. In the ‘cognitive model’, rote counting and symbolic comparison skills (both domain-specific skills) significantly predicted membership in the ‘arithmetic group’. We also observed weak effects for visuospatial STM and number line estimation. The ‘cognitive model’ had a considerably higher conditional R^2 value than the ‘home model’. When assessing all variables simultaneously in the step-wise regression model, we found significant effects for symbolic comparisons and, notably, phonological awareness. Weaker effects were also found for visuospatial STM, counting and number line estimation. We found no significant contributions from any of the home variables.

Subsequently, we examined which variables predicted higher scores on the arithmetic fluency task (TTA), within the ‘arithmetic group’. As shown in the right columns of Table 4, we found significant effects for age and parental expectations in the ‘home model’. In the ‘cognitive model’, we found significant effects for visuospatial STM, number line estimation and symbolic comparisons. In the step-wise model, we found significant effects for visuospatial STM, number line estimation and symbolic comparisons, but not for counting and phonological awareness. Weaker effects were also found for parental numeracy expectations and formal (but not informal) activities.

Taken together, our results show that symbolic comparison skills significantly differentiated between the ‘arithmetic’ and ‘non-arithmetic group’, and also significantly predict higher TTA scores within the arithmetic group. Visuospatial STM and number line estimation showed weak contributions when differentiating between the two groups, but they showed stronger contributions when predicting higher scores within the ‘arithmetic group’. In contrast, children’s counting skills and phonological awareness differentiated between the two groups, but they did not predict higher arithmetic performance within this subgroup.

3.4: Applied Math Ability

We fitted a mixed-effects model with applied math scores as a continuous outcome variable, in the entire sample. In the 'home model', we found significant contributions from age, parental education, parental expectations and informal numeracy activities (see Table 5). In the 'cognitive model', we found significant contributions from visuospatial STM, non-verbal reasoning, counting and symbolic comparisons. In the step-wise model, we observed strong contributions from counting and symbolic comparisons. Notably, we also found a strong contribution from vocabulary, a literacy-specific skill. Modest contributions were also found for non-verbal reasoning and informal numeracy-related home activities.

Table 5

Results of the Linear (Mixed-Effects) Regression for Applied Math

	Applied math scores (ENT) (linear regression) *n* = 222			
Predictor	B	SE (B)	*t*	*p*
Home model				
(Intercept)	5.105	0.121	42.087	<0.001***
Age	0.460	0.123	3.735	<0.001***
Parental education level	0.330	0.128	2.579	0.011*
Numeracy expectations	0.521	0.142	3.666	<0.001***
Numeracy importance	-0.168	0.135	-1.250	0.213
Numeracy activities formal	-0.191	0.126	-1.511	0.132
Numeracy activities informal	0.355	0.130	2.726	0.007**
	Conditional R^2 = .240			
Cognitive model				
(Intercept)	5.069	0.100	50.744	<0.001***
Verbal STM	0.161	0.109	1.480	0.140
Visuospatial STM	0.344	0.111	3.106	0.002**
Non-verbal reasoning	0.293	0.107	2.723	0.007**
RAN	0.163	0.109	1.495	0.136
Rote counting	0.421	0.122	3.436	0.001**
Number line estimation	0.155	0.103	1.511	0.132
Symbolic comparisons	0.582	0.129	4.512	<0.001***
	Conditional R^2 = .458			

Backward step-wise model				
(Intercept)	5.101	0.098	51.826	<0.001***
Numeracy activities informal	0.214	0.104	2.053	0.041*
Visuospatial STM	0.348	0.113	3.087	0.002**
Non-verbal reasoning	0.207	0.108	1.924	0.056 .
Rote counting	0.439	0.119	3.699	<0.001***
Symbolic comparisons	0.547	0.125	4.376	<0.001***
Vocabulary	0.464	0.107	4.325	<0.001***
	Conditional R^2 = .505			

Note. * p < .05, ** p < .01, *** p < .001

3.5: Additional Analysis: Letter Knowledge

Given the apparent importance of letter knowledge for early reading, we conducted an additional analysis to examine the predictors of children's letter knowledge scores, in the entire sample. The results of this analysis can be found in Table S3 in the Supplementary Materials. In short, we found significant contributions from age, parental education, parental expectations and formal literacy activities in the 'home model'. In the 'cognitive model', we found strong contributions from RAN and phonological awareness. In the step-wise model, we found significant contributions from phonological awareness, rote counting, parental literacy expectations, formal activities, RAN and symbolic comparison skills.

4. Discussion

The current study aimed to systematically investigate the predictors of precocious reading and math within a large sample of kindergartners. We examined the contributions from a variety of home-related variables and a wide range of domain-specific, domain-general and cross-domain cognitive skills. For both reading and math, we found that the contributions from the home variables were notably weaker compared to the cognitive variables. Therefore, our initial focus here will be on discussing the results related to the cognitive variables.

4.1: Cognitive Predictors of Reading

In our group comparisons, we observed that children in the ‘reading group’ outperformed their non-reading peers across all cognitive tasks; not only on literacy-specific but also on domain-general and numeracy-specific tasks. In our regression models, three domain-specific skills (vocabulary, phonological awareness and letter knowledge) were found to predict membership in the ‘reading group’, with letter knowledge showing the strongest contribution. Within this subgroup, letter knowledge again emerged as the strongest predictor of reading fluency scores. An additional analysis with letter knowledge as an outcome variable showed significant contributions from RAN, phonological awareness, counting and symbolic comparisons.

Our finding that precocious reading (word decoding) in kindergarten is predicted most strongly by literacy-specific skills, most notably letter knowledge, aligns with prior studies on early reading in general (Blachman, 2000; Blaiklock, 2004; Snel et al., 2016) and precocious reading in particular (Bergman Deitcher et al., 2021; Olson et al., 2006; Silvén et al., 2004). However, it is important to point out that since letter knowledge refers to the ability to convert written letter symbols into sounds, it could be regarded as a necessary precondition for word decoding, or even as an elementary stage of word decoding in itself. In fact, letter knowledge tasks have been used as a proxy of early reading abilities in Dutch speaking children in previous studies (Vanbinst et al., 2020; Vandermosten et al., 2017). Our results showed a robust association between letter knowledge and word decoding, although they could still be distinguished from each other. Our approach of utilizing letter knowledge both as a predictor of word decoding and as an outcome variable in itself has enabled us to more comprehensively assess the predictors of early (precocious) reading.

4.2: Cognitive Predictors of Arithmetic and Applied Math

In our group comparisons, we observed that children in the 'arithmetic group' outperformed the children in the 'non-arithmetic group' across all numeracy-specific, literacy-specific and domain-general cognitive tasks. We found that membership in this group was predicted by a variety of domain-specific and domain-general skills, most notably visuospatial STM, counting and symbolic comparisons (and phonological awareness). When assessing the predictors of arithmetic fluency scores within this group, we found significant contributions from visuospatial STM, number line estimation and symbolic comparisons.

Our finding that counting and symbolic comparison skills are predictive of arithmetic abilities in kindergarten is in line with a multitude of earlier studies (e.g. De Smedt et al., 2013; Hawes et al., 2019; Kolkman et al., 2013; Merkley & Ansari, 2016). Furthermore, our finding that visuospatial STM, number line estimation and symbolic comparison skills were the strongest predictors of arithmetic fluency scores *within* the 'precocious' arithmetic subgroup offers an elaboration of the results obtained by Bakker and colleagues, who found that high mathematical achievement in 8-10 year old children was associated with higher spatial visualization ability and visuospatial working memory (Bakker et al., 2022; 2023), but who did not specifically include measures of number line estimation ability.

One notable result of our study is that rote counting significantly differentiated between the 'arithmetic' and 'non-arithmetic' group, but it did not predict higher arithmetic scores within this subgroup. In contrast, symbolic number line estimation appeared to show the opposite pattern. This might suggest that rote counting mostly serves as a predictor of 'basic' arithmetic abilities, while children who have mastered the 'basic' arithmetic principles likely already possess sufficient counting skills to solve problems under 100 (note that the counting task was ended when a child reached 101, potentially causing a ceiling effect). Variation in arithmetic fluency scores within the 'arithmetic group' was not predicted by variation in counting skills, but rather by variation in symbolic comparison and number line estimation skills, which represent more advanced numerical skills for which counting is likely a necessary but not sufficient prerequisite. Moreover, since visuospatial STM and number line estimation are related to visuospatial processing and/or the mapping of numbers onto space, our results align with earlier studies showing that math precocity in 8-10 year olds is related to high spatial visualization ability and visuospatial WM (Bakker et al., 2022; Kroesbergen & Schoevers, 2017; Myers et al., 2017). Our results provide some first evidence that this pattern can already be observed in 4-6 year old children, before the start of formal education.

Next, our analyses regarding applied math showed strong contributions from counting and symbolic comparison skills, while weaker effects were also found for visuospatial STM and non-verbal reasoning. We also found a strong effect of vocabulary, as we will discuss in the next section. Taken together with our results regarding arithmetic, we found that early math abilities in kindergarten are not only predicted by numeracy-specific skills, but also domain-general cognitive skills (e.g. visuospatial STM) and even literacy-specific skills such as phonological awareness and vocabulary.

4.3: Co-development of Reading and Arithmetic

Our results showed that children in the 'reading group' outperformed their non-reading peers across the entire range of cognitive tasks, and the same was true for children in the 'arithmetic group' compared to their peers, even though the overlap between the two groups was only slightly above 50%. Our regression analyses showed that reading abilities were most strongly associated with literacy-specific skills, although some contributions were found for numeracy-specific skills such as counting and symbolic comparisons. In contrast, arithmetic and applied math abilities were strongly and consistently predicted by a variety of numeracy-specific, domain-general and literacy-specific skills. Together, these results show a considerable degree of co-development between early (precocious) reading and math.

When looking more specifically at reading, we found that counting skills were a (modest) predictor of membership in the 'reading group', and we found that counting and symbolic comparison skills significantly predicted letter knowledge scores. These results also align with our observation that rote counting correlated strongly with reading and letter knowledge (see Figure 2). As mentioned previously, the influences of numeracy-specific skills on early reading have been relatively scarcely investigated in the literature. A study by Vanbinst et al. (2020) showed that number recognition skills in kindergarten predicted children's letter knowledge (cross-sectionally), even after controlling for age, general intelligence and phonological awareness. Nevertheless, Vanbinst et al. (2020) found no significant association between symbolic comparison skills and letter knowledge, but this association was statistically significant in our analyses. Moreover, we also found a high correlation between letter knowledge and symbolic comparison skills (Figures 2). Together, our results corroborate earlier studies showing strong associations between symbolic number and letter knowledge in both typical and precocious learners (Austin et al., 2011; Bergman Deitcher et al., 2021; Piasta et al., 2010). These results align with the notion that learning the rules of the symbolic number system is similar to mastering any other symbolic representational system (e.g. alphabetic language; Dehaene et al., 2003; LeFevre et al., 2010). This notion is related to the theoretical framework of the 'linguistic pathway' in early numerical development (LeFevre et al., 2010; Purpura & Napoli, 2015), as discussed earlier.

When assessing the literacy-related predictors of arithmetic, we found that phonological awareness significantly predicted membership in the 'arithmetic group'. This is in line with results from earlier studies (De Smedt et al., 2010; Fuchs et al., 2005), although some studies did not find this relationship (Purpura et al., 2011). More specifically, we found that phonological awareness predicted 'arithmetic group' membership, but not higher arithmetic fluency scores within this subgroup. Taken together, our results suggest that phonological awareness and rote counting are associated with 'basic' arithmetic skills in kindergarten, whereas 'precocious' arithmetic fluency at this age is associated with higher-order numerical abilities and spatial skills. This could be an indication of qualitative (rather than merely quantitative) differences between precocious math learners and their typically developing peers, which might be further explored in future research.

When assessing children's applied math scores, we found a strong contribution from vocabulary. This finding is corroborated by the observation that vocabulary correlated more strongly with applied math than with any other cognitive skill (see Figure 2). This result also aligns with findings from Purpura et al. (2011), who found that print knowledge and vocabulary (but not phonological awareness) were significant longitudinal predictors of numeracy skills and applied math abilities throughout kindergarten.

On a conceptual level, our findings regarding the co-development of reading and arithmetic might point towards shared cognitive foundations (Collins & Laski, 2019; Peng et al., 2020; Purpura et al., 2017), towards bidirectional influences between both domains (Coolen et al., 2021; Peng & Kievit, 2020), or towards a combination of these two mechanisms. Furthermore, the fact that children in the respective 'reading' and 'arithmetic' groups outperformed their peers across all cognitive tasks, paired with the relatively high correlations between many cognitive tasks, might be viewed as indicative of a so-called 'positive manifold'. This term refers to the observation that children who perform well on one type of cognitive task typically tend to perform well on other cognitive tasks (Van Der Maas et al., 2006). This observation is related to the notion of the general intelligence factor (*g*-factor), which posits a common underlying factor that influences performance across different cognitive domains (Miller-Cotto & Byrnes, 2020; Van Der Maas et al., 2006). In the developmental literature, the *g*-factor is connected to the age differentiation hypothesis, which posits that the relationship(s) between general intelligence and more specific abilities (e.g.

reading and math) are strongest in early childhood, and become weaker in later childhood and adolescence (Breit et al., 2022; Van Der Maas et al., 2006). However, in our current study, four observations constrain the hypothetical influence of an underlying *g*-factor in early (precocious) reading and math development. First, the overlap between the 'reading group' and the 'arithmetic group' was only slightly above 50%, as discussed previously. Second, the correlation between reading and arithmetic fluency scores of children who were included in both subgroups was only relatively weak (r = .22). Third, reading and math abilities were generally more strongly correlated with domain-specific skills compared to domain-general skills (see Figure 2). Fourth, in the regression models, the domain-general cognitive skills contributed relatively weakly to reading abilities, although they did contribute more strongly to arithmetic and applied math abilities. Taken together, our results suggest that while there appears to be a considerable degree of co-development between (precocious) reading and arithmetic, there is still a notable degree of differentiation (i.e. domain-specificity) between these domains. Longitudinal measurements will be needed to examine whether the observed patterns of co-development are indicative of shared cognitive foundations, bidirectional influences, or a combination of the two.

4.4: Home Environment

As previously mentioned, the overall contributions from the home variables were considerably weaker compared to the cognitive variables. With regards to reading, we found that children were more likely to be in the 'reading group' if parental expectations were higher and if parents reported more formal activities, but the contributions from these variables were severely reduced when the cognitive variables were taken into account. In the literature, formal literacy-related activities have been associated with letter knowledge and word reading abilities in kindergarten and first grade (Sénéchal & LeFevre, 2002; Skwarchuk et al., 2014). However, it should be noted that in our study (as in many other studies), the term 'formal' activities encompasses code-related activities such as shared reading or practicing ‘letter booklets’ together. It is conceivable that parents might only engage in such activities if they perceive their child to have a basic understanding of phonology and letter-sound associations. As such, the differential contribution of formal vs. informal literacy activities on early reading might be (partly) a result of a selection bias and/or reversed causality. Moreover, it can be argued that the ‘formal’ activity items in our study were generally of a higher difficulty level (and/or higher didactic instruction level) compared to the ‘informal’ items. Therefore, the differential contribution of formal vs. informal activities could be (partly) a result of the general difficulty level, rather than the formal vs. informal nature of the activities.

The observation that parental literacy expectations showed a (modest) association with children’s reading ability aligns with other studies from the field (Martini & Sénéchal, 2012). However, it should be noted that in our study (as in various other studies), parental expectations might be strongly influenced by the parent’s appraisal of the child’s current abilities, rather than their expectations for their child’s development in later years. In this way, parents’ expectations might be more favorable if their child already demonstrates some elementary letter knowledge or word decoding skills, which might (partly) explain the (cross-sectional) association between parental expectations and children’s early reading abilities.

With regards to the home predictors of arithmetic, our regression analyses only found a modest contribution of informal activities when predicting ‘arithmetic group’ membership, and a modest effect of numeracy expectations on arithmetic fluency scores within this group. Informal (but not formal) activities were also a modest predictor of applied math scores. In contrast, we found a modest contribution from formal (but not informal) activities to arithmetic fluency scores within the ‘arithmetic group’. Similarly to formal activities in the literacy domain, this result might be (partly) explained by the notion that parents might only engage in ‘formal’ (or ‘advanced’) numeracy activities if they perceive their child to have a basic understanding of number symbols and the relations between numbers. Another explanation could be that children with a basic understanding of these concepts might benefit more strongly from these activities (Silver et al., 2024). This would explain why only arithmetic scores within the ‘arithmetic group’ were significantly predicted by formal numeracy activities.

Contrary to our expectations, our regression analyses showed no significant contributions from parental education levels for either reading or arithmetic. In the group comparisons, parental education levels did differ significantly between ‘readers’ and ‘non-readers’ (Table 1), but not between the ‘arithmetic’ and ‘non-arithmetic’ group (Table 2). Furthermore, it should be noted that parental education levels were relatively weakly correlated with the frequency of (formal and informal) literacy- and numeracy-related home activities (Figure 2). Together, these results correspond to recent findings from James-Brabham et al. (2023), who found no relation between SES metrics (which included parental education level) and the frequency of home math activities, and no relation between home math activities and children’s mathematical abilities (James-Brabham et al., 2023).

Moreover, contrary to our expectations, we observed that parental education levels, parents’ appraisal of importance, parental enjoyment and digital activities were all relatively weakly correlated with reading, arithmetic and applied math abilities (see Figure 2). In the group comparisons, we found no significant differences with regards to digital activities or parents’ own literacy/numeracy enjoyment. Our regression models also showed no significant contributions from parents’ appraisal of literacy/numeracy importance.

4.5: Strengths and Limitations

One major strength of the current study is the extensive scope of cognitive and home-related variables that were included. Furthermore, reading and math were investigated concurrently within the same sample, allowing us to systematically compare both domains and to examine their co-development. Moreover, our study is among the first to describe the degree of co-occurrence (i.e. overlap) between precocious reading and arithmetic abilities in kindergarten. We observed that the degree of overlap between the ‘reading group’ and ‘arithmetic group’ was slightly above 50%, which roughly matches the higher end of the commonly observed levels of comorbidity between reading and math difficulties such as dyslexia and dyscalculia (Landerl & Moll, 2010; Vanbinst et al., 2020; Willcutt et al., 2013).

One limitation of our study is that both the ‘reading group’ and the ‘arithmetic group’ were composed based on pre-task scores, using a cut-off that was essentially arbitrary. This approach resulted in a relatively large number of children being included in these groups. However, we addressed this issue by subsequently examining the predictors of higher reading and arithmetic fluency scores within these respective subgroups. This allowed us to mitigate the potential drawbacks associated with a lenient inclusion criterion (Bakker, Pelgrims, et al., 2023). As described previously, we argue that the logistic regression analyses (assessing the predictors of group membership) assessed the predictors of ‘basic’ word reading and arithmetic abilities, whereas the regression analyses *within* these subgroups provided insight into the predictors of ‘advanced’ (i.e. precocious) reading and arithmetic.

On a general note, it could be argued that the differentiation between ‘cognitive’ and ‘home’ variables in our study introduces the risk of creating a false dichotomy. After all, it is plausible that some of the ‘cognitive’ skills in our study were at least partially influenced by children’s home environments. This might particularly be true for children’s knowledge of letters and numerical symbols and their vocabulary, but possibly also for other skills such as phonological awareness and counting. We already partially addressed this issue by running an additional analysis with letter knowledge as an outcome variable (in the entire sample). Nevertheless, caution is still warranted when interpreting our results through the lens of a strict dichotomy between ‘cognitive’ and ‘home’ characteristics, as this could oversimplify the complex interplay between cognitive and home-related factors.

With regards to the home environment, it should be noted that our parental questionnaire only included ten items related to literacy activities and ten items related to numeracy activities. Also, similarly to most studies in this field, our questionnaire used parental self-reports to assess the frequency of various home activities. Self-reports may not necessarily paint an accurate picture, because they introduce the risk of a social desirability bias (Kleemans et al., 2012; Purpura et al., 2020), and because parents might actually engage in activities that are not covered by the questionnaire. Furthermore, it is important to note that these self-reports only assess the frequency (i.e. quantity) of the home activities, but they say little about the quality of the interactions. As such, these questionnaires are unable to assess to what extent parents are able to offer stimulation of sufficient didactic quality, or to appropriately target their child’s zone of proximal development (Daucourt et al., 2021; Kleemans et al., 2012). Future research can address these issues by including interviews, observations or even controlled interventions in their research design (James-Brabham et al., 2023; Mutaf-Yildiz et al., 2020; Skwarchuk et al., 2014). Moreover, in our current study, parental expectations, parental enjoyment and parents’ appraisal of importance were all assessed using only one question per domain. Future research might obtain more reliable results by using composite scale scores to assess these characteristics. Furthermore, previous studies have indicated that precocious learners tend to show higher levels of intrinsic motivation and ‘need for cognition’ compared to their peers (Bakker et al., 2022; Hansen et al., 2022; Olson et al., 2006; Preckel et al., 2020). Future research can assess whether these motivational characteristics are associated with higher levels of child-led home activities in precocious learners (Trickett et al., 2022), or whether precocious learners might use the stimulation they receive at home in more effective ways compared to their peers.

Lastly, it is important to note that our sample was relatively homogenous with regards to ethnicity, native language and socio-economic status. The majority of parents in our sample were native Dutch speakers with relatively high levels of education. These characteristics were prevalent in our sample despite our inclusive invitation to all (public) schools across a wide geographical area. Additionally, there were no exclusion criteria imposed on the participation of children from the participating schools. Nevertheless, to ensure more representative and generalizable results, future research could enhance its recruitment procedures to actively encourage the participation of children from more diverse socio-economic backgrounds (Coolen et al., 2021; Howard et al., 2020; Peng & Kievit, 2020).

4.6: Conclusions

Our study showed that early precocious reading and math abilities (before formal education) are differentially predicted by various domain-specific, domain-general and cross-domain cognitive skills. Contributions from children's home environment remained relatively small. For reading, we primarily observed contributions from literacy-specific skills, most notably letter knowledge. For arithmetic, we found significant contributions from a range of domain-specific and domain-general cognitive skills. Importantly, the predictors of 'basic' arithmetic skills were slightly different from the predictors of arithmetic fluency, potentially pointing at qualitative differences between precocious and typical arithmetic development. Together, our findings shed more light on the cognitive and home-related predictors of precocious reading and math development during kindergarten.

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