# THE CONNECTION BETWEEN MATHEMATICAL AND READING ABILITIES AND DISABILITIES

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# THE CONNECTION BETWEEN MATHEMATICAL AND READING ABILITIES AND DISABILITIES

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# Do Reading and Arithmetic Fluency Share the Same Cognitive Base?

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We examined the role of different cognitive-linguistic skills in reading and arithmetic fluency, and whether the effects of these skills are mediated by reading and arithmetic accuracy. One hundred twenty-six English-speaking Grade 1 children (67 females, 59 males; $M_{age} = 6.41$ years) were followed from the beginning of Grade 1 (Time 1) to the end of Grade 1 (Time 2). At Time 1, they were assessed on measures of non-verbal IQ, speed of processing, working memory, phonological awareness, rapid automatized naming (RAN), and number sense. At Time 2, they were assessed on measures of reading and arithmetic accuracy as well as on measures of reading and arithmetic fluency. Results of path analysis showed first that when reading and arithmetic fluency were included in the model as separate outcomes, RAN was predictive of both and that speed of processing and working memory were predictive of only arithmetic fluency. Second, RAN, speed of processing, and working memory had both direct and indirect effects (*via* reading and arithmetic accuracy) on the covariation of reading and arithmetic fluency. Irrespective of how reading and arithmetic fluency were treated in the analyses, the effects of non-verbal IQ, phonological awareness, and number sense were all indirect. Taken together, these findings suggest that reading and arithmetic fluency draw on a broader network of cognitive-linguistic skills, whose effects can sometimes be indirect through reading and arithmetic accuracy.

**Keywords: reading fluency, arithmetic fluency, rapid automatized naming, phonological awareness, speed of processing, working memory, number sense**

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## INTRODUCTION

For decades, research on the predictors of reading and mathematics skills has focused on each academic skill separately. Cognitive skills such as phonological awareness (the ability to identify and manipulate the speech sounds) and rapid automatized naming (RAN; the ability to name as fast as possible highly familiar stimuli) have been described as fundamental for learning to read (e.g., Hulme and Snowling, 2015). Likewise, number sense (an intuitive understanding of numbers, their magnitude, and relations) and counting have been viewed as critical for the development of mathematics skills (e.g., Geary, 2011). However, recent cross-domain research has revealed that there is considerable overlap in the predictors of reading and mathematics skills (e.g., Koponen et al., 2007, 2016, 2020; Korpipää et al., 2017; Purpura et al., 2017; Cirino et al., 2018). For example, in one of the pioneering studies, Koponen et al. (2007) showed that counting (assessed in kindergarten) and RAN (assessed in Grade 4) were significant predictors of both reading and arithmetic fluency in Grade 4.

Despite the recent proliferation of cross-domain studies examining the role of different cognitive predictors of reading and mathematics skills, several issues remain unclear. First, only a handful of studies have examined the predictors of the shared variance (i.e., covariation) between reading and mathematics skills, they have all been conducted in Finnish (a transparent alphabetic orthography), and have focused on fluency (e.g., Koponen et al., 2013, 2020; Korpipää et al., 2017). Given the possible impact of orthographic transparency on reading development and its predictors (e.g., Georgiou et al., 2008; Moll et al., 2014), their findings need to be replicated in orthographies that are less transparent than Finnish. Second, to our knowledge, none of the previous studies that examined the role of different cognitive skills in the covariation of reading and arithmetic fluency have examined if the effects of these predictors are mediated by reading and mathematics accuracy. Finally, with one exception (see Koponen et al., 2020), all previous studies that examined the predictors of the covariation of reading and mathematics skills have focused on counting as a math-related skill (e.g., Koponen et al., 2007, 2013, 2016; Korpipää et al., 2017). Thus, we do not know if other basic number skills (e.g., number sense) are also important. To address these shortcomings, we aimed to examine if reading-related skills (phonological awareness and RAN), math-related skills (number sense), and general cognitive abilities (non-verbal IQ, speed of processing, and working memory) account for the covariance between reading and arithmetic fluency in English, an opaque alphabetic orthography, and if the effects of these skills are mediated by the effects of reading and arithmetic accuracy.

## The Predictors of the Covariation Between Reading and Arithmetic

Several studies have shown that reading and mathematics are highly correlated (e.g., Koponen et al., 2007; Landerl and Moll, 2010; Codding et al., 2015; Balhinez and Shaul, 2019; Erbeli et al., 2020), and that comorbid disabilities occur far more often than isolated reading, and mathematics disabilities (e.g., Dirks et al., 2008; Willcutt et al., 2013; Koponen et al., 2018). Researchers have also argued that the observed covariation of reading and mathematics skills may be partly due to the fact that the development of both academic skills relies on similar cognitive processes (e.g., Koponen et al., 2007, 2020; Zoccolotti et al., 2020). Thus, examining the predictors of the covariation can reveal important information about the cognitive base of reading and mathematics acquisition.

Two slightly different approaches have been used to examine the unique and shared predictors of reading and mathematics skills. First, some researchers have created a latent factor to represent the shared variance between reading and mathematics skills and then regressed that factor on different predictors (Koponen et al., 2007, 2013, 2016, 2020; Korpipää et al., 2017). This makes sense if we are looking at what cognitive processes underlie what is common between reading and mathematics, but, at the same time, it does not allow us to say what processes are unique predictors of each academic skill. For example, it is possible that a cognitive process might be a significant predictor of reading, but not of what is shared between reading and mathematics. The second approach might be considered a mirror image of the first. Researchers have included both reading and mathematics tasks as dependent variables in the same model (allowing them to co-vary), and then used several predictors to examine which ones predict both outcomes and which ones predict only reading or mathematics (e.g., Slot et al., 2016; Hornung et al., 2017; Peterson et al., 2017; Yang et al., 2021). Even though this approach can show us what cognitive processes predict each outcome measure, it does not tell us if they predict the covariation between the two outcomes. For this reason, we employed both approaches in our study.

Obviously, an important question in this line of research is what cognitive processing skills are included as predictors. Previous studies have considered three kinds of skills: linguistic skills (e.g., Cirino et al., 2018; Zhang and Lin, 2018; de Megalhães et al., 2021), basic number skills (e.g., Koponen et al., 2016, 2020; Cirino et al., 2018), and general cognitive abilities (e.g., Cattell, 1987; Gathercole et al., 2004; Alloway and Alloway, 2010; Georgiou et al., 2015). In regard to the linguistic skills, researchers have focused mostly on the role of phonological awareness and RAN, both of which are considered components of phonological processing (e.g., Wagner and Torgesen, 1987). Phonological awareness is important for learning to read because it is involved in matching the letters (i.e., graphemes) in words to their corresponding sounds (i.e., phonemes) and supports the blending of the sounds in word recognition. Likewise, it is important in mathematics because some mathematics tasks (e.g., counting) involve processing of verbal codes (see triple-code model of numerical cognition; Dehaene, 1992; Dehaene et al., 2003; see also De Smedt et al., 2010). More specifically, when asked to solve a mathematics problem, children may convert the terms, operators, and quantities into sound-based codes and unimpaired access to these codes can support the execution of the problems. However, evidence from previous studies is mixed. Whereas, some cross-domain studies have reported significant effects of phonological awareness in both reading and mathematics (e.g., Slot et al., 2016; Cirino et al., 2018; Zhang and Lin, 2018; de Megalhães et al., 2021), others have reported significant effects only on reading (e.g., Durand et al., 2005; Peterson et al., 2017) or no significant effects on either academic skill (e.g., Yang et al., 2021). Studies on the predictors of the shared variance between reading and mathematics skills have also reported mixed findings. Whereas, Korpipää et al. (2017) found that phonological awareness (measured with an initial sound identification task at the Fall of Kindergarten) was not a significant predictor of the time-invariant covariation between reading and arithmetic fluency,[1] Koponen et al. (2020) found that phonological awareness (measured with a syllable and phoneme deletion task at the Spring of Grade 1) was a significant predictor of the covariation between reading and arithmetic fluency at the Fall of Grade 2.

[1]Because they assessed reading and arithmetic fluency in both Grades 1 and 7, they created both a time-specific covariance factor and a time-invariant covariance factor of reading and arithmetic fluency across the two grades.

Beyond phonological awareness, researchers have also examined the role of RAN in both reading and mathematics skills (particularly arithmetic fact fluency; e.g., Koponen et al., 2007, 2013, 2016, 2020; Georgiou et al., 2013; Hornung et al., 2017; Balhinez and Shaul, 2019). For example, in a longitudinal study with Finnish children followed from kindergarten to Grade 3, Koponen et al. (2016) found that RAN was a significant predictor of both reading and arithmetic fluency, even after controlling for the effects of phonological awareness, verbal short-term memory, vocabulary, counting, and mother's education.

Examining the relation between RAN and reading/mathematics skills in the same study is interesting in light of theoretical accounts that have been put forward to explain their relation. For example, (e.g., Wagner and Torgesen, 1987; Torgesen et al., 1994, 1997) have argued that RAN reflects the speed of access to, and retrieval of, phonological representations from long-term memory. If phonological representations are of low quality, this will interfere with the retrieval, manipulation, and retention of phonological codes, which, in turn, will impede reading development. However, researchers have also argued that if phonological representations for number words and number facts in long-term memory are weak, this will affect how quickly they can be retrieved from long-term memory, which, in turn, will impact mathematics development (e.g., Simmons and Singleton, 2008; De Smedt et al., 2010). To the extent the conceptualization of RAN as an index of children's ability to access and retrieve phonological representations from long-term memory is correct, RAN should predict the covariation of reading and mathematics skills (at least of tasks such as word reading fluency and addition fluency that rely on quick access to phonological representations in long-term memory). Koponen et al. (2016, 2020) findings are in line with this prediction.

Examining the role of RAN in the covariation of reading and mathematics skills is also interesting because some math researchers have used RAN tasks as measures of speed of processing (e.g., Berg, 2008; Chan and Ho, 2010; Vanbinst et al., 2015). Kail and colleagues (Kail and Hall, 1994; Kail et al., 1999) have also argued that speed of processing is *per se* important in tasks such as reading and mathematics that require timely integration of information within and between cognitive sub-processes. If RAN is a measure of speed of processing, then it should predict the shared variance between reading and arithmetic fluency tasks because both outcomes are speeded. If this is the case, then RAN's effects on the covariation should also disappear after controlling for other measures of speed of processing. Existing research has shown that controlling for speed of processing accounts for only a small part of the RAN-reading relation (e.g., Bowey et al., 2005; Georgiou et al., 2016); if RAN specifically captures access to the phonological representations for number words and facts, the same should be true for arithmetic fluency. This, however, may not be the case: in a study with Greek-speaking children, Georgiou et al. (2013) showed that speed of processing was enough to eliminate RAN's effects on arithmetic fluency, but not on reading fluency, suggesting that different mechanisms account for RAN-reading and RAN-arithmetic fluency connections.

Beyond the linguistic skills, basic number skills (e.g., counting, number sense) may be associated with the covariation of reading and mathematics skills. Most previous studies have focused on counting (Koponen et al., 2007, 2016, 2020; Korpipää et al., 2017). Koponen et al. (2007), for example, showed that counting (measured in kindergarten) was a significant predictor of the covariation of single-digit calculation and text reading in Grade 4 over and above the effects of letter knowledge and RAN. Koponen et al. (2020) further showed that a latent factor consisting of counting and RAN in Grade 1 (called "serial retrieval fluency") was a significant predictor of the covariation of reading and arithmetic fluency in Grade 2 over and above the effects of letter knowledge, phonological awareness, number comparison, and number writing. Interestingly, number comparison and number writing also predicted the covariation. To our knowledge, no studies have examined the role of number sense in the covariation of reading and mathematics skills. However, in a cross-domain study with 130 Grade 1–5 Dutch children, Slot et al. (2016) found that number sense was predictive of only mathematics skills. Thus, in this study we aimed to replicate this finding.

Finally, general cognitive abilities, such as non-verbal IQ, speed of processing, and working memory may predict the covariation of reading and mathematics skills. In regard to non-verbal IQ, several studies have shown that it is associated with both academic skills (e.g., Deary et al., 2007; Roth et al., 2015; Peng et al., 2019). For example, in their meta-analysis, Peng et al. (2019) estimated the average correlation between non-verbal IQ (fluid intelligence) with reading and mathematics to be 0.38 and 0.41, respectively. Korpipää et al. (2017) also showed that non-verbal IQ was a significant predictor of the time-invariant covariation of reading and arithmetic fluency; a finding that needs replication. In regard to working memory, researchers have argued that it is particularly important for reading comprehension (Kendeou et al., 2014) because children must retain information in their short-term memory while processing other parts of text. However, it may also contribute to word recognition because young children may hold the sound of individual letters in their memory while visually processing the upcoming letters within a word before blending of the individual sounds takes place. Likewise, it is needed when solving different mathematics problems [e.g., $(3 + 6) * 6 = ?$] because individuals need to first hold part of the solution in their memory (e.g., the result of $3 + 6$) before executing another operation (e.g., multiplying by 6). However, evidence on the role of working memory in reading and mathematics skills is mixed (e.g., Alloway and Alloway, 2010; Peterson et al., 2017; Balhinez and Shaul, 2019; de Megalhães et al., 2021; Yang et al., 2021). For example, Balhinez and Shaul (2019) showed that working memory was a significant predictor of both reading and arithmetic fluency in Grades 1 and 2. In turn, working with a sample of Grade 5 and 5 children, de Megalhães et al. (2021) showed that working memory was a significant predictor of arithmetic accuracy and fluency, but not of reading accuracy and fluency. Finally, Yang et al. (2021) showed that working memory was not a significant predictor of either reading or mathematics skills in Grade 1. Clearly, more research is needed on the role of working memory in the covariation of reading and mathematics skills.

To summarize, even though a few studies have examined the role of different cognitive processes in reading and mathematics skills in the same study (e.g., Hornung et al., 2017; Peterson et al., 2017; Cirino et al., 2018; Balhinez and Shaul, 2019; Yang et al., 2021), very few have examined the predictors of the covariation of reading and mathematics skills (Koponen et al., 2007, 2016, 2020; Korpipää et al., 2017). Given that both the dependent variables and the predictors are measured with complex, multifaceted tasks, failing to take the covariance between reading and mathematics skills into account does not allow us to draw firm conclusions on the shared cognitive base of these academic skills.

## The Present Study

The present study aimed to answer the following two research questions:

1) To what extent do linguistic skills (phonological awareness and RAN), number skills (number sense), and general cognitive abilities (non-verbal IQ, speed of processing, and working memory) predict reading and arithmetic fluency, and their covariation? Based on the findings of previous studies (e.g., Koponen et al., 2007, 2020; Korpipää et al., 2017), we expected that RAN would be a significant predictor of both academic skills as well as of their covariation. Because previous studies have provided mixed findings for the rest of the predictors, we did not formulate any specific hypotheses for them.
2) To what extent the effects of the linguistic skills, number skills, and general cognitive abilities on the covariation of reading and arithmetic fluency will be mediated by the effects of reading and arithmetic accuracy? We did not formulate any specific hypotheses here because no previous studies have examined the role of reading/arithmetic accuracy in these relations.

The findings of this study are expected to contribute to the literature in two important ways. First, as mentioned above, findings on the predictors of the covariation of reading and arithmetic fluency need to be replicated in a language with a less transparent orthography. This not only allows us to validate the previous findings, but also to examine the possible mediating role of reading and mathematics accuracy. Because reading accuracy reaches ceiling by the end of Grade 1 in Finland (Seymour et al., 2003), this may have prevented Koponen et al. (2007, 2016, 2020) and Korpipää et al. (2017) from testing the mediating role of reading accuracy. Given that RAN and number sense are related to reading and arithmetic accuracy (e.g., Leppänen et al., 2004; Slot et al., 2016; Zhang and Lin, 2018) and reading and arithmetic accuracy are significant predictors of reading and arithmetic fluency (e.g., Nunes et al., 2012; Fuchs et al., 2016), it is possible that the effects of RAN and number sense on the covariation of reading and arithmetic fluency are mediated. Second, to our knowledge, this is the first study to examine the role of number sense in the covariation of reading and arithmetic fluency. All previous studies had examined the role of counting (Koponen et al., 2007, 2016, 2020; Korpipää et al., 2017).

# METHOD

## Participants

Our sample consisted of 126 English-speaking children (67 females, 59 males; $M_{age}$ = 6.41 years, $SD$ = 0.45) followed from the beginning of Grade 1 (October/November, Time 1) to the end of Grade 1 (May/June, Time 2). They were recruited on a voluntary basis (155 children attending Grade 1 in the participating schools were initially invited to participate in the study) from six public elementary schools in Edmonton, Canada. The schools were located in different parts of the city in order to increase the representation of different demographics in our study. Ninety percent of the children were White, 4% East Asian, and 4% Middle Eastern, and 2% Indigenous. None of the children were experiencing any intellectual, emotional, or sensory difficulties (based on school records). Parental and school consent was obtained prior to testing. Ethics approval was also obtained from the University of Alberta (Pro00065133).

## Materials

### Non-verbal IQ

Non-verbal Matrices from the Cognitive Assessment System-2 (CAS-2; Naglieri et al., 2014) was administered to assess non-verbal IQ. Children were presented with a page containing a pattern of shapes/geometric designs that was missing a piece and were asked to choose among five or six alternatives the piece that would accurately complete the pattern. There were 44 items arranged in terms of increasing difficulty and the test was discontinued after four consecutive errors. A participant's score was the total number correct. Cronbach's alpha reliability in our sample was 0.94.

### Working Memory

The Backward Digit Span task from Wechsler Intelligence Scale for Children-III (Wechsler, 2002) was used to assess working memory. Children were asked to repeat a sequence of digits in the reverse order. The strings started with only two digits and one digit was added at each difficulty level (the maximum length was seven digits). The task was discontinued when participants failed both trials of a given length. A participant's score was the total number of correctly recalled trials. Cronbach's alpha reliability in our sample was 0.78.

### Speed of Processing

To assess speed of processing we administered the Matching Numbers task from the CAS-2 (Naglieri et al., 2014). Children were presented with four pages, each consisting of eight rows of numbers with six numbers in each row. The numbers ranged in length from one to six digits. Children were asked to find and underline the two numbers in each row that were the same within a time limit (e.g., 18 22 25 17 33 22). Naglieri et al. (2014) reported test-retest reliability to be 0.75.

### Phonological Awareness

To assess phonological awareness, we administered the Elision task from the Comprehensive Test of Phonological Processing-2 (Wagner et al., 2013). Children were asked to first listen to a word and then say the word without saying one of its sounds (e.g., Say the word *bold* without saying the/b/sound). The task was discontinued after three consecutive errors and a participant's score was the total number correct (max = 33). Cronbach's alpha reliability in our sample was 0.92.

### Rapid Automatized Naming

To assess RAN we administered Digit Naming from the RAN/RAS test battery (Wolf and Denckla, 2005). Children were asked to name as fast as possible five digits (2, 4, 5, 7, 9) that were repeated 10 times each and arranged semi-randomly in five rows of ten. Prior to beginning the timed naming, the children were asked to name the digits in a practice trial to ensure familiarity. The time to name all digits was the participant's score. The score was multiplied by −1 to ease the interpretation of our results (a higher score means better performance). Only a few naming errors occurred (mean number of errors was <1) and for this reason they were not considered further. Wolf and Denckla (2005) reported test-retest reliability for Digit Naming to be 0.92.

### Number Sense

To assess number sense, we administered the Number Sets task (Geary et al., 2009). Children were presented with four pages and each page included a target number at the top (e.g., 5) and sets indicated by two or three linked boxes with Arabic numerals (e.g., 2) and concrete objects (e.g., ▲▲▲). Children were asked to circle all the sets that can be put together to match the target number. The target number of the first two pages was 5 and the time limit was 60 secs per page. The target number of the last two pages was 9 and the time limit was 90 s per page. Signal detection method was used to calculate each child's sensitivity (*d'*) in detecting the correct sets based on the number of hits and the number of false alarms (see Geary et al., 2009, for details). Cronbach's alpha reliability in our sample was 0.90.

### Reading Accuracy

The Word Identification task (Form H) from the Woodcock Reading Mastery Tests—Revised (Woodcock, 1998) was used to assess reading accuracy. Children were asked to read out loud a list of words of increasing difficulty. The task was discontinued after six consecutive errors and a participant's score was the total number correct (max = 104). Cronbach's alpha reliability in our sample was 0.94.

### Reading Fluency

To assess reading fluency, we administered two tasks: Sight Word Efficiency (SWE; Form A) from the Test of Word Reading Efficiency (Torgesen et al., 2011) and CBM-Maze (Deno, 1985). In SWE, children were presented with a list of 108 words, divided into four columns of 27 words each, and asked to read them as fast as possible. An 8-word practice list was presented first to ensure familiarity with the task demands. The number of words read correctly within a 45 s time limit was the participant's score. Torgesen et al. (2011) reported test–retest reliability of 0.93 for ages 6 to 7. In CBM-Maze, children were exposed to a 96-word passage in which every seventh word was replaced by three options (with the exception of the first sentence that remained intact). The passage was deemed by a group of Grade 1 teachers to be appropriate for this grade level. Children were asked to circle the option that was correctly completing the meaning of each sentence. A participant's score was the number of correct answers minus the number of incorrect answers within a 3 min time limit. Cronbach's alpha reliability in our sample was 0.90. CBM-Maze correlated 0.80 with SWE in our sample. A composite score for reading fluency was subsequently created by averaging the *z*-scores of SWE and CBM-Maze and used in the analyses.

### Arithmetic Accuracy

The Mathematics Reasoning task from WIAT-III (Wechsler, 2009) was used to assess arithmetic accuracy. The Mathematics Reasoning task is a verbal problem-solving task that measures children's ability to count, identify geometric shapes, and solve single- and multistep word problems. The task was discontinued after four consecutive errors and a participant's score was the total number correct (max = 67). Cronbach's alpha reliability in our sample was 0.88.

### Arithmetic Fluency

To assess arithmetic fluency, we administered three tasks: Addition Fluency and Subtraction Fluency from WIAT-III (Wechsler, 2009) and Missing Number (Clarke and Shinn, 2004). In Addition and Subtraction Fluency, children were asked to solve as many additions or subtractions as possible within a 1-min time limit by writing their response in the space provided beside each problem. Each subtest included two pages (24 items on each page for a total of 48 problems). A participant's score was the total correct number of additions and subtractions completed within the time limit. Wechsler (2009) has reported test-retest reliability for Addition and Subtraction fluency to be 0.76 and 0.90, respectively. The Missing Number task consisted of three pages of 21 boxes each, arranged in seven rows of three. Each box contained a sequence of four numbers (three numbers and a blank; e.g., 2 3 _ 5). Children were asked to say out loud what number goes in the blank in each box. A participant's score was the total number correct within a 1-min time limit (max = 63). Clarke and Shinn (2004) reported test-retest reliability to be 0.79. Missing Number correlated 0.58 with Addition Fluency and 0.57 with Subtraction Fluency. A composite score for arithmetic fluency was subsequently created by averaging the *z*-scores of these three tasks and used in the analyses.

## Procedure

At Time 1, children were assessed on measures of non-verbal IQ, speed of processing, working memory, phonological awareness, RAN, and number sense. At Time 2, they were assessed on measures of reading/arithmetic accuracy and fluency. At both times, testing was conducted in a quiet room at children's school during school hours by graduate students who received extensive training on test administration and scoring. At both times, testing was completed in one sitting and the order of task administration was fixed across participants. At Time 1, testing lasted ∼40 min and at Time 2∼30 min.

## Statistical Analyses

To examine the unique contributions of the cognitive skills to reading fluency, arithmetic fluency, and the covariation of

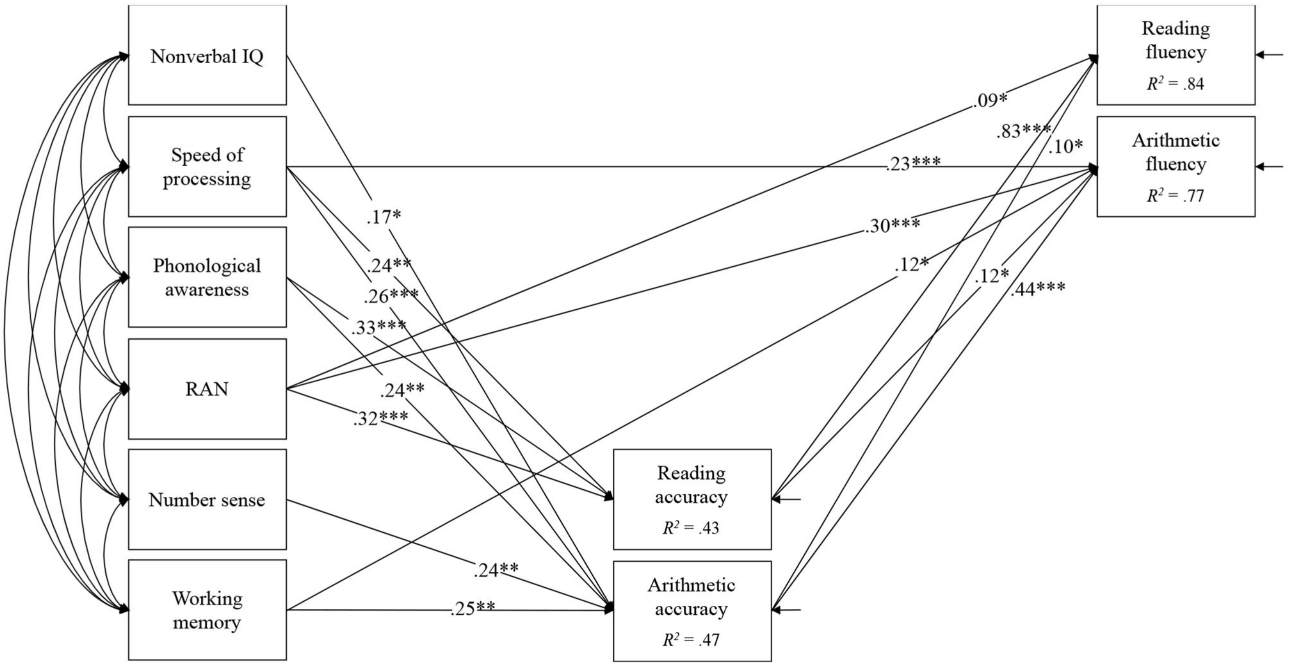


**FIGURE 1 |** Path model for reading fluency and arithmetic fluency. Non-significant paths are not shown for clarity purposes. *$p$ < 0.05, **$p$ < 0.01, ***$p$ < 0.001.

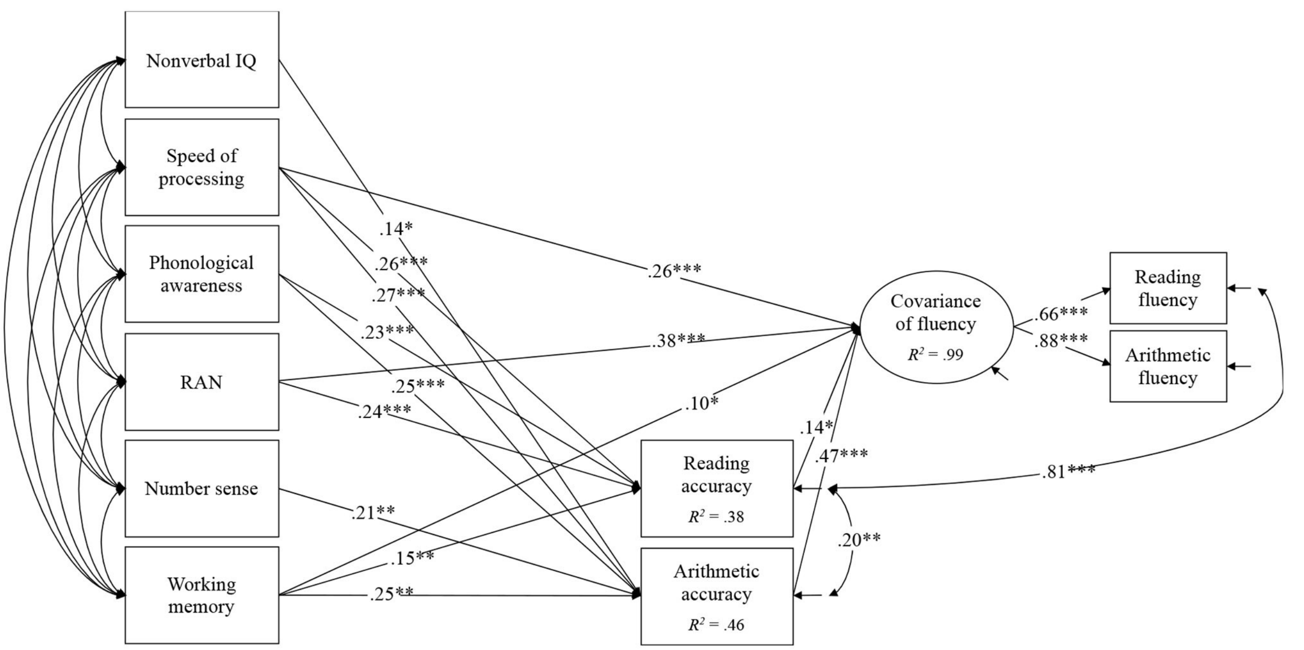


**FIGURE 2 |** Latent variable model for the covariation of reading fluency and arithmetic fluency. Non-significant paths are not shown for clarity purposes. *$p$ < 0.05, **$p$ < 0.01, ***$p$ < 0.001.

the two, we constructed the following two sets of models. First, a path model for the predictors of reading fluency and arithmetic fluency was constructed (**Figure 1**). Reading accuracy and arithmetic accuracy were included in the model to test their mediating roles in the relations between the cognitive skills and reading/arithmetic fluency. Non-significant paths were eliminated one at a time from the initial model to evaluate a more parsimonious model with fewer paths. Second, a latent variable model for the covariation of reading fluency and arithmetic fluency was constructed (**Figure 2**). Additionally, to examine

**TABLE 1 |** Descriptive statistics for the measures used in the study.

| Measure | *M* | *SD* | Range |
|---|---|---|---|
| Time 1 (beginning of Grade 1) | | | |
| Non-verbal IQ (max = 44) | 10.61 | 3.68 | 0–25 |
| Working memory (max = 12) | 3.15 | 1.24 | 0–7 |
| Speed of processing (max = 32) | 10.28 | 3.12 | 4–21 |
| Phonological awareness (max = 33) | 10.46 | 4.42 | 2–20 |
| RAN | 40.90 | 14.19 | 21–122 |
| Number sense | 2.64 | 0.67 | 1.06–3.74 |
| Time 2 (end of Grade 1) | | | |
| Word identification (max = 104) | 43.96 | 13.39 | 5–82 |
| Sight word efficiency (max = 108) | 43.77 | 16.19 | 0–73 |
| CBM-Maze (max = 13) | 4.86 | 3.46 | 0–12 |
| Math reasoning (max = 67) | 20.59 | 5.29 | 11–36 |
| Addition fluency (max = 48) | 6.89 | 5.12 | 0–26 |
| Subtraction fluency (max = 48) | 6.67 | 4.39 | 0–25 |
| Missing number (max = 63) | 14.95 | 5.83 | 3–30 |

*RAN, rapid automatized naming. With the exception of Number Sense, the descriptive statistics are on the raw scores of each task.*

**TABLE 2 |** Correlations between the variables.

| | 1. | 2. | 3. | 4. | 5. | 6. | 7. | 8. | 9. |
|---|---|---|---|---|---|---|---|---|---|
| 1. T1 NVIQ | | | | | | | | | |
| 2. T1 WM | 0.11 | | | | | | | | |
| 3. T1 SoP | 0.28** | 0.31** | | | | | | | |
| 4. T1 PA | 0.17 | 0.38** | 0.24* | | | | | | |
| 5. T1 RAN | 0.00 | 0.27** | 0.35** | 0.35** | | | | | |
| 6. T1 NS | −0.02 | −0.06 | 0.23* | 0.13 | 0.27** | | | | |
| 7. T2 RA | 0.19* | 0.31** | 0.43** | 0.50** | 0.52** | 0.25** | | | |
| 8. T2 RF | 0.22* | 0.32** | 0.49** | 0.39** | 0.53** | 0.30** | 0.91** | | |
| 9. T2 AA | 0.31** | 0.43** | 0.50** | 0.46** | 0.35** | 0.32** | 0.49** | 0.58** | |
| 10. T2 AF | 0.17 | 0.49** | 0.63** | 0.48** | 0.62** | 0.32** | 0.62** | 0.66** | 0.75** |

*T1, Time 1; T2, Time 2; NVIQ, Non-verbal IQ; WM, working memory; SoP, speed of processing; PA, phonological awareness; NS, number sense; RA, reading accuracy; RF, reading fluency; AA, arithmetic accuracy; AF, arithmetic fluency.*
**p <0.05; **p <0.01.*

the indirect effect of the cognitive skills on reading fluency, arithmetic fluency, and the covariance factor of fluency through reading accuracy and arithmetic accuracy, we performed a series of mediation analyses using these models. A bias-corrected bootstrapping technique (Hayes and Scharkow, 2013) with 5,000 resamples was used to establish confidence intervals for the indirect effects (Preacher and Hayes, 2008).

All analyses were conducted using Mplus 8.6 (Muthén and Muthén, 1998–2017). Little's Missing Completely at Random test (Little, 1988) showed that our missing data (either due to attrition or to children's decision to discontinue a task) were missing completely at random ($\chi^2 = 16.32$, $df = 18$, $p = 0.57$), and thus were handled by the full information maximum likelihood estimation. The model fit of each model was assessed using the chi-square value and a set of fit indices: the comparative fit index (CFI), the Tucker-Lewis index (TLI), the root-mean-square error of approximation (RMSEA), and the standardized root-mean-square residual (SRMR). A non-significant chi-square value, CFI and TLI values above 0.95, an RMSEA value below 0.06, and an SRMR value below 0.08 indicate a good model fit (Kline, 2015).

# RESULTS

## Descriptive Statistics and Correlations

The descriptive statistics for the measures used in the study are presented in **Table 1**. Before conducting any further analyses, we examined the distributional properties of the measures. RAN at Time 1 was positively skewed and log transformation was performed to normalize its distribution. The transformed scores were used in subsequent analyses. In addition, outliers on some measures (defined as more than 3 *SD* above/below the mean) were winsorized to the next non-outlier's score ±1 to avoid overemphasizing their effects on the results (Tabachnick and Fidell, 2012).

The zero-order correlations among all of the variables are presented in **Table 2**. The correlations with the linguistic/number skills (i.e., phonological awareness, RAN, and number sense) ranged from 0.30 to 0.53 for reading fluency and from 0.32 to 0.62 for arithmetic fluency. RAN showed the strongest association with both reading and arithmetic fluency. Additionally, in all instances, the cognitive measures correlated more strongly with arithmetic fluency than reading fluency.

## Structural Models and Mediational Analyses

The path model for reading fluency and arithmetic fluency is shown in **Figure 1**. The model showed an excellent fit, $\chi^2(6) = 4.62$, $p = 0.59$, CFI = 1.00, TLI = 1.00, RMSEA = 0, 90%CI [0, 0.10], SRMR = 0.03. The results showed that RAN predicted both reading fluency ($\beta = 0.09$) and arithmetic fluency ($\beta = 0.30$) even when the effects of reading accuracy and arithmetic accuracy were controlled. Additionally, speed of processing ($\beta = 0.23$), and working memory ($\beta = 0.12$) had a direct effect on arithmetic fluency.

The model for the cognitive predictors of the covariation of reading fluency and arithmetic fluency is shown in **Figure 2**. In order to have a well-fitting model, we had to allow the residuals of reading accuracy and reading fluency to covary. The model fit the data very well ($\chi^2 = 15.51$, $df = 12$, $p = 0.24$, CFI = 0.99, TLI = 0.98, RMSEA = 0.05, 90%CI [0, 0.11], SRMR = 0.04), and the results showed that RAN ($\beta = 0.38$), speed of processing ($\beta = 0.26$), and working memory ($\beta = 0.10$) predicted the covariance factor of fluency over and above the significant effects of reading and arithmetic accuracy. Importantly, the predictor variables accounted for a large amount of variance in the covariance factor (99%).

Finally, the results of the mediation analyses are shown in **Table 3**. The results showed that speed of processing and phonological awareness had indirect effects on reading fluency, arithmetic fluency, and the covariance of fluency via both reading and arithmetic accuracy. RAN also had indirect effects on the same outcome variables via reading accuracy, while those of non-verbal IQ and number sense were mediated by arithmetic accuracy. Moreover, working memory had indirect effects on reading and arithmetic fluency *via* arithmetic accuracy, and it

**TABLE 3 |** Indirect effects of the cognitive predictors on reading fluency, arithmetic fluency, and the covariance of fluency.

| Path | Estimate | Bootstrapped 95% CI |
|---|---|---|
| Reading and arithmetic fluency | | |
| NVIQ → AA → RF | 0.017 | [0.002, 0.050] |
| NVIQ → AA → AF | 0.073 | [0.017, 0.143] |
| SoP → RA → RF | 0.195 | [0.081, 0.312] |
| SoP → RA → AF | 0.029 | [0.006, 0.067] |
| SoP → AA → RF | 0.026 | [0.003, 0.069] |
| SoP → AA → AF | 0.113 | [0.055, 0.187] |
| PA → RA → RF | 0.269 | [0.148, 0.378] |
| PA → RA → AF | 0.041 | [0.006, 0.092] |
| PA → AA → RF | 0.024 | [0.006, 0.057] |
| PA → AA → AF | 0.106 | [0.037, 0.188] |
| RAN → RA → RF | 0.266 | [0.150, 0.376] |
| RAN → RA → AF | 0.040 | [0.009, 0.087] |
| NS → AA → RF | 0.024 | [0.002, 0.063] |
| NS → AA → AF | 0.103 | [0.042, 0.177] |
| WM → AA → RF | 0.025 | [0.005, 0.062] |
| WM → AA → AF | 0.109 | [0.048, 0.189] |
| Covariance of fluency | | |
| NVIQ → AA → CoF | 0.066 | [0.003, 0.136] |
| SoP → RA → CoF | 0.037 | [0.008, 0.081] |
| SoP → AA → CoF | 0.129 | [0.063, 0.209] |
| PA → RA → CoF | 0.032 | [0.005, 0.083] |
| PA → AA → CoF | 0.118 | [0.040, 0.207] |
| RAN → RA → CoF | 0.035 | [0.009, 0.080] |
| NS → AA → CoF | 0.098 | [0.039, 0.167] |
| WM → RA → CoF | 0.021 | [0.004, 0.052] |
| WM → AA → CoF | 0.115 | [0.052, 0.196] |

*NVIQ, Non-verbal IQ; SoP, speed of processing; PA, phonological awareness; NS, number sense; WM, working memory; RA, reading accuracy; AA, arithmetic accuracy; RF, reading fluency; AF, arithmetic fluency; CoF, covariation of fluency.*

also had indirect effects on the covariance of fluency via reading and arithmetic accuracy. To summarize, these results indicate that speed of processing and RAN predict reading and arithmetic fluency and the covariation of the two both directly and indirectly through reading and arithmetic accuracy (except the direct effect of speed of processing on reading fluency). Additionally, working memory had direct effects on arithmetic fluency and the covariance factor of fluency over and above its indirect effects via reading and arithmetic accuracy. In contrast, phonological awareness and number sense predict reading fluency, arithmetic fluency, and the covariance factor of fluency only indirectly through the accuracy measures.

## DISCUSSION

The purpose of this study was to examine the shared and unique predictors of reading and arithmetic fluency and whether their effects are mediated by reading and mathematics accuracy. To this end, we used two slightly different approaches: First, we used reading and arithmetic fluency as separate outcomes in the same model. Our findings showed that only RAN Digits predicts both outcomes over and above the effects of reading and mathematics accuracy. Speed of processing and working memory predicted only arithmetic fluency. In regard to RAN Digits, our finding replicates those of previous studies (Koponen et al., 2007, 2013, 2016; Hornung et al., 2017) and suggests that word reading fluency and arithmetic fact retrieval rely on how quickly one could access the phonological representations of words or numbers. Notably, this is independent of the effects of speed of processing. The unique effect of RAN Digits on reading and arithmetic fluency over and above the effects of speed of processing has already been documented (e.g., Georgiou et al., 2009; however, see also Georgiou et al., 2013; Cui et al., 2017). The fact that processing speed and working memory predicted only arithmetic fluency may be due to the strong effects of reading accuracy on reading fluency that left very little room for other variables to make any significant contributions. In fact, when we reran our analyses without reading accuracy, both speed of processing and working memory predicted reading fluency. However, this finding may also reflect the fact that both speed of processing and working memory tasks involved processing of numbers and this brought them closer to arithmetic fluency.

Second, we tested a model in which the cognitive-linguistic skills were used as predictors of the covariation of reading and arithmetic fluency. This approach allows us to examine what skills predict what is shared between reading and arithmetic fluency. For example, if these two are related because they both require speeded responses, then speed of processing should predict their covariation. Our findings were slightly different than those of the first approach. More specifically, RAN, speed of processing, and working memory were unique predictors of the covariation of reading and arithmetic fluency. This suggests first that the cognitive base of reading and arithmetic fluency consists of multiple cognitive processes. Obviously, both outcomes require speeded responses (hence the effects of speed of processing). However, on top of that, they also require quick access and retrieval of phonological representations stored in long-term memory (hence the effects of RAN and working memory). Second, it shows that some cognitive processes (i.e., speed of processing and working memory) might be related more to what reading and arithmetic share than what is unique to them (see **Figure 1**), when it is used as a separate outcome in the analyses. This implies that depending on the approach used researchers may draw slightly different conclusions.

Phonological awareness and number sense contributed to the covariance of reading and arithmetic fluency indirectly through the effects of reading and mathematics accuracy. The strong connection between phonological awareness and reading accuracy is not surprising and has been reported in several previous studies (see e.g., Melby-Lervåg et al., 2012; Ruan et al., 2018, for evidence from meta-analyses). Successful decoding relies on children's ability to blend the sounds in words. However, perhaps less expected is the significant effect of phonological awareness on mathematics accuracy. Previous studies on the relation between phonological awareness and mathematics skills provided mixed findings (for significant effects see Cirino et al., 2018; Zhang and Lin, 2018; Yang and McBride, 2020 for non-significant effects see Durand et al., 2005; Koponen et al., 2016;

Peterson et al., 2017; Yang et al., 2021). An explanation for the mixed findings may relate to the type of mathematics task used as an outcome in different studies. According to the triple-code model (Dehaene, 1992; Dehaene et al., 2003), three types of codes are used in numerical processing: a visual code, a verbal code, and an analog magnitude code. Phonological awareness may be predictive of mathematics tasks like Mathematic Reasoning that include more items requiring processing of verbal codes than some other tasks. This explanation is independent of the complexity of the mathematics problems and whether the solution to a given problem can be retrieved directly from memory. For example, De Smedt et al. (2010) showed that phonological awareness was a significant predictor of only arithmetic problems with a small problem size and concluded that this is likely due to the fact that these problems can be solved by rapid retrieval of the problem's solution from long-term memory. This explanation is problematic as it has also been used to explain why RAN predicts more strongly arithmetic fluency tasks such as addition and multiplication fluency (but not subtraction or division fluency) that involve rapid retrieval of an answer from memory (e.g., Georgiou et al., 2013, 2020; Cui et al., 2017). In our study, phonological awareness predicted arithmetic accuracy but not fluency. This suggests that it is not the rapid access but the integrity/quality of the accessed phonological codes that matters in this case.

In contrast to phonological awareness, number sense appears to have a more domain specific contribution as it predicted only mathematics accuracy (see Jordan et al., 2010; Slot et al., 2016, for a similar finding) and through the effects of mathematics accuracy the covariance of reading and arithmetic fluency. This suggests that in the early phases of reading and mathematics development, there is a set of skills such as non-verbal IQ and number sense that may exert domain specific rather than domain general effects.

Some limitations of the present study should be reported. First, we used single measures of each predictor variable. Obviously, administering more tasks would strengthen each construct, but given the time restrictions associated with assessing young children, we had to make a tough choice between covering more constructs with a single task and assessing fewer constructs with more measures. We opted for the former. Second, our study included Grade 1 children and our findings may not generalize to other grade levels. This is important to note because the effects of some cognitive-linguistic skills (e.g., RAN) on reading and mathematics may vary across grade levels (e.g., Araújo et al., 2015). Third, we did not include counting in our study. A pilot study we ran prior to collecting these data produced ceiling effects in counting and for this reason we did not assess it. This does not allow us to compare our findings to those of previous studies that assessed counting (Koponen et al., 2007, 2016; Korpipää et al., 2017). Fourth, we did not administer a measure of vocabulary. Finally, our RAN, speed of processing, and working memory tasks involved numbers and this may have inflated their relation with mathematics accuracy and fluency. A future study should replicate our findings using also neutral RAN, speed of processing, and working memory tasks.

## CONCLUSION

Do reading and arithmetic fluency share a similar cognitive base? Our findings add to those of previous studies (e.g., Koponen et al., 2007, 2020; Korpipää et al., 2017; Cirino et al., 2018; Balhinez and Shaul, 2019) and show that the answer is not straightforward. On the one hand, there was a set of cognitive skills (i.e., RAN, speed of processing, and working memory) that exerted both a direct and an indirect effect on the covariance of reading and arithmetic fluency. For these processing skills we can say with some confidence that they are part of a cognitive base that supports both reading and arithmetic fluency. On the other hand, there was a second set of processing skills (i.e., non-verbal IQ, phonological awareness, and number sense) that predicted the covariation of reading and arithmetic fluency through the effects of reading and mathematics accuracy. In fact, number sense and non-verbal IQ predicted only mathematics accuracy, which suggests that some processing skills might be uniquely associated with mathematics (see Slot et al., 2016; de Megalhães et al., 2021; for a similar finding). Taken together, these findings suggest that reading and arithmetic fluency do not rely on a single cognitive process, but rather on a broader network of linguistic and general cognitive abilities. Future studies should replicate our findings following the same children over a longer period of time and in different languages.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethics Board of the University of Alberta. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

## AUTHOR CONTRIBUTIONS

GG and RP designed the study. GG prepared the data for the analysis and wrote the introduction, method, and discussion sections of the manuscript. TI ran the analyses and wrote the results section of the manuscript. All authors interpreted the data and discussed the results.

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## REFERENCES


Alloway, T. P., and Alloway, R. G. (2010). Investigating the predictive roles of working memory and IQ in academic attainment. *J. Exp. Child Psychol.* 106, 20–29. doi: 10.1016/j.jecp.2009.11.003

Araújo, S., Reis, A., Petersson, K. M., and Faísca, L. (2015). Rapid automatized naming and reading performance: a meta-analysis. *J. Educ. Psychol.* 107, 868–883. doi: 10.1037/edu0000006

Balhinez, R., and Shaul, S. (2019). The relationship between reading fluency and arithmetic fact fluency and their shared cognitive skills: a developmental perspective. *Front. Psychol.* 10:1281. doi: 10.3389/fpsyg.2019.01281

Berg, D. H. (2008). Working memory and arithmetic calculation in children: the contributory roles of processing speed, short-term memory, and reading. *J. Exp. Child Psychol.* 99, 288–308. doi: 10.1016/j.jecp.2007.12.002

Bowey, J. A., McGuigan, M., and Ruschena, A. (2005). On the association between serial naming speed for letters and digits and word-reading skill: towards a developmental account. *J. Res. Read.* 28, 400–422. doi: 10.1111/j.1467-9817.2005.00278.x

Cattell, R. B. (1987). *Intelligence: Its structure, Growth, and Action*. Amsterdam: Elsevier.

Chan, B. M., and Ho, C. S. (2010). The cognitive profile of Chinese children with mathematics difficulties. *J. Exp. Child Psychol.* 107, 260–279. doi: 10.1016/j.jecp.2010.04.016

Cirino, P. T., Child, A. E., and Macdonald, K. T. (2018). Longitudinal predictors of the overlap between reading and math skills. *Contemp. Educ. Psychol.* 54, 99–111. doi: 10.1016/j.cedpsych.2018.06.002

Clarke, B., and Shinn, M. R. (2004). A preliminary investigation into the identification and development of early mathematics curriculum-based measurement. *School Psych. Rev.* 33, 234–248. doi: 10.1080/02796015.2004.12086245

Codding, R. S., Petscher, Y., and Truckenmiller, A. (2015). CBM reading, mathematics, and written expression at the secondary level: examining latent composite relations among indices and unique predictions with a state achievement test. *J. Educ. Psychol.* 107, 437–450. doi: 10.1037/a0037520

Cui, J., Georgiou, G. K., Zhang, Y., Li, Y., Shu, H., and Zhou, X. (2017). Examining the relationship between rapid automatized naming and arithmetic fluency in Chinese kindergarten children. *J. Exp. Child Psychol.* 154, 146–163. doi: 10.1016/j.jecp.2016.10.008

de Megalhães, C. G., Mervis, C. B., and Cardoso-Martins, C. (2021). Cognitive predictors of arithmetic, reading, and spelling in Brazilian-Portuguese children. *Read. Writ.* 34, 171–198. doi: 10.1007/s11145-020-10062-0

De Smedt, B., Taylor, J., Archibald, L., and Ansari, D. (2010). How is phonological processing related to individual differences in children's arithmetic skills? *Dev. Sci.* 13, 508–520. doi: 10.1111/j.1467-7687.2009.00897.x

Deary, I. J., Strand, S., Smith, P., and Fernandes, C. (2007). Intelligence and educational achievement. *Intelligence* 35, 13–21. doi: 10.1016/j.intell.2006.02.001

Dehaene, S. (1992). Varieties of numerical abilities. *Cogn. Int. J. Cogn. Sci.* 44, 1–42. doi: 10.1016/0010-0277(92)90049-N

Dehaene, S., Piazza, M., Pinel, P., and Cohen, L. (2003). Three parietal circuits for number processing. *Cogn. Neuropsychol.* 20, 487–506. doi: 10.1080/02643290244000239

Deno, S. L. (1985). Curriculum-based measurement: the emerging alternative. *Except. Child.* 52, 219–232. doi: 10.1177/001440298505200303

Dirks, E., Spyer, G., van Lieshout, E. C. D. M., and de Sonneville, L. (2008). Prevalence of combined reading and arithmetic disabilities. *J. Learn. Disabil.* 41, 460–473. doi: 10.1177/0022219408321128

Durand, M., Hulme, C., Larkin, R., and Snowling, M. (2005). The cognitive foundations of reading and arithmetic skills in 7-to 10-year-olds. *J. Exp. Child Psychol.* 91, 113–136. doi: 10.1016/j.jecp.2005.01.003

Erbeli, F., Shi, Q., Campbell, A. R., Hart, S. A., and Woltering, S. (2020). Developmental dynamics between reading and math in elementary school. *Dev. Sci.* 56, 912–914. doi: 10.1111/desc.13004

Fuchs, L. S., Geary, D. C., Fuchs, D., Compton, D. L., and Hamlett, C. L. (2016). Pathways to third-grade calculation versus word-reading competence: are they more alike or different? *Child Dev.* 87, 558–567. doi: 10.1111/cdev.12474

Gathercole, S. E., Pickering, S. J., Knight, C., and Stegmann, Z. (2004). Working memory skills and educational attainment: evidence from national curriculum assessments at 7 and 14 years of age. *Appl. Cogn. Psychol.* 18, 1–16. doi: 10.1002/acp.934

Geary, D. (2011). Cognitive predictors of achievement growth in mathematics: a 5-year longitudinal study. *Dev. Psychol.* 47, 1539–1552. doi: 10.1037/a0025510

Geary, D. C., Bailey, D. H., Littlefield, A., Wood, P., Hoard, M. K., and Nugent, L. (2009). First-grade predictors of mathematical learning disability: a latent class trajectory analysis. *Cogn. Dev.* 24, 411–429. doi: 10.1016/j.cogdev.2009.10.001

Georgiou, G., Aro, M., Liao, C.-H., and Parrila, R. (2016). Modeling the relationship between rapid automatized naming and literacy skills across languages varying in orthographic consistency. *J. Exp. Child Psychol.* 143, 48–64. doi: 10.1016/j.jecp.2015.10.017

Georgiou, G., Parrila, R., and Kirby, J. (2009). RAN components and reading development from Grade 3 to Grade 5: what underlies their relationship? *Sci. Stud. Read.* 13, 508–534. doi: 10.1080/10888430903034796

Georgiou, G., Parrila, R., and Papadopoulos, T. (2008). Predictors of word decoding and reading fluency in English and Greek: a cross-linguistic comparison. *J. Educ. Psychol.* 100, 566–580. doi: 10.1037/0022-0663.100.3.566

Georgiou, G., Wei, W., Inoue, T., and Deng, C. (2020). Are the relations of rapid automatized naming with reading and mathematics accuracy and fluency bidirectional? Evidence from a 5-year longitudinal study with Chinese children. *J. Educ. Psychol.* 112, 1506–1520. doi: 10.1037/edu0000452

Georgiou, G. K., Manolitsis, G., and Tziraki, N. (2015). "Is intelligence relevant in reading "μ?να" and in calculating "3+5"?" in *Cognition, Intelligence and Achievement,* eds T. C., Papadopoulos, R. Parrila, and J. R. Kirby (Cambridge, MA: Academic Press), 225–243.

Georgiou, G. K., Tziraki, N., Manolitsis, G., and Fella, A. (2013). Is rapid automatized naming related to reading and mathematics for the same reason(s)? a follow-up study from kindergarten to Grade 1. *J. Exp. Child Psychol.* 115, 481–496. doi: 10.1016/j.jecp.2013.01.004

Hayes, A. F., and Scharkow, M. (2013). The relative trustworthiness of inferential tests of the indirect effect in statistical mediation analysis: does method really matter? *Psychol. Sci.* 24, 1918–1927. doi: 10.1177/0956797613480187

Hornung, C., Martin, R., and Fayol, M. (2017). General and specific contributions of RAN to reading and arithmetic fluency in first graders: a longitudinal latent variable approach. *Front. Psychol.* 8:1746. doi: 10.3389/fpsyg.2017.01746

Hulme, C., and Snowling, M. J. (2015). Learning to read: What we know and what we need to understand better. *Child Dev. Perspect.* 7, 1–5. doi: 10.1111/cdep.12005

Jordan, N. C., Glutting, J., and Ramineni, C. (2010). The importance of number sense to mathematics achievement in first and third grades. *Learn. Individ. Differ.* 20, 82–88. doi: 10.1016/j.lindif.2009.07.004

Kail, R., and Hall, L. K. (1994). Speed of processing, naming speed, and reading. *Dev. Psychol.* 30, 949–954. doi: 10.1037/0012-1649.30.6.949

Kail, R., Hall, L. K., and Caskey, B. J. (1999). Processing speed, exposure to print, and naming speed. *Appl. Psycholinguist* 20, 303–314. doi: 10.1017/S0142716499002076

Kendeou, P., van den Broek, P., Helder, A., and Karlsson, J. (2014). A cognitive view of reading comprehension: implications for reading difficulties. *Learn. Disabil. Res. Pract.* 29, 10–16. doi: 10.1111/ldrp.12025

Kline, R. B. (2015). *Principles and Practice of Structural Equation Modeling, 4th edn*. New York, NY: Guilford Press.

Koponen, T., Aro, M., Poikkeus, A.-M., Niemi, P., Lerkkanen, M.-K., Ahonen, T., et al. (2018). Comorbid fluency difficulties in reading and math: longitudinal stability across early grades. *Except. Child.* 84, 298–311. doi: 10.1177/0014402918756269

Koponen, T., Aunola, K., Ahonen, T., and Nurmi, J. E. (2007). Cognitive predictors of single-digit and procedural calculation skills and their covariation with reading skill. *J. Exp. Child Psychol.* 97, 220–241. doi: 10.1016/j.jecp.2007.03.001

Koponen, T., Eklund, K., Heikkil,ä, R., Salminen, J., Fuchs, L., Fuchs, D., et al. (2020). Cognitive correlates of the covariance in reading and arithmetic fluency: importance of serial retrieval fluency. *Child Develop.* 91, 1063–1080. doi: 10.1111/cdev.13287

Koponen, T., Salmi, P., Eklund, K., and Aro, T. (2013). Counting and RAN: predictors of arithmetic calculation and reading fluency. *J. Educ. Psychol.* 105, 162–175. doi: 10.1037/a0029285

Koponen, T., Salmi, P., Torppa, M., Eklund, K., Aro, T., Aro, M., et al. (2016). Counting and rapid naming predict the fluency of arithmetic and reading skills. *Contemp. Educ. Psychol.* 44, 83–94. doi: 10.1016/j.cedpsych.2016.02.004

Korpipää, H., Koponen, T., Aro, M., Tolvanen, A., Aunola, K., Poikkeus, A.-M., et al. (2017). Covariation between reading and arithmetic skills from grade 1 to grade 7. *Contemp. Educ. Psychol.* 5, 131–140. doi: 10.1016/j.cedpsych.2017.06.005

Landerl, K., and Moll, K. (2010). Comorbidity of learning disorders: prevalence and familial transmission. *J. Child Psychol. Psychiatry* 51, 287–294. doi: 10.1111/j.1469-7610.2009.02164.x

Leppänen, U., Niemi, P., Aunola, K., and Nurmi, J.-E. (2004). Development of reading skills among preschool and primary school pupils. *Read. Res. Q.* 39, 72–93. doi: 10.1598/RRQ.39.1.5

Little, R. J. A. (1988). A test of missing completely at random for multivariate data with missing values. *J. Am. Stat. Assoc.* 83, 1198–1202. doi: 10.1080/01621459.1988.10478722

Melby-Lervåg, M., Lyster, S.-A., and Hulme, C. (2012). Phonological skills and their role in learning to read: a meta-analytic review. *Psychol. Bull.* 138, 322–352. doi: 10.1037/a0026744

Moll, K., Ramus, F., Bartling, J., Bruder, J., Kunze, S., Neuhoff, N., et al. (2014). Cognitive mechanisms underlying reading and spelling development in five European orthographies. *Learn. Instruc.* 29, 65–77. doi: 10.1016/j.learninstruc.2013.09.003

Muthén, L. K., and Muthén, B. O. (1998–2017). *Mplus User's Guide, 8th Edn,* Muthén and Muthén.

Naglieri, J. A., Das, J. P., and Goldstein, S. (2014). *Cognitive Assessment System, 2nd* Edn, Austin, Texas: Brief. PRO-ED.

Nunes, T., Bryant, P., and Barros, R. (2012). The development of word recognition and its significance for comprehension and fluency. *J. Educ. Psychol.* 104, 959–973. doi: 10.1037/a0027412

Peng, P., Wang, T. F., Wang, C. C., and Lin, X. (2019). A meta-analysis on the relation between fluid intelligence and reading/mathematics: effects of tasks, age, and social economics status. *Psychol. Bull.* 145, 189–236. doi: 10.1037/bul0000182

Peterson, R. L., Boada, R., McGrath, L. M., Willcutt, E. G., Olson, R. K., and Pennington, B. F. (2017). Cognitive prediction of reading, math, and attention: shared and unique influences. *J. Learn. Disabil.* 50, 408–421. doi: 10.1177/0022219415618500

Preacher, K. J., and Hayes, A. F. (2008). Asymptotic and resampling strategies for assessing and comparing indirect effects in multiple mediator models. *Behav. Res. Methods* 40, 879–891. doi: 10.3758/BRM.40.3.879

Purpura, D. J., Schmitt, S. A., and Ganley, C. M. (2017). Foundations of mathematics and literacy: the role of executive functioning components. *J. Exp. Child Psychol.* 153, 15–34. doi: 10.1016/j.jecp.2016.08.010

Roth, B., Becker, N., Romeyke, S., Schäfer, S., Domnick, F., and Spinath, F. M. (2015). Intelligence and school grades: a meta-analysis. *Intelligence* 53, 118–137. doi: 10.1016/j.intell.2015.09.002

Ruan, Y., Georgiou, G., Song, S., Li, Y., and Shu, H. (2018). Does writing system influence the associations between phonological awareness, morphological awareness and reading? A meta-analysis. *J. Educ. Psychol.* 110, 180–202. doi: 10.1037/edu0000216

Seymour, P., Aro, M., and Erskine, J. (2003). Foundation literacy acquisition in European orthographies. *Br. J. Psychol.* 94, 143–174. doi: 10.1348/000712603321661859

Simmons, F. R., and Singleton, C. (2008). Do weak phonological representations impact on arithmetic development? A review of research into arithmetic and dyslexia. *Dyslexia* 14, 77–94. doi: 10.1002/dys.341

Slot, E. M., van Viersen, S., de Bree, E. H., and Kroesbergen, E. H. (2016). Shared and unique risk factors underlying mathematical disability and reading and spelling disability. *Front. Psychol.* 7:803. doi: 10.3389/fpsyg.2016.00803

Tabachnick, B. G., and Fidell, L. S. (2012). *Using Multivariate Statistics, 6th Edn.* London: Pearson.

Torgesen, J. K., Wagner, R. K., and Rashotte, C. A. (1994). Longitudinal studies of phonological processing and reading. *J. Learn. Disabil.* 27, 276–286. doi: 10.1177/002221949402700503

Torgesen, J. K., Wagner, R. K., and Rashotte, C. A. (2011). *Test of Word Reading Efficiency, 2nd Edn.* Austin, TX: Pro-ED.

Torgesen, J. K., Wagner, R. K., Rashotte, C. A., Burgess, S., and Hecht, S. (1997). Contributions of phonological awareness and rapid automatic naming ability to the growth of word-reading skills in second-to fifth grade children. *Sci. Stud. Read.* 1, 161–185. doi: 10.1207/s1532799xssr0102_4

Vanbinst, K., Ghesquière, P., and De Smedt, B. (2015). Does numerical processing uniquely predict first graders' future development of single-digit arithmetic? *Learn. Individ. Differ.* 37, 153–160. doi: 10.1016/j.lindif.2014.12.004

Wagner, R., Torgesen, J. K., Rashotte, C. A., and Pearson, N. A. (2013). *Comprehensive Test of Phonological Processing, 2nd Edn.* Austin, TX: Pro-Ed. doi: 10.1037/t52630-000

Wagner, R. K., and Torgesen, J. K. (1987). The nature of phonological processing and its causal role in the acquisition of reading skills. *Psychol. Bull.* 101, 192–212. doi: 10.1037/0033-2909.101.2.192

Wechsler, D. (2002). *Wechsler Individual Achievement Test (WIAT-II), 2nd Edn.* San Antonio, TX: The Psychological Corporation. doi: 10.1037/t15173-000

Wechsler, D. (2009). *Wechsler Individual Achievement Test-third edition (WIAT-III), 2nd Edn.* San Antonio, TX: The Psychological Corporation.

Willcutt, E. G., Petrill, S. A., Wu, S., Boada, R., DeFries, J. C., Olson, R. K., et al. (2013). Comorbidity between reading disability and math disability: concurrent psychopathology, functional impairment, and neuropsychological functioning. *J. Learn. Disabil.* 46, 500–516. doi: 10.1177/0022219413477476

Wolf, M., and Denckla, M. B. (2005). *Rapid Automatized Naming and Rapid Alternating Stimulus Tests (RAN/RAS).* Austin, TX: Pro-ED.

Woodcock, R. W. (1998). *Woodcock reading mastery test-revised.* Washington, DC: American Guidance Service.

Yang, X., and McBride, C. (2020). How do phonological processing abilities contribute to early Chinese reading and mathematics? *Educ. Psychol.* 40, 893–911. doi: 10.1080/01443410.2020.1771679

Yang, X., McBride, C., Ho, C. S.-H., and Chung, K. K. H. (2021). Longitudinal associations of phonological processing skills, Chinese word reading, and arithmetic. *Read. Writing* 33, 1679–1699. doi: 10.1007/s11145-019-09998-9

Zhang, X., and Lin, D. (2018). Cognitive precursors of word reading versus arithmetic competencies in young Chinese children. *Early Child. Res. Q.* 42, 55–65. doi: 10.1016/j.ecresq.2017.08.006

Zoccolotti, P., De Luca, M., Marinelli, C. V., and Spinelli, D. (2020). Predicting individual differences in reading, spelling, and math in a sample of typically developing children: a study in the perspective of comorbidity. *PLoS ONE* 15:e0231937. doi: 10.1371/journal.pone.0231937

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REVIEW
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# Mathematics Disability vs. Learning Disability: A 360 Degree Analysis

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A fundamental issue for research in mathematics disability (MD) and reading disability (RD) is: If these disabilities are clearly distinct, why is there so high a level of comorbidity, together with the converse; if these disabilities are so similar, why are there clear differences in underlying causes and aetiology? In order to address this puzzle, we introduce the "360 degree analysis" (360DA) framework and apply it to the overlap between RD and MD. The 360DA process starts by analyzing the issue from four perspectives: theoretical, developmental, affective, and pedagogical. Under 360DA, these analyses are then integrated to provide insights for theory, and for individual assessment and support, together with directions for future progress. The analyses confirm extensive similarities between arithmetic and reading development in terms of rote learning, executive function (EF), and affective trauma, but also major differences in terms of the conceptual needs, the motor coordination needs, and the methods of scaffolding. In terms of theory, commonalities are interpreted naturally in terms of initial general developmental delay followed by domain-independent affective trauma following school failure. Dissociations are interpreted in terms of cerebellar vs. hippocampal learning networks, sequential vs. spatial processing, and language vs. spatial scaffolding, with a further dimension of the need for accurate fixation for reading. The framework has significant theoretical and applied implications.

**Keywords: mathematics disability, reading disability, learning and skill acquisition, affective, developmental**

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## INTRODUCTION

This article contributes to the special issue on the links between mathematics disability (MD) and reading disability (RD). It builds upon our earlier analysis (Nicolson and Fawcett, 2007), in which we highlighted the need for a re-convergence of research and practice in learning disabilities. In the article, we highlighted the decades of increasing differentiation after the 1970s, with each disability developing its own paradigm, from theory to practice to support structures, whereas the high comorbidity between the disorders suggested that there might well be common factors. At the theoretical level, we built on the long-established distinction between procedural and declarative memory (Anderson, 1982; Squire et al., 1993) to introduce the distinction between declarative learning (scaffolded by the declarative networks, with key structure: the hippocampus) and procedural learning (scaffolded by the procedural system, with key structures: the cerebellum and the basal ganglia). In the intervening years, the existence of these networks has been fully established (Bostan et al., 2013; Buckner and Krienen, 2013), and the strength and breadth of the comorbidities have also been fully established. Nonetheless, these insights do not appear to have led either to greater convergence of theory or to significant changes in support, as evidenced by the need for special issues such as this.

In this article, we aim to stimulate fruitful convergence between the different paradigms for learning disabilities by advocating a doubly integrated approach, which attempts to find commonalities between the learning disabilities and also to provide a broad framework that integrates the diverse theoretical and applied approaches to their analysis and treatment. The 360 degree analysis (360DA) process provides all-round analysis from all angles, by analogy with the best-practice approaches developed for appraisals in business. Our focus here is on MD vs. RD, but the approach is of general applicability. Our own research specialism is in RD, and so we have limited our detailed analyses to RD, in the hope that MD specialists will feel empowered to undertake similar analyses themselves.

Let us begin by laying out the issues regarding RD and MD established *via* the rightly influential study of Willcutt et al. (2013, p. 500) of twins within the Colorado Learning Disabilities Research Center program. The authors concluded that "*Groups with RD only, MD only, and RD + MD were significantly impaired vs. the control group on nearly all measures, and the group with RD + MD was more impaired than the groups with MD and RD alone on measures of internalizing psychopathology, academic functioning, and seven of 10 neuropsychological constructs… deficits in reading and math were associated with shared weaknesses in working memory, processing speed, and verbal comprehension. In contrast, reading difficulties were uniquely associated with weaknesses in phoneme awareness and naming speed, and math deficits were uniquely associated with weaknesses in set shifting*." It is important to note in the light of our discussion below that the researchers declined to use a discrepancy criterion and do not report gender analyses.

A key finding with respect to this special edition is that the numbers diagnosed with RD only, MD only, and RD + MD were 241 (39%), 183 (30%), and 188 (31%), respectively, highlighting the high comorbidity between the disorders. As Gilger and Kaplan (2001) argue, "*in developmental disorders comorbidity is the rule not the exception*," as ably discussed by contributors to this issue.

In terms of incidence, percentages depend critically on the criteria used – one is essentially placing an arbitrary cutoff on the normal distribution – and whether or not a strict inclusionary criterion is applied. The traditional specific learning disability definition was: "a disorder in children who, despite conventional classroom experience, fail to attain the language skills of reading, writing, and spelling commensurate with their intellectual abilities" (from the definition by the World Federation of Neurology, 1968, p. 26). The definition is an exclusionary one, serving to exclude children of low overall intelligence from being diagnosed with dyslexia. If exclusionary criteria are omitted, as has been practiced in the United States (Stuebing et al., 2002; Fletcher et al., 2004), thereby including any child struggling with reading, or math, or attention, the incidence at least trebles, comorbidity balloons, and theoretical explanations become hopelessly confounded (Nicolson, 1996; Stein, 2018).

Traditional estimates for the male/female ratio for RD as specific learning disability were around 4:1 (Miles et al., 1998), though inclusionary estimates suggest ratios closer to parity (Shaywitz, 1998). By contrast, more girls than boys suffer from MD; especially, if math anxiety is taken into account (Goetz et al., 2013), though again ratios approach parity with inclusionary criteria (Devine et al., 2013). A recent study in Germany (Moll et al., 2014) investigated reading disorder, and spelling disorder (SD) and arithmetic disorder (AD) in 1633 grade 3 or 4 children. They established high comorbidity rates between all three disorders, and (perhaps, surprisingly) that SD co-occurred more frequently with AD than with reading disorder. Gender ratios varied somewhat with the deficit criterion used, but for comorbid reading + spelling disorder (equivalent to RD) there were 60% male, whereas for AD (equivalent to MD) there were around 35% male. It is inevitable that the ratios do approach parity as the inclusionary criteria are relaxed owing to the mixing of the preponderance of boys with RD and girls with MD. We will use the gender dissociation between specific RD and specific MD as a theoretical scalpel to tease apart the two learning disabilities.

We complement the other contributions by picking out three fundamental issues for comparison of reading disability and math disability: Why are there overlaps, why are there differences, and what are the implications for subsequent progress? We advocate the importance of the 360DA process combining theoretical, cognitive, affective, and educational perspectives, arguing that these may all be integrated within a task analysis perspective.

## A 360 DEGREE ANALYSIS

We propose the 360DA as a means of combining the multiple different perspectives provided by the increasing depth and narrowness of scope provided by increasing specialization of methodology (Nicolson et al., 2021). It is intended to allow integration of a number of perspectives – individuals as well as groups, strengths as well as weaknesses, future opportunities as well as past and present performance, emotion as well as cognition, the situation as well as the person, and 360 degree assessment, theory, support, and involvement. In this paper, we first consider four major perspectives for developmental disorders: theory, development, affect, and pedagogy. Following these analyses, we then attempt to provide an integration in terms of answers to key questions, including the theoretical and pedagogical implications.

### The Theoretical Perspective: History

In terms of underlying theory, it is valuable (Morton and Frith, 1995) to distinguish different levels of explanation – the behavioral level (symptoms), the cognitive (mental function) level, and the brain (structure or function) level, and now the genetic level. Nicolson and Fawcett (2007) advocate the introduction of a neural network-level intermediate between the cognitive level and the brain level.

For RD, ongoing behavioral symptoms are reading dysfluency and developmental delay in phonological processing, with the initial symptoms being delay in phonemic awareness. At the cognitive level, there is a variety of theories advanced to explain subsets of the underlying symptoms. The leading theory remains the phonological deficit theory (Stanovich, 1988; Vellutino et al., 2004). Alternative prominent frameworks include the magnocellular deficit theory (Stein, 2001), which is at the brain level, and the automatization deficit theory (Nicolson and Fawcett, 1990) at the cognitive level which was followed up by the cerebellar deficit theory (Nicolson et al., 2001) at the brain level and the procedural deficit theory (Nicolson and Fawcett, 2007) at the neural networks level. There are also theories at the visual attention level faculty, for example, Facoetti et al. (2003), and current theorists have incorporated within the phonological deficit framework the additional elements of the double-deficit theory, namely working memory and speed of processing (Vellutino et al., 2004). The original double-deficit hypothesis (Wolf and Bowers, 1999) gained force from the demonstration that remediation was more difficult for children with a double deficit – both in phonological processing and in speed of processing – than for those with just a single deficit.

For MD, the symptoms are arithmetic dysfluency and developmental delay in acquiring the mathematical milestones together with persistent failure in acquiring number bonds. Two broad hypotheses – numerosity deficit and symbol-magnitude mapping deficit – advocate a domain-specific disorder, whereas the executive function (EF) hypothesis posits domain general issues. The numerosity deficit hypothesis proposed a core deficit in processing quantity (Butterworth et al., 2011) and number sense (Dehaene et al., 2004; Decarli et al., 2020). The symbol-magnitude mapping deficit hypothesis proposed a specific weakness in automatically mapping symbols to their internal magnitude representations (Rubinsten and Henik, 2006; Rousselle and Noel, 2007). The domain general EF deficit highlighted problems to working memory (Rotzer et al., 2009; Toll et al., 2011) and attention (Ashkenazi et al., 2009), rather than as a specific deficit in number processing.

We return to theoretical frameworks within the integration section.

## The Developmental Perspective

One of the most potent critiques (Frith, 2001; Goswami, 2003) of the naive application of information processing measures such as working memory, processing speed, executive function, and attention to developmental disabilities is that this approach does not naturally take account of developmental processes within individuals as pioneered by Inhelder and Piaget (1958), Bruner (1960), Flavell (1977), and Vygotsky (1986). In particular, of course, a single cross-sectional analysis of differences in attainment is unable to establish the underlying causes and can only be considered a description rather than explanation.

In response to such critiques, there have been systematic attempts to undertake longitudinal, multi-year analyses, whereby a cohort of children at risk of dyslexia are followed through from birth to say 10 years of age. Two such studies for dyslexia, the Jyyvyskala study (Lyytinen et al., 2004) in Finland and (Blomert and Willems, 2010; van der Leij, 2013) in the Netherlands, provided a wealth of information, but unfortunately without clear theoretical implications.

A recent smaller-scale longitudinal study, directed by Snowling et al. (2021), provides a valuable illustration of the strengths (and pitfalls) of a non-developmental longitudinal analysis. The study followed three groups: language disorder (LaD), risk of RD and typical development (TD) from 4 years to 8 years, using sets of age-appropriate tests annually for tests 1–5 (T1–T5). An initial study (Gooch et al., 2014) identified that both language skill and motor skill contributed unique variance from T1 to T2. Of particular interest here, the team were able to investigate MD as well as RD, concluding (Snowling et al., 2021) that "*Poor language was associated with each disorder and appears to be a cognitive risk factor for RD, MD, and RD&MD*" (abstract). The basket of tests, though large, was not designed to test between theories and (with the exception of motor skill) used tests that would be expected to reveal difficulties given the expanded phonological deficit framework and, therefore, did not include measures of speech rate, sensory processing ability, eye movement control, or internalized speech, thereby limiting the scope for theoretical progress.

The authors did not report individual analyses, as would be undertaken at school for an Individual Education Plan, and so it was not possible to analyze the individual responses to interventions administered, although, presumably the majority of the LaD and Risk of RD participants would have been receiving additional support by the school. Furthermore, as highlighted by all the influential developmental psychologists from Inhelder and Piaget (1958) and Vygotsky (1986) to Frith (1986) and Goswami and Bryant (1990), development of skills occurs in a series of stages, with fluency in some sub-skills being the prerequisite for acquisition of more complex skills, whether those skills be motor, cognitive, or executive function.

## The Affective Perspective

It is now established that dyslexic individuals of any age suffer more stress and "internalising disorders" than their typically achieving peers (Livingston et al., 2018; Francis et al., 2019; Haft et al., 2019). Surprisingly, this insight has not been explicitly integrated into theoretical or educational approaches to dyslexia. By contrast, "math anxiety" has been extensively studied. It is present even at the beginning of formal schooling (Maloney, 2012). Furthermore, the anxiety was triggered by anticipation rather than performance of mathematics tests (Lyons and Beilock, 2012), supported by brain imaging studies that indicated that the cognitive information-processing deficits arising from mathematics anxiety can be traced to brain regions and circuits that have been consistently implicated in specific phobias and generalized anxiety disorders in adults (Young et al., 2012).

In terms of situation-specific stress, the stressor leads to hypothalamic–pituitary–adrenal (HPA) activity causing cortisol to be released, diverting blood from the brain to the muscles for the "fight, flight, or freeze" response. Even mild stressors actually affect the brain circuits involved in learning. Basically, stress shifts processing from the declarative system to the action-based procedural system – the fight or flight – as one might expect in order to escape from that situation (Schwabe and Wolf, 2013).

After prolonged stress, changes in plasticity take place, primarily in the neural circuits involving the hippocampus and amygdala (McEwen, 2012). This impairs hippocampal function, which can have two effects: to impair hippocampal involvement in episodic, declarative, contextual, and spatial memory and to impair hippocampal regulation of hormonal regulation *via*, particularly the termination of the stress response, leading to elevated HPA activity and further exacerbating the actions of adrenal steroids in the long-term effects of repeated and chronic stress exposure.

Unfortunately, even a single failure in the presence of classmates leads to a feeling of shame. Like stress, shame leads to greater expression of cortisol (Gruenewald et al., 2004), even in 4-year-old children (Lewis and Ramsay, 2002). Children with learning weaknesses in a particular domain are subjected to continual stressful and shame-inducing experiences that singly and in combination may lead to their escalation into full-blown learning disorders in that domain, and these toxic experiences may lead to generalization to other domains of schoolwork.

## The Pedagogical Perspective

This perspective includes two aspects: first the learning processes involved and then task analysis for the skills in question.

### The "Learning Process" Approach

A particularly surprising omission in research on the learning disorders, highlighted initially by Nicolson and Fawcett (1990), is the failure of almost all research – cross-sectional or longitudinal – to analyze the processes of learning itself, to distinguish between "learning product" (attainment) and "learning process" (registration, execution, consolidation, automatization, for example). In their "Dyslexic Automatisation Deficit" theory, they established that their dyslexic participants showed incomplete task automaticity (as revealed by deficits under dual task conditions) and attributed this to dysfunction in one of the many "learning" processes involved in skill automatization. In subsequent work, they established differences in the long-term acquisition of skill on a simple reaction time game (Nicolson and Fawcett, 2000), on lack of cerebellar activation on acquiring a simple motor sequence (Nicolson et al., 1999), on eye blink conditioning (Nicolson et al., 2002), on adapting to prisms (Brookes et al., 2007) and various other forms of long-term procedural learning (Nicolson et al., 2010).[1] These studies led to their cerebellar deficit theory (Nicolson et al., 2001), their specific procedural deficit theory (Nicolson and Fawcett, 2007), and their recent Delayed Neural Commitment theory (Nicolson and Fawcett, 2019), in which they provided a plasticity-based framework for understanding the underlying learning differences. The key point, however, is that any theoretical or empirical approach that does not look at the fine grain of the processes of skill acquisition (rather than the products) is not able to provide a rationale for change in educational processes for any given child.

### The Task Analysis Perspective

One of the most programmatic and influential analyses of learning and instruction was provided by Gagne (1965), and although, now dated it provides a valuable resource for anyone wishing to explore methods of instruction in greater depth. In brief, Gagne (1965) distinguished five key capabilities, namely information, intellectual skills, cognitive strategies, motor skills, and attitude. Theory of instruction of Gagne (1965) suggests that the overall method for training any skill is first to do a thorough task analysis, determining what the sub-skills involved are, and what their pre-requisites are and so on, thus identifying a hierarchical tree of sub-skills that make up the skill. For each sub-skill, it is necessary to determine which of the five types of capability it is, and then to devise a method for instruction on that sub-skill.

#### *Early Mathematics*

It may help to start with an informal task analysis for the early stages in mathematics development. One of the earliest stages involves the realization that objects are discrete, and then, grasping the idea that similar objects can be combined together with the numbers 1, 2, and 3 corresponding to groups of bigger size. This conceptual revolution is often scaffolded by linking the number to a sequence of actions – one clap, two claps; one step, two steps; one finger, two fingers, and so on. These concepts can then be applied to a range of objects and actions, and reinforced by repetition. The graphemes to represent one and two on paper come later, but there are only 10 including zero.

Conceptually after the fingers, the discrete number line is a key concept, with implicitly the idea of equal intervals between each unit in the sequence. Strips of paper or even a ruler can be used to help with this concept. Place order is one of the most challenging early concepts, typically requiring considerable practice – laying out the blocks in the spatial block fashion so that, for instance, 12 is represented as 10 + 2. Dienes' blocks provide a common scaffolding involving the concept of area. The number facts 8 + 5 and the times tables are generally learned by rote and may be seen as a form of association learning.

Even this simplistic analysis allows us to identify a number of different component knowledge and skill aspects to mathematics. We have the conceptual level: the very idea of number; the number fact level; the place order convention; and then the operator for addition. Of course the operator plus is the simplest one, often scaffolded by using blocks to manually represent the process. The visual grapheme "+" is of course an item to learn. We are grateful to a referee for pointing out that a key conceptual advance needed is that of unitizing, wherein the two addends somehow become equivalent to the one outcome. The next operation typically is subtraction, which is generally shown as the inverse operation for addition,

[1]It is worth noting that they use the term procedural learning to refer to proceduralization of skill, the first stage in skill automatization (Anderson, 1982). By contrast, some theorists refer to the "serial reaction time task," where a participant becomes faster when responding to a long repeating sequence of key presses, which is more appropriately labeled as "sequence-based statistical learning." For true procedural learning, the participant needs to be consciously aware of the task, and to be able to consolidate the skills at least overnight.

and addition and subtraction can relatively easily be facilitated using the fingers for sums going to less than 10. Multiplication is a more complex mental conceptual idea, almost certainly scaffolded by the concept of repeated addition – so three sixes are six and six and six. This is often most easily shown in the way of a two-dimensional spatial representation, which can then be counted. Division is the most complex operation, often scaffolded by the concept of dividing a cake into parts, but is made particularly complex by having to unlearn the concept of discrete units 1, 2, and 3 and replace this with a more continuous line as one sees, for example, on the ruler.

There is clearly an explicit "skill building" program needed, with first the number concepts, then the addition operator and addition facts, then the subtraction process, operator and facts, then the multiplication process, operator, times tables, and finally the fourth operator, division. Without fluent knowledge of the times tables, non-trivial division sums just cannot be done effectively.

In order to be fluent in early arithmetic, it is therefore important to have the conceptual development necessary, the understanding of the operators and how they work and how they are different, to have built up a series of number bonds or factual knowledge base. For fluency, it is necessary to have internalized all of these facts and processes so that they are accessed automatically, leaving full working memory to complete any sums. Key scaffolders include one's fingers and actions, external objects, the number line, and spatial arrays to represent area.

It is also important to highlight the EF skills required for early arithmetic learning. There is the essential requirement of what one might call "math readiness." This is strongly related to the concept of "reading readiness" (Petty, 1939), which was a major explanatory construct throughout the mid-twentieth century, but was downplayed in mainstream reading instruction (despite its emphasis in Reading Recovery) until re-emerging in the twenty-first century (Duncan et al., 2007). A key development is the recent literature on the development of executive function from 3 to 6 years, and in particular the role of executive functions in "school readiness" (Fitzpatrick et al., 2014). An early review (Blair, 2002) highlighted the importance not only of the "cool EF" capabilities described above but also the emotional and social EF ("hot EF") requirements for school readiness.

Both reading readiness and classroom readiness are needed to benefit from classroom teaching of reading. Reading readiness includes established skills such as phonological awareness and letter knowledge, together with appropriate eye fixation control and knowledge about print. Classroom readiness includes both the cool EFs of working memory, response inhibition and task maintenance, and the hot EFs of emotional control, anger control, and aggression control.

### *Learning to Read*

Acquisition of reading does overlap in many aspects, but is fundamentally different in several key dimensions. Unlike mathematics, the fundamental underpinning of reading – language comprehension – is already established well before reading instruction takes place. The key conceptual requirement therefore is to attempt to map the print symbols on the printed page onto the established language capabilities.

Print is an abstract, written representation of speech. It omits salient aspects of speech, such as loudness, pitch, emphasis, emotion, and prosody. It introduces gaps between words which are not there in speech, and it provides a "one size fits all" representation for all the many pronunciations of any given word.

Over and above these distortions, it introduces a classification of words into syllables and of syllables into phonemes that is both abstract and arbitrary. The phonemes are then mapped on to letters in a way that is neither consistent nor transparent. Finally, in order to read a word it is necessary to fixate each grapheme on the page in turn, to say the corresponding phoneme, to blend in the next phoneme, and hopefully to map the utterance onto the underlying representation for the target word.

There are, therefore, similarities with math learning: There is a need to learn the "letter facts," the graphemes and their link to phonemes; there is a clear skill of holding phonemes in working memory, while acquiring the next one to blend with it. Conceptually, however, the major issue is that of analysis – that spoken words can split into syllables (which are meaningless) and that syllables can be split into phonemes – which are even more meaningless (and may be poorly represented in the learner's expressive speech skills).

Conceptually, there is a need to recognize that the words in a book go across the page from left to right (in English), and the lines go down the page (Clay, 1993), but there is no scaffolding provided by spatial characteristics of the world (the number line, the spatial area, and the fraction of pie). By contrast with mathematics, there is an overwhelming need to be able to fixate accurately on a single grapheme for the time needed to recognize it, to move fixation accurately to the next letter, recognize that, register both letters in working memory, move to the end of the word letter by letter, then assemble the component phonemes into the corresponding sound, and recognize the sound as a word, all the time retaining the location of the target word in visual working memory, so that the following word may then be fixated.

**Figure 1**, adapted from our contribution to Marien et al. (2014) through the inclusion of the development of mathematics skills, highlights the interplay between the procedural and executive skills of speed, language, fixation, and phonics in early reading development (single line) compared with the much stronger contribution of declarative skills to the development of mathematics skills (dotted line). Entries with a double line represent skills shared between mathematics and reading. It is of course schematic, but we hope it highlights the clear differences between the types of skill required, together with the clear overlap in the need for executive function skills.

## DISCUSSION

In the introduction, we posed three questions: Why is there comorbidity, why is there differentiation, and what are the implications for subsequent progress? We proposed that the

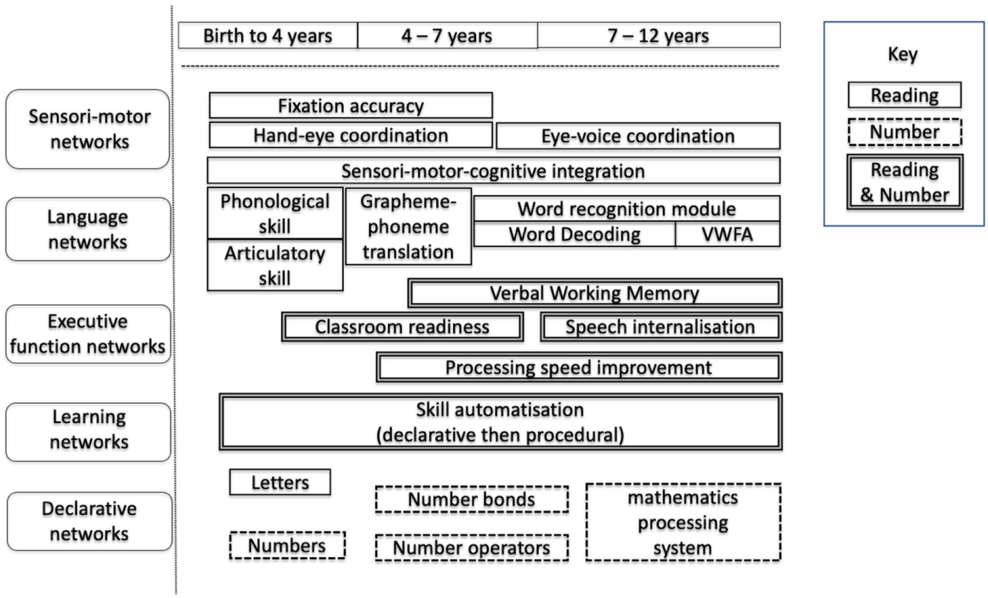


**FIGURE 1 |** The development of reading skill and mathematics skill.

process of 360DA could cast light on these issues and are now in position to take stock. We start with the four perspectives then return to the three questions.

## Theoretical Perspective

In terms of theoretical interpretation, the results go beyond all of the extant theories. The phonological deficit hypothesis is best seen as at the symptom level rather than a causal explanation. It is unable to account for the dissociation between mathematics and reading and excludes non-language components of reading such as eye movements. The executive function/attention hypotheses may be seen as reflecting symptoms of some underlying unspecified cause but again do not differentiate between MD and RD. Magnocellular deficit provides a systematic explanation for difficulties in reading but provides no explanation for the comorbidity between the two. Our multi-level explanation in terms of automatization deficit, cerebellar deficit, and procedural learning deficit does provide a principled explanation of the range of problems in reading disability but was not designed to provide an explanation for mathematics disability. None of these theories explicitly takes into account the affective dimension, and therefore, in our view all these theories should be augmented to create a two stage developmental explanation with first a developmental delay leading to lack of school readiness for executive function, reading readiness, or math readiness as appropriate, which leads to school failures, for which the ensuing shame and stress lead to affective trauma and essentially disables learning in that context.

## Developmental Perspective

We defer analyses of the specific skills to the section on pedagogical perspective, and here, we focus on the generic cognitive development processes that take place in pre-school and early-school years. Piaget's well-established stages of cognitive development do provide some pointers, with the pre-operational stage and concrete operations stage of particular relevance. Furthermore, as outlined earlier, Piaget's key concepts of internalization and bricolage are particularly relevant. Internalization (which is similar to automatization) indicates that a concept or skill has become so well assimilated that it can actually be used in more complex operations, the process he referred to as bricolage. Letter-sound pairings and number bonds would be examples for reading and arithmetic, respectively.

The more recent developmental frameworks tend to emphasize the issue of executive function and its development, as discussed earlier. The need for executive function skills to have developed sufficiently to support classroom readiness, working memory, and processing speed is of course critical to the transition to formal schooling. The evidence that SES disadvantage leads to delay in executive function development (Waters et al., 2021) is particularly concerning in this regard.

In terms of the generic developmental perspective, we would suggest that the issues involved are equivalent for both RD and MD and therefore contribute to the shared (comorbidity) data.

## Affective Perspective

The affective perspective is particularly interesting, potentially contributing either to increased differentiation or increased comorbidity, depending on the degree to which stress and anxiety transfer from the weakest skill to other areas of schoolwork. As noted earlier, situation-specific stress leads to marked impairment in the ability to learn in that situation (reading in the case of RD). However, impaired performance on reading might well lead not only to reading-related stress but also to the more general (and equally toxic) feeling of shame, and shame will attach to the more general school environment. Shame has similar consequences in terms of blocking as does stress (Cesare et al., 2018) and will therefore impair not only reading but also mathematics.

In either case, the affective dimension is a potent blocker of learning, but very much more pervasive if allowed to generalize. Consequently, it is very important for a teacher to clearly differentiate between the two disciplines, so that the better subject is not dragged down by the weaker one. Indeed, it may well be that an early specific diagnosis of LD (or MD) will serve to avoid this cross-subject transfer of shame.

## Pedagogical Perspective

In terms of pedagogic interpretation, a key implication is that for children at risk of mathematics failure, spatial, and conceptual play will be particularly important for scaffolding the necessary underlying skills. Computer games can provide invaluable judgment-free support (Rasanen et al., 2009). For children at risk of reading failure, eye fixation ability perhaps *via* non-reading games (Franceschini et al., 2013) will be an invaluable adjunct to phonological support.

As noted above, a lack of mathematics readiness or reading readiness or classroom readiness at the start of formal instruction is the trigger for the school failure that leads to further problems. It may well be that delaying the start of formal reading instruction or formal math instruction until executive function is well developed as practiced in the Scandinavian countries, would be beneficial for all children. Interestingly, work by Suggate et al. (2013) in New Zealand showed that delaying the start of formal reading instruction by a year led to no noticeable problems at the age of 10 for high performing children and much better performance for low performing children at that age.

## Why Differentiation?

Task analysis indicated that reading has a much stronger reliance on language skills, on eye fixation ability, and on visual/verbal co-processing, skills which may be characterized as procedural, relating to a cerebellar/cortical circuitry. By contrast, the specific requirements for early mathematics are more conceptual, and are scaffolded by spatial abilities, thereby implicating the hippocampal circuitry.

It may well be that the gender dissociation found for the specific forms of RD and MD may also be attributable to differences in these underlying skills. For example, a child with specific reading difficulties may have specific problems in phonological skills or a specific difficulty in steadily fixating the material on the page, both of which will lead to impaired reading ability. By contrast, a child with problems in understanding the number line or its spatial representation will have conceptual difficulties leading to impairments in mathematical learning.

This explanation is consistent with long-standing evidence that girls tend to have a relative advantage in language skills, whereas boys have a relative advantage with spatial skills, though there is a strong movement to challenge these beliefs (Hyde, 2005). Recent large-scale evidence does suggest that there is a significant advantage for boys in spatial processing (Wong and Yeung, 2019) and in spatial processing of numbers (Zhang et al., 2020). The importance of spatial processing for early mathematics was confirmed by a meta-analysis of 75 studies (Peng et al., 2020) that established key attributes as deficits in phonological processing, processing speed, working memory, attention, executive function, and visuospatial skills. Gender differences in language have been confirmed by large-scale studies in Germany (Lange et al., 2016) and Taiwan (Lung et al., 2011), and a very large recent US analysis (Reilly et al., 2019) concluded that "*language and verbal abilities represent one exception to the rule of gender similarities.*"

Interestingly, this phonological/spatial dissociation hypothesis is directly consistent with the Moll et al. (2014). German study cited earlier which established that there was greater comorbidity between SD and MD than between SD and RD. Since both reading and spelling are dependent on phonological processing, this dissociation between them highlights the importance of the dissociating sub-skill, namely binocular fixation.

In conclusion, the 360DA framework has revealed both commonalities and dissociations between MD and RD. The comorbidities may be attributed to two common aspects, initially a developmental delay in some of the underlying skills lacking scaffolding from visual and language skills, respectively, followed by the trauma and learning disability attributable to failure to acquire these school attributes.

## Why Comorbidity?

As demonstrated above, there is scope for comorbidity in three of the four perspectives. First, there are shared needs for fact internalization in terms of the letter facts and number facts, and even though the internalization process is driven largely by the procedural system, the initial stages involve the two systems working together (Doyon et al., 2003). Second, in terms of the developmental perspective, a delay in developing the executive function skills needed to cope with classroom instruction will—irrespective of reading readiness or arithmetic readiness – lead to problems in carrying out the teacher's instructions, and hence failure at both reading and arithmetic. Early failures of this type will lead to stress, and probably shame, thereby triggering the potent affect dimension, effectively disabling the learning process for the skill involved. If the stress is limited to just arithmetic or just reading, this will lead to (specific) MD or RD, respectively, whereas if it generalizes to the entire school situation, the disability will be comorbid for MD and RD, and the child will probably show clear attention deficits as a consequence of the "fight, flight, or freeze" responses resulting from the HPA axis cortisol deposits.

## How Should We Proceed?

Arguably the most effective way forward is to acknowledge the crucial role of the classroom teacher in classroom learning and support. As we have stressed above, there is a major risk that an initial delay in executive function development leads to a deficit in classroom readiness, leading to failure, to situation specific stress, leading to a learning disability, which may or may not generalize to the broader classroom environment. By the time, a child is referred to an educational psychologist or other expert, the failures will have occurred and the stress patterns will have been set up. It should surely be an intrinsic component of teacher training to be fully aware of the toxic effects of failure stress on learning abilities. The 360DA process provides a simple framework for teacher empowerment in this process.

In terms of assessment, a key issue is "assessment for support." Information processing analysis such as executive function, working memory, and speed of processing provides little explicit basis for support unless this leads to a clear problem, though see Diamond (2013) for advocacy of early support for executive function. Surprisingly, effective, hierarchical, task analysis of the skills involved has not been the target of systematic approaches within educational settings. By contrast, task analysis was at one stage the major component of pedagogical support at the individual level (Gagne, 1965).

We advocate the use of the 360DA process outlined here, aimed at developing an individually based intervention program date designed around the theoretical cognitive, affective, and pedagogical approach.

## CONCLUSION

Fifty years ago, the theoretical approach to the developmental disorders was in terms of minimal brain dysfunction (Wender, 1978), and support methods included both occupational therapy and specific task-focused approaches (Gagne, 1965), and in the United States the opportunity to repeat a year, thereby allowing developmental maturation to take place.

Moving forward, phonological deficit theorists take the commonality between RD and MD to advocate that language disorder may be at the root of both (Snowling et al., 2021). By contrast, advocates of procedural learning deficits take the commonality as indicating further support for procedural deficits in both disorders (Evans and Ullman, 2016). From our own perspective, in this article, we highlight the importance of our automatization deficit framework, together with our procedural learning deficit framework. To take a devil's advocate approach, it does appear these interpretations of the data reflect more the preconceptions of the theorists than an objective analysis of the way forward. An example, perhaps, of Maslow's Hammer (*I suppose it is tempting, if the only tool you have is a hammer, to treat everything as if it were a nail*; Maslow, 1966).

We have, however, outlined a methodology for escaping from this scientific solipsism. First, incidence analysis does provide a clear theoretical dissociation at the group level highlighting the difference in incidence between male and female for both disorders. Second, task analysis highlights the multiple factors that can contribute to failure to acquire fluency in either skill. It also provides an analysis of the conceptual and applied scaffolding techniques that are used either naturally or *via* intervention to assist an individual child gaining necessary mastery. Third, the theoretical and task analyses do allow us to develop a principled analysis of the developmental task requirements for each domain, thereby allowing us to pinpoint not only areas, where each individual may be affected, but, ideally, interventions designed specifically to address each limitation.

In summary, MD and RD overlap in some areas and are distinct in other areas. Starting with the later developmental stages, irrespective of the causes of the failure, failure at either mathematics or reading will lead to trauma and stress. This essentially disables the learning process for that domain, leading to the development of a toxic, learned helplessness stage, where a child is not able to focus effectively on the task in hand.

Second, it is likely that the rote learning aspect of the conversion of the symbols on the page to their mental concepts is common to both disorders. Furthermore, there are overlaps between learning the grapheme-phoneme conversion rules, and the rules of number, but in fact the rules of number are generally learned by a rote repetition strategy, thereby leading to problems from knowledge internalization, whereas the grapheme-phoneme conversion problem is very much more complex requiring high levels of phonemic awareness and tolerance of arbitrary and inconsistent mappings.

In conclusion, we developed the 360DA framework to provide a methodology for "due diligence" in the developmental disorders, attempting to avoid premature commitment to a single perspective, or analysis of a single disorder. We applied the two-stage methodology of 360DA, first presenting the evidence on four perspectives at the group level – theory, development, affect, pedagogy – and then integrating these findings at the explanatory, theoretical, and pedagogical levels. This comprehensive and systematic approach led to significant integration, with clear implications for the major aims of research in this area – to enhance the education of each individual child, and to improve the overall educational system. The analyses are incomplete, but novel, and we hope they provide the methodology and the inspiration for further researchers to break out of the straitjacket of discipline-limited approaches.

## AUTHOR CONTRIBUTIONS

RN and AF contributed to the conceptual analysis and wrote the manuscript. All authors contributed to the article and approved the submitted version

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## REFERENCES

Anderson, J. R. (1982). Acquisition of cognitive skill. *Psychol. Rev.* 89, 369–406.

Ashkenazi, S., Rubinsten, O., and Henik, A. (2009). Attention, automaticity, and developmental dyscalculia. *Neuropsychology* 23, 535–540. doi: 10.1037/a0015347

Blair, C. (2002). School readiness–integrating cognition and emotion in a neurobiological conceptualization of children's functioning at school entry. *Am. Psychol.* 57, 111–127. doi: 10.1037//0003-066x.57.2.111

Blomert, L., and Willems, G. (2010). Is there a causal link from a phonological awareness deficit to reading failure in children at familial risk for dyslexia? *Dyslexia* 16, 300–317. doi: 10.1002/dys.405

Bostan, A. C., Dum, R. P., and Strick, P. L. (2013). Cerebellar networks with the cerebral cortex and basal ganglia. *Trends Cogn. Sci.* 17, 241–254. doi: 10.1016/j.tics.2013.03.003

Brookes, R. L., Nicolson, R. I., and Fawcett, A. J. (2007). Prisms throw light on developmental disorders. *Neuropsychologia* 45, 1921–1930. doi: 10.1016/j.neuropsychologia.2006.11.019

Bruner, J. (1960). *The Process of Education*. Cambridge, MA: Harvard University Press.

Buckner, R. L., and Krienen, F. M. (2013). The evolution of distributed association networks in the human brain. *Trends Cogn. Sci.* 17, 648–665. doi: 10.1016/j.tics.2013.09.017

Butterworth, B., Varma, S., and Laurillard, D. (2011). Dyscalculia: from brain to education. *Science* 332, 1049–1053. doi: 10.1126/science.1201536

Cesare, C., Alessandro, P., Valentino, Z., Diana, B., Realdon, O., Todisco, P., et al. (2018). Negative social emotions and cognition: shame, guilt and working memory impairments. *Acta Psychol.* 188, 9–15. doi: 10.1016/j.actpsy.2018.05.005

Clay, M. M. (1993). *An Observation Survey of Early Literacy Achievement*. Auckland, NZ: Heinemann.

Decarli, G., Paris, E., Tencati, C., Nardelli, C., Vescovi, M., Surian, L., et al. (2020). Impaired large numerosity estimation and intact subitizing in developmental dyscalculia. *PLoS One* 15:e0244578. doi: 10.1371/journal.pone.0244578

Dehaene, S., Molko, N., Cohen, L., and Wilson, A. J. (2004). Arithmetic and the brain. *Curr. Opin. Neurobiol.* 14, 218–224. doi: 10.1016/j.conb.2004.03.008

Devine, A., Soltesz, F., Nobes, A., Goswami, U., and Szűcs, D. (2013). Gender differences in developmental dyscalculia depend on diagnostic criteria. *Learn. Instr.* 27, 31–39. doi: 10.1016/j.learninstruc.2013.02.004

Diamond, A. (2013). Executive functions. *Annu. Rev. Psychol.* 64, 135–168. doi: 10.1146/annurev-psych-113011-143750

Doyon, J., Penhune, V., and Ungerleider, L. G. (2003). Distinct contribution of the cortico-striatal and cortico-cerebellar systems to motor skill learning. *Neuropsychologia* 41, 252–262. doi: 10.1016/s0028-3932(02)00158-6

Duncan, G. J., Claessens, A., Huston, A. C., Magnuson, K., Huston, A. C., Klebanov, P., et al. (2007). School readiness and later achievement. *Dev. Psychol.* 43, 1428–1446. doi: 10.1037/0012-1649.43.6.1428

Evans, T. M., and Ullman, M. T. (2016). An extension of the procedural deficit hypothesis from developmental language disorders to mathematical disability. *Front. Psychol.* 7:1318. doi: 10.3389/fpsyg.2016.01318

Facoetti, A., Lorusso, M. L., Paganoni, P., Umiltà, C., and Mascetti, G. G. (2003). The role of visuospatial attention in developmental dyslexia: evidence from a rehabilitation study. *Brain Res. Cogn. Brain Res.* 15, 154–164. doi: 10.1016/s0926-6410(02)00148-9

Fitzpatrick, C., McKinnon, R. D., Blair, C. B., and Willoughby, M. T. (2014). Do preschool executive function skills explain the school readiness gap between advantaged and disadvantaged children? *Learn. Instr.* 30, 25–31. doi: 10.1016/j.learninstruc.2013.11.003

Flavell, J. H. (1977). *Cognitive Development*. Englewood Cliffs, NJ: Prentice-Hall.

Fletcher, J. M., Coulter, W. A., Reschly, D. J., and Vaughn, S. (2004). Alternative approaches to the definition and identification of learning disabilities: some questions and answers. *Ann. Dyslexia* 54, 304–331. doi: 10.1007/s11881-004-0015-y

Franceschini, S., Gori, S., Ruffino, M., Viola, S., Molteni, M., and Facoetti, A. (2013). Action video games make dyslexic children read better. *Curr. Biol.* 23, 462–466. doi: 10.1016/j.cub.2013.01.044

Francis, D. A., Caruana, N., Hudson, J. L., and McArthur, G. M. (2019). The association between poor reading and internalising problems: a systematic review and meta-analysis. *Clin. Psychol. Rev.* 67, 45–60. doi: 10.1016/j.cpr.2018.09.002

Frith, U. (1986). A developmental framework for developmental dyslexia. *Ann. Dyslexia* 36, 67–81. doi: 10.1007/BF02648022

Frith, U. (2001). What framework should we use for understanding developmental disorders? *Dev. Neuropsychol.* 20, 555–563. doi: 10.1207/S15326942DN2002_6

Gagne, R.M. (1965). *The Conditions of Learning*. New York: Holt, Rinehart & Winston.

Gilger, J. W., and Kaplan, B. J. (2001). Atypical brain development: a conceptual framework for understanding developmental learning disabilities. *Dev. Neuropsychol.* 20, 465–481. doi: 10.1207/S15326942DN2002_2

Goetz, T., Bieg, M., Luedtke, O., Pekrun, R., and Hall, N. C. (2013). Do girls really experience more anxiety in mathematics? *Psychol. Sci.* 24, 2079–2087. doi: 10.1177/0956797613486989

Gooch, D., Hulme, C., Nash, H. M., and Snowling, M. J. (2014). Comorbidities in preschool children at family risk of dyslexia. *J. Child Psychol. Psychiatry* 55, 237–246. doi: 10.1111/jcpp.12139

Goswami, U. (2003). Why theories about developmental dyslexia require developmental designs. *Trends Cogn. Sci.* 7, 534–540. doi: 10.1016/j.tics.2003.10.003

Goswami, U., and Bryant, P. E. (1990). *Phonological Skills and Learning to Read*. Hillsdale, NJ: Lawrence Erlbaum Associates.

Gruenewald, T. L., Kemeny, M. E., Aziz, N., and Fahey, J. L. (2004). Acute threat to the social self: shame, social self-esteem, and cortisol activity. *Psychosom. Med.* 66, 915–924. doi: 10.1097/01.psy.0000143639.61693.ef

Haft, S. L., Duong, P. H., Ho, T. C., Hendren, R. L., and Hoeft, F. (2019). Anxiety and attentional bias in children with specific learning disorders. *J. Abnorm. Child Psychol.* 47, 487–497. doi: 10.1007/s10802-018-0458-y

Hyde, J. S. (2005). The gender similarities hypothesis. *Am. Psychol.* 60, 581–592. doi: 10.1037/0003-066X.60.6.581

Inhelder, B., and Piaget, J. (1958). *The Growth of Logical Thinking From Childhood to Adolescence*. New York: Basic Books.

Lange, B. P., Euler, H. A., and Zaretsky, E. (2016). Sex differences in language competence of 3-to 6-year-old children. *Appl. Psycholinguist.* 37, 1417–1438. doi: 10.1017/S0142716415000624

Lewis, M., and Ramsay, D. (2002). Cortisol response to embarrassment and shame. *Child Dev.* 73, 1034–1045. doi: 10.1111/1467-8624.00455

Livingston, E. M., Siegel, L. S., and Ribary, U. (2018). Developmental dyslexia: emotional impact and consequences. *Aust. J. Learn. Difficult.* 23, 107–135. doi: 10.1080/19404158.2018.1479975

Lung, F.-W., Chiang, T.-L., Lin, S.-J., Chen, P.-F., and Shu, B.-C. (2011). Gender differences of children's developmental trajectory from 6 to 60 months in the Taiwan birth cohort pilot study. *Res. Dev. Disabil.* 32, 100–106. doi: 10.1016/j.ridd.2010.09.004

Lyons, I. M., and Beilock, S. L. (2012). When math hurts: math anxiety predicts pain network activation in anticipation of doing math. *PLoS One* 7:e48076. doi: 10.1371/journal.pone.0048076

Lyytinen, H., Aro, M., Eklund, K., Erskine, J., Guttorm, T., Laakso, M. L., et al. (2004). The development of children at familial risk for dyslexia: birth to early school age. *Ann. Dyslexia* 54, 184–220. doi: 10.1007/s11881-004-0010-3

Maloney, E. A. (2012). Math anxiety: who has it, why it develops, and how to guard against it. *Trends Cogn. Sci.* 16:526. doi: 10.1016/j.tics.2012.06.008

Marien, P., Ackermann, H., Adamaszek, M., Barwood, C. H. S., Beaton, A., Desmond, J., et al. (2014). Consensus paper: language and the cerebellum: an ongoing enigma. *Cerebellum* 13, 386–410. doi: 10.1007/s12311-013-0540-5

Maslow, A. H. (1966). *The Psychology of Science*. New York: Harper Row

McEwen, B. S. (2012). Brain on stress: How the social environment gets under the skin. *PNAS.* 109, 17180–17185.

Miles, T. R., Haslum, M. N., and Wheeler, T. J. (1998). Gender ratio in dyslexia. *Ann. Dyslexia* 48, 27–55.

Moll, K., Kunze, S., Neuhoff, N., Bruder, J., and Schulte-Körne, G. (2014). Specific learning disorder: prevalence and gender differences. *PLoS One* 9:e103537. doi: 10.1371/journal.pone.0103537

Morton, J., and Frith, U. (1995). "Causal modelling: a structural approach to developmental psychopathology," in *Manual of Developmental Psychopathology*. *Vol. 2.* eds. D. Cicchetti and D. J. Cohen (New York: Wiley), 274–298.

Nicolson, R. I. (1996). Developmental dyslexia; past, present and future. *Dyslexia Int. J. Res. Pract.* 2, 190–207. doi: 10.1002/(SICI)1099-0909(199611)2:3<190::AID-DYS62>3.0.CO;2-6

Nicolson, R. I., Blouchou, P., and Hofmeester, N. (2021). "From positive dyslexia to dyslexia360." in *British Dyslexia Association International Conference 2021 – Advancing Dyslexia and Dyscalculia; May, 2021*.

Nicolson, R. I., Daum, I., Schugens, M. M., Fawcett, A. J., and Schulz, A. (2002). Eyeblink conditioning indicates cerebellar abnormality in dyslexia. *Exp. Brain Res.* 143, 42–50. doi: 10.1007/s00221-001-0969-5

Nicolson, R. I., and Fawcett, A. J. (1990). Automaticity: a new framework for dyslexia research? *Cognition* 35, 159–182. doi: 10.1016/0010-0277(90)90013-a

Nicolson, R. I., and Fawcett, A. J. (2000). Long-term learning in dyslexic children. *Eur. J. Cogn. Psychol.* 12, 357–393. doi: 10.1080/09541440050114552

Nicolson, R. I., and Fawcett, A. J. (2007). Procedural learning difficulties: reuniting the developmental disorders? *Trends Neurosci.* 30, 135–141. doi: 10.1016/j.tins.2007.02.003

Nicolson, R. I., and Fawcett, A. J. (2019). Development of dyslexia: the delayed neural commitment framework. *Front. Behav. Neurosci.* 13:112. doi: 10.3389/fnbeh.2019.00112

Nicolson, R. I., Fawcett, A. J., Berry, E. L., Jenkins, I. H., Dean, P., and Brooks, D. J. (1999). Association of abnormal cerebellar activation with motor learning difficulties in dyslexic adults. *Lancet* 353, 1662–1667. doi: 10.1016/S0140-6736(98)09165-X

Nicolson, R. I., Fawcett, A. J., Brookes, R. L., and Needle, J. (2010). Procedural learning and dyslexia. *Dyslexia* 16, 194–212. doi: 10.1002/dys.408

Nicolson, R. I., Fawcett, A. J., and Dean, P. (2001). Developmental dyslexia: the cerebellar deficit hypothesis. *Trends Neurosci.* 24, 508–511. doi: 10.1016/s0166-2236(00)01896-8

Peng, P., Lin, X., Unal, Z. E., Lee, K., Namkung, J., Chow, J., et al. (2020). Examining the mutual relations between language and mathematics: a meta-analysis. *Psychol. Bull.* 146, 595–634. doi: 10.1037/bul0000231

Petty, M. C. (1939). An experimental study of certain factors influencing reading readiness. *J. Educ. Psychol.* 30, 215–230. doi: 10.1037/h0059222

Rasanen, P., Salminen, J., Wilson, A. J., Aunio, P., and Dehaene, S. (2009). Computer-assisted intervention for children with low numeracy skills. *Cogn. Dev.* 24, 450–472. doi: 10.1016/j.cogdev.2009.09.003

Reilly, D., Neumann, D. L., and Andrews, G. (2019). Gender differences in reading and writing achievement: evidence from the national assessment of educational progress (NAEP). *Am. Psychol.* 74, 445–458. doi: 10.1037/amp0000356

Rotzer, S., Loenneker, T., Kucian, K., Martin, E., Klaver, P., and von Aster, M. (2009). Dysfunctional neural network of spatial working memory contributes to developmental dyscalculia. *Neuropsychologia* 47, 2859–2865. doi: 10.1016/j.neuropsychologia.2009.06.009

Rousselle, L., and Noel, M.-P. (2007). Basic numerical skills in children with mathematics learning disabilities: a comparison of symbolic vs non-symbolic number magnitude processing. *Cognition* 102, 361–395. doi: 10.1016/j.cognition.2006.01.005

Rubinsten, O., and Henik, A. (2006). Double dissociation of functions in developmental dyslexia and dyscalculia. *J. Educ. Psychol.* 98, 854–867. doi: 10.1037/0022-0663.98.4.854

Schwabe, L., and Wolf, O. T. (2013). Stress and multiple memory systems: from 'thinking' to 'doing'. *Trends Cogn. Sci.* 17, 60–68. doi: 10.1016/j.tics.2012.12.001

Shaywitz, S. E. (1998). Current concepts: dyslexia. *N. Engl. J. Med.* 338, 307–312. doi: 10.1056/NEJM199801293380507

Snowling, M. J., Moll, K., and Hulme, C. (2021). Language difficulties are a shared risk factor for both reading disorder and mathematics disorder. *J. Exp. Child Psychol.* 202:105009. doi: 10.1016/j.jecp.2020.105009

Squire, L. R., Knowlton, B., and Musen, G. (1993). The structure and organisation of memory. *Annu. Rev. Psychol.* 44, 453–495. doi: 10.1146/annurev.ps.44.020193.002321

Stanovich, K. E. (1988). Explaining the differences between the dyslexic and the garden-variety poor reader: the phonological-core variable-difference model. *J. Learn. Disabil.* 21, 590–604. doi: 10.1177/002221948802101003

Stein, J. F. (2001). The magnocellular theory of developmental dyslexia. *Dyslexia* 7, 12–36. doi: 10.1002/dys.186

Stein, J. F. (2018). Does dyslexia exist? *Lang. Cogn. Neurosci.* 33, 313–320. doi: 10.1080/23273798.2017.1325509

Stuebing, K. K., Fletcher, J. M., LeDoux, J. M., Lyon, G. R., Shaywitz, S. E., Shaywitz, B., et al. (2002). Validity of IQ-discrepancy classifications of reading disabilities: a meta-analysis. *Am. Educ. Res. J.* 39, 469–518. doi: 10.3102/00028312039002469

Suggate, S. P., Schaughency, E. A., and Reese, E. (2013). Children learning to read later catch up to children reading earlier. *Early Child. Res. Q.* 28, 33–48. doi: 10.1016/j.ecresq.2012.04.004

Toll, S. W. M., Van der Ven, S. H. G., Kroesbergen, E. H., and Van Luit, J. E. H. (2011). Executive functions as predictors of math learning disabilities. *J. Learn. Disabil.* 44, 521–532. doi: 10.1177/0022219410387302

van der Leij, A. (2013). Dyslexia and early intervention: what did we learn from the dutch dyslexia programme? *Dyslexia* 19, 241–255. doi: 10.1002/dys.1466

Vellutino, F. R., Fletcher, J. M., Snowling, M., and Scanlon, D. M. (2004). Specific reading disability (dyslexia): what have we learned in the past four decades? *J. Child Psychol. Psychiatry* 45, 2–40. doi: 10.1046/j.0021-9630.2003.00305.x

Vygotsky, L. (1986). *Thought and Language*. Cambridge, MA: MIT Press.

Waters, N. E., Ahmed, S. F., Tang, S., Morrison, F. J., and Davis-Kean, P. E. (2021). Pathways from socioeconomic status to early academic achievement: the role of specific executive functions. *Early Child. Res. Q.* 54, 321–331. doi: 10.1016/j.ecresq.2020.09.008

Wender, P. (1978). "Minimal brain dysfunction: an overview," in *Psychopharmacology: A Decade of Progress*. eds. M. A. Lipton, A. DiMascio and K. F. Killam (New York: Raven Press).

Willcutt, E. G., Petrill, S. A., Wu, S., Boada, R., Defries, J. C., Olson, R. K., et al. (2013). Comorbidity between reading disability and math disability: concurrent psychopathology, functional impairment, and neuropsychological functioning. *J. Learn. Disabil.* 46, 500–516. doi: 10.1177/0022219413477476

Wolf, M., and Bowers, P. G. (1999). The double-deficit hypothesis for the developmental dyslexias. *J. Educ. Psychol.* 91, 415–438. doi: 10.1037/0022-0663.91.3.415

Wong, W. I., and Yeung, S. P. (2019). Early gender differences in spatial and social skills and their relations to play and parental socialization in children from Hong Kong. *Arch. Sex. Behav.* 48, 1589–1602. doi: 10.1007/s10508-019-1415-8

World Federation of Neurology (1968). *Report of research group on dyslexia and world illiteracy*. Dallas: WFN.

Young, C. B., Wu, S. S., and Menon, V. (2012). The neurodevelopmental basis of math anxiety. *Psychol. Sci.* 23, 492–501. doi: 10.1177/0956797611429134

Zhang, T., Chen, C., Chen, C., and Wei, W. (2020). Gender differences in the development of semantic and spatial processing of numbers. *Br. J. Dev. Psychol.* 38, 391–414. doi: 10.1111/bjdp.12329

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# Home Literacy and Numeracy Interact and Mediate the Relationship Between Socio-Economic Status and Early Linguistic and Numeracy Skills in Preschoolers

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This longitudinal study aimed at evaluating the relationships between socio-economic status (SES) and early literacy and numeracy skills, testing home literacy and home numeracy as mediators. It also investigated the interaction of home literacy and numeracy on early literacy and numeracy skills. The study involved 310 preschool children attending the second and the third year. Parents completed questionnaires on SES and home literacy and numeracy. In the first session, children were administered language measures and non-symbolic numeracy skills and, in the second wave, tasks of early literacy and symbolic numeracy skills. Structural equation models (SEMs) showed that SES was predictive of early language and literacy skills and non-symbolic numeracy skills. In addition, home literacy and home numeracy significantly mediated the relationships between SES and children's skills. Finally, home literacy and home numeracy showed a significant negative interaction on symbolic numeracy skills. Implications for research and educational settings are discussed.

**Keywords: socio-economic status, early literacy, early numeracy, home literacy, home numeracy**

## INTRODUCTION

The role of the home environment in early literacy and numeracy development has received progressively increasing attention, also according to theoretical models such as Neuroconstructivism (Westermann et al., 2007), that emphasize the role of environmental variables on children's cognitive development. Children who grow up in families with low socio-economic status (SES) often exhibit delays in school readiness. These delays might undermine their academic goals and might lead to a lifelong trajectory of underachievement, school dropout, and underemployment, compared to children from families of higher SES (Bradley and Corwyn, 2002). Delays in school readiness are part of a larger set of disparities associated with low SES, which confers elevated risks in diverse areas of behavioral skills (Adler and Newman, 2002) and health outcomes (Case et al., 2002). Sirin (2005) defines SES as "*the individual's or a family's ranking on a hierarchy according to access to or control over some combination of valued commodities such as wealth, power, and social status*" (Sirin, 2005, p. 418). Bollen et al. (2001) suggest that

(SES) "*refers to the position of individuals, families, households, or other aggregates on one or more dimensions of stratification. These dimensions include income, education, prestige, wealth, or other aspects of standing that members of society deem salient.*" (p. 157). However, the debate on how to operationalize SES is still ongoing. The choice of SES measure usually includes education, occupation, and income (Brese and Mirazchiyski, 2013), but also possessions (e.g., books and personal computers) and, in some cases, the concept extends to cultural and social capital (e.g., relationships). The choice of measures might depend on many factors (Broer et al., 2019), such as the conceptual relevance at the time of the study, the applicability of the measure to the specific populations being studied, and comparability with measures used in other studies. Parental education has been identified as the index with the strongest associations with children's educational outcomes (Davis-Kean, 2005), strongly correlated with other important SES indicators (Sirin, 2005). As suggested by Hannon et al. (2020), disadvantage does not inhere in individuals; but might be the results of relationships between individuals, society, and the school system. It is, therefore, possible that disadvantaged families' literacy does not match school literacy as closely as does advantaged families' literacy. Living in poverty predicts parents' resource strain in terms of both material resources and emotional and psychological resources, possibly impacting the quantity and quality of home literacy and numeracy activities the children are exposed to Elliott (2020). In this regard, many studies have found evidence of a positive relationship between home literacy and early literacy skills (Sénéchal et al., 1998) and between home numeracy and early numeracy skills (Skwarchuk et al., 2014). However, past research demonstrates that associations between SES and home literacy are typically moderate in magnitude (Linver et al., 2002; Davis-Kean, 2005; Mistry et al., 2010; Elliott, 2020), suggesting high levels of variability within both low- and high-SES families in their support for home learning.

Furthermore, less evidence has been collected about the relationship between SES, home numeracy, and early numeracy skills. Finally, although many studies investigated the effects of SES on school achievements longitudinally (see for a review Bradley and Corwyn, 2002), fewer longitudinal studies are available that consider the impact of SES on specific literacy and numeracy subdomains in preschool years, including the home learning environment as mediator (e.g., Park, 2008; Elliott, 2020). Further, no evidence is available in this regard for the Italian context. Based on these considerations, in a sample of Italian preschoolers, the present study investigated how SES is related to different subdomains of language and literacy skills and symbolic and non-symbolic numeracy skills in preschool children in two different time moments, the second and third year. Further, it analyzed the interaction of home literacy and numeracy on early literacy and numeracy skills.

## SES, Early Literacy and Numeracy Skills, and Home-Related Activities

Considering the influence of SES on development, children from low SES families have been found to lag behind their high-SES peers in language skills, such as vocabulary, grammar, narrative skills, phonological awareness, speed of language processing (see Hoff, 2013 for a review), listening comprehension (Bonifacci et al., 2020), and reading attitudes (Hemmerechts et al., 2017). There is also some evidence that SES might be related to math skills (e.g., Reardon and Portilla, 2016), although less evidence has been collected in this regard and with somehow contrasting results.

Previous studies have shown that parental involvement at home is unequally distributed by SES (Bradley and Corwyn, 2002; Buckingham et al., 2014). Hemmerechts et al. (2017) also found that children with a lower SES experience more late parental involvement in literacy activities than children with a higher SES and that late parental involvement in literacy activities is an adjustment for worse or better reading literacy during primary school. Thus, SES levels might influence cognitive and literacy development mediating the educational opportunities that can be achieved (e.g., exposure to books, reading practice, quality of schools, etc.), with possible long-term outcomes (Suggate et al., 2018). It has been suggested that home activities may serve as a buffer that promotes resilience in the context of low-SES (Benzies and Mychasiuk, 2009), although literature reports diverse effects sizes and patterns of moderators (Inoue et al., 2020).

Considering language and literacy skills, Hoff (2003) found a higher degree of lexical diversity (type/token ratio) and more complex utterances (mean length of utterances, MLUs) in children of high-SES mothers, compared to those with lower SES. Further, SES levels might influence linguistic and literacy development mediating the educational opportunities that can be achieved (e.g., exposure to books, reading practice, quality of schools, etc.). The quality of the home literacy environment (Sénéchal et al., 1998) is a good predictor of children's literacy attainments. van Steensel (2006) followed a sample of children in the Netherlands from the end of kindergarten until second grade and found a tendency toward an enriched home literacy environment as the educational level (EL) of the mother increased. Sénéchal (2006) suggested that home literacy experiences might be viewed as proximal variables that can directly affect child outcomes, whereas SES should be considered a distal cause.

Considering the relationship between SES and math skills, most authors suggested a positive relationship (Duncan and Magnuson, 2011; Reardon and Portilla, 2016), although there are more minor studies than the literacy domain and significant differences between countries and different school systems (Baird, 2012). In addition, SES disparities are differently related to subcomponents of numeracy skills, with higher discrepancies in the verbal and symbolic aspects of numeracy skills and minor differences in performance in non-verbal and non-symbolic tasks (for a review, see Jordan and Levine, 2009). There was also contrasting evidence concerning the relationship between SES and the quantity of home learning activities (Elliott and Bachman, 2018). Silinskas et al. (2010) showed that mothers and fathers with low SES backgrounds reported more teaching of reading and numeracy than mid-SES parents; also, the lower the children's academic performance at the beginning of primary school, the more teaching by mothers and fathers was reported. These results suggest that parents might adaptively adjust the frequency of home literacy and numeracy activities to the child's performance level, even when they had low SES. Similar results were found by LeFevre et al. (2010) and Niklas and Schneider (2014). There are, however, studies that did not find a relationship between SES and home numeracy (de Keyser et al., 2020). Others instead found that higher SES children were exposed to higher quality numeracy activities than lower SES children (DeFlorio and Beliakoff, 2015).

Finally, SES might differently interact with home literacy/numeracy effects. For example, Leyva et al. (2017) found that maternal writing support predicted gains in children's reading skills in ethnically diverse low-income mothers. Still, numeracy support did not predict improvements in children's math skills.

## Early Literacy and Numeracy Skills

Complex mathematical abilities and mature literacy skills (decoding and reading comprehension) are trained at school, but during preschool years children already spontaneously develop basic calculation skills (Levine et al., 1992) and show literacy-related skills such as phonemic awareness and letter knowledge (Ehri et al., 2001). Also, it has to be underlined that literacy and numeracy skills are related (Cirino et al., 2018; Koponen et al., 2020), and some studies found that early literacy predicts early numeracy skills (Tobia et al., 2016) and later mathematical skills (Hecht et al., 2001).

Early numeracy abilities involve the understanding of magnitudes and the development of numerical processing skills and are manifested during the first few months of life in humans from various cultural backgrounds (Xu et al., 2005). The approximate number system (ANS) (Dehaene, 1992, 2001) is a core mechanism involved in number processing that allows to quickly understand, approximate, and manipulate numerical quantities. Based on von Aster and Shalev's (2007) model, non-symbolic numerical processing is followed by the acquisition of verbal labels for numbers, and then the child progressively acquires the written code for numbers. Previous literature has documented that the main predictors of math skills from preschool to primary school include quantity comparison (Clarke and Shinn, 2004) and number knowledge (Göbel et al., 2014). In addition, some studies found a specific effect of other basic number skills such as size seriation and counting (Tobia et al., 2016). From a developmental perspective, some studies proposed that language is essential for the growth of numerical competencies (Hauser et al., 2010), and mathematical language was found to be a unique significant predictor of numeracy performance (Purpura and Logan, 2015). The relationship between non-verbal approximate numerical abilities and symbolic number knowledge is, therefore, controversial. Some authors suggest that ANS forms a crucial conceptual foundation for understanding symbolic number words (Gallistel and Gelman, 1992, 2000; Wagner and Johnson, 2011). However, other studies failed to find a relationship between the two (Huntley-Fenner and Cannon, 2000).

As far as literacy is concerned, previous reviews have outlined how letter knowledge and phonemic awareness represent strong predictors of later decoding skills (Torppa et al., 2006; Caravolas et al., 2013; see Bellocchi et al., 2017 for Italian). Conversely, general linguistic skills, such as vocabulary and morpho-syntactic comprehension, might act as first precursors of the emergence of early literacy skills (phonological awareness and letter knowledge) but are instead considered a direct longitudinal predictor of later reading comprehension skills (Foorman et al., 2015; Hulme et al., 2015).

## Home Literacy and Home Numeracy

Many studies have addressed the role of home literacy activities in literacy development (Evans et al., 2000; Sénéchal and LeFevre, 2002; Foy and Mann, 2003; Hood et al., 2008; Stephenson et al., 2008) and that of home numeracy activities in numeracy development (Blevins-Knabe and Musun-Miller, 1996; Pan et al., 2006; LeFevre et al., 2009; Kleemans et al., 2012, 2016). Most of the literature on home literacy and home numeracy was obtained through parents' self-report questionnaires (e.g., Sénéchal and LeFevre, 2002; LeFevre et al., 2009), suggesting that parents' reports can be considered suitable tools in this research field (Sim et al., 2019).

Previous research found that home literacy, that is, exposure to books and reading in the familiar context, is positively related to early language skills such as expressive and receptive language (Payne et al., 1994; Roberts et al., 2005) and early literacy skills, such as letter knowledge, phonological awareness (Evans et al., 2000; Foy and Mann, 2003; Hood et al., 2008; Stephenson et al., 2008). Some studies also suggested that parents may also foster the development of writing competence (Wollman-Bonilla, 2001; Reutzel et al., 2005; Saint-Laurent and Giasson, 2005; Puranik et al., 2018; Hofslundsengen et al., 2019; Guo et al., 2020). In addition, the Home Literacy Model (Sénéchal and LeFevre, 2002; Sénéchal, 2006; Sénéchal et al., 2017) suggests that parent–child interactions on code-related activities, such as the teaching of reading and spelling (formal activities), are related to reading development. In contrast, meaning-related activities, such as parents' shared book reading with their children (informal activities) (Sénéchal, 2006), are predictors of oral language skills and later reading comprehension (Hulme et al., 2015).

However, some contrasting results are reported in the literature on the relationship between home literacy and early literacy skills. A study by Inoue et al. (2020), conducted on children from first to second grade, found that home literacy formal activities were associated with better letter knowledge or phonological awareness in Dutch and Greek, while access to literacy resources was related to emergent literacy skills in all languages. On the counterpart, informal activities such as shared book reading did not predict any cognitive or early literacy skills in any language. Bonifacci et al. (2021) did not find direct relationships between home literacy and early literacy skills in a path model including cognitive skills, although the two domains had significant correlation indexes.

Indeed, many pieces of evidence now indicate that parents also matter in the development of children's numeracy skills and recognize the influential role of home numeracy activities (LeFevre et al., 2009), defined as the parent–child interactions that include experiences with numerical content in daily-life settings (Mutaf Yildiz et al., 2018). Considering the role of home numeracy in early numeracy skills, positive relationships have been found (Blevins-Knabe and Musun-Miller, 1996; Pan et al., 2006; LeFevre et al., 2009; Kleemans et al., 2012, 2016; Bonifacci et al., 2021). Home numeracy can be conceived as a multifaceted domain, and its relationship with children's numeracy skills might be differentiated based on direct (formal) versus indirect (informal) activities (LeFevre et al., 2009; Skwarchuk et al., 2014). Direct activities focus on counting and teaching numbers and have been found to be related to children's symbolic numeracy abilities. In contrast, indirect activities have been found to be related to children's non-symbolic numeracy abilities. They involve playing games with numbers (e.g., dice) or doing everyday activities where you need to count. Other authors also highlighted the importance of "math talk," which can be considered another aspect of home numeracy and is referred to how parents use number words in everyday life (Braham et al., 2018). Elliott et al. (2017) found that parents' use of numbers larger than 10 was positively and significantly related to children's numeracy skills even when controlling for parents' overall talk. It has also been found that intervention directed to parents leads to enhanced home numeracy activities and significant gains in children's early numeracy skills (Niklas and Schneider, 2014). However, some studies did not find a significant association between home numeracy and children's early numeracy skills (e.g., Blevins-Knabe et al., 2000; de Keyser et al., 2020). Other studies showed differential effects of formal and informal home numeracy activities on different domains of number processing skills (Manolitsis et al., 2013; Kleemans et al., 2016; Mutaf Yildiz et al., 2018). Mutaf Yildiz et al. (2018) found that formal home numeracy was related to enumeration skills; informal home numeracy was related to calculation and symbolic processing, but there were no relationships with non-symbolic processing. In a meta-analysis by Mutaf- Yildiz et al. (2020), it was concluded that only advanced home numeracy interactions were associated with children's numeracy skills, but not basic ones.

A relatively minor number of studies have directly investigated the cross-domain effects of home literacy on numeracy and those of home numeracy on literacy. These studies tried to understand whether home-learning experiences might have specific effects only on their direct domains (home literacy for literacy and home numeracy for numeracy) or, instead if there are cross-domains effects, that is home literacy affecting early numeracy skills and home numeracy affecting early literacy skills (Melhuish et al., 2008; Skwarchuk et al., 2014). Baker (2014) found that the home literacy environment was related to reading but not numeracy in Mexican preschool children, whereas other studies have reported that numeracy skills are associated with home literacy experiences at least as strongly as with home numeracy experiences (LeFevre et al., 2009, 2010; Anders et al., 2012). Similarly, Soto-Calvo et al. (2020) found that home literacy was predictive of numeracy skills. Huntsinger et al. (2016) demonstrated that home numeracy activities predicted both numeracy and literacy skills, both concurrently and longitudinally, whereas home literacy activities predicted reading scores concurrently. Similarly, Napoli and Purpura (2018) reported that the home literacy environment was not broadly predictive of children's literacy and numeracy skills, but they found that the home numeracy activities predict a specific aspect of children's literacy development (vocabulary). Bonifacci et al. (2021) found that home numeracy was directly linked to early numeracy, but in their SEM model, there was no reciprocal interaction between home literacy and numeracy skills and between home numeracy and literacy skills. In this study, however, cognitive skills of executive functions (EFs) and working memory were also included in the model.

## The Present Study

Within a longitudinal design involving 4- and 5-years old children attending preschool, the present study was aimed at evaluating the relationships of SES with early language and literacy skills and that of SES with early non-symbolic and symbolic numeracy skills, considering the role of home literacy and numeracy as potential mediators. Further, we evaluated the interaction of home literacy and numeracy on early language/literacy and symbolic/non-symbolic numeracy skills, including SES as a potential mediator. Home literacy and home numeracy were evaluated as single constructs and included both direct (formal) and indirect (informal) activities. To fulfill the project's aim, we administered children two different sets of measures in the first and second waves of assessment. In the first wave, we evaluated measures that were thought to be adequate for the age range, and that first emerge in the developmental trajectory of literacy and numeracy skills. Therefore, we included vocabulary and morpho-syntactic comprehension as a proxy of language skills and non-symbolic quantity comparison and seriation as precursors of numeracy skills. Then, in the second wave, we choose measures of letter knowledge, early writing, and phonological awareness as indexes of early literacy skills and symbolic number recognition and biunivocal correspondence as indexes of early numeracy skills.

The main objectives and expected results of the study were the following:

1. Considering SES, we aimed to evaluate if it predicts both home literacy and numeracy activities and children skills. Based on previous studies, strong evidence suggests that SES predicts early language skills (vocabulary, morpho-syntactic comprehension) and, in turn, early literacy skills. However, for the latter, an intervening role of school activities might damper the influence of SES. Concerning early numeracy, minor evidence is available and reported high variability between countries and different school systems (Baird, 2012). Some authors suggested a more substantial role of SES for symbolic, rather than non-symbolic, numeracy skills. Within this framework, we expect SES to predict both early language and literacy skills. We also expect a relationship between SES and early numeracy skills, although possibly lower than the relationship between language and literacy measures. Further, we expect stronger relationships in the first wave of assessment due to the potential intervening role of school activities on the second wave. Finally, we also expect SES to have a direct relationship with both home literacy and home numeracy (Jordan and Levine, 2009).

2. Regarding home literacy and home numeracy activities, we expect direct relationships between home literacy and language and literacy skills and between home numeracy and non-symbolic and symbolic numeracy skills. Further, we aim to evaluate if they mediate the role of SES on children's skills.
3. Finally, we aim to evaluate the interaction's effect between home literacy and numeracy on children's literacy and numeracy skills, including SES as a mediator. Since relatively more studies reported an effect of home literacy on numeracy compared to that of home numeracy on literacy, we expect the interaction to be associated with numeracy skills rather than with language and literacy skills.

Previous results on the Italian context did not find a direct relationship between home literacy and early literacy skills, nor evidence of an interaction between language and numeracy skills. Therefore, variations due to different socio-educational contexts might be expected with respect to previous literature.

# MATERIALS AND METHODS

## Participants

A total of 310 Italian monolingual children (females = 55.2%) were involved in the study in two times points: in the spring of the second year of preschool (mean age = 56.95 months ± 3.66), and 1 year later, in the spring of the third year of preschool (mean age = 68.55 months ± 3.47). Parents of children received the questionnaires about SES and home literacy and numeracy. All children attended a public all-day preschool program in Italy where the Laboratory for the Assessment of Learning Disabilities (LADA) of Bologna University's Department of Psychology was running the LOGOS project, funded by the Municipality of Bologna, which is aimed at the early identification of literacy and numeracy skills. None of the children had been referred to neuropsychiatric units for any range of developmental disorders or sensory or neurological impairments. Thus, the sample was relatively homogeneous for educational exposure, considering that all the teachers received training on early literacy and numeracy skills within the project. The Italian preschool program is a 3-year program that involves children from 3 to 6 years. During these preschool years, formal instruction regarding literacy and numeracy skills is not provided. However, children are engaged in activities that are aimed at improving socialization and numeracy and linguistic development.

The parents of all children involved in the study gave their informed consent, and the Bioethical Committee of the University of Bologna approved the LOGOS project (prot. 1470, October 2, 2017).

## Materials

### Background Information

Information regarding the parents' socio-EL and occupation was collected and scored, according to the Four Factor Index of Social Status (SES) (Hollingshead, 2011), to achieve a composite score for each child's SES. For the present study, indexes of EL and occupation (O) were used. Thus, a score from 1 to 7 is given for EL and a score between 1 and 9 for occupation. SES scores for fathers and mothers were then calculated according to the formula EL × 3 + O × 5, and a compound SES score for children derived from the mean of the two values.

### Home Literacy and Home Numeracy Questionnaire

A questionnaire assessing home literacy and home numeracy activities was administered to parents. Parents could complete it together or by who spends more time with the child, usually the mother. In line with other studies that adopted a similar approach, we opted for a short questionnaire that is easy to fill out by parents to encourage greater adherence to the study (Stephenson et al., 2008; Manolitsis et al., 2013; see also Bernabini et al., 2020b; Bonifacci et al., 2021). The questionnaire included four questions on home literacy activities. Two were referred to more formal activities ["How often do you and your child read or write letters of the alphabet?"; "How often do you and your child use games (even on Tablet or PC) that involve letters?"] and two to informal activities (e.g., "How often do you and your child sing nursery rhymes?"; "How often do you and your child read books or tell stories?"). Then, there were four questions on home numeracy activities, two related to direct (formal) activities ["How often do you and your child read or write numbers"; "How often do you and your child use games (even on Tablet or PC) that involve numbers"?] and two related to indirect (informal) activities ["How often do you and your child count objects?"; "How often do you and your child do simple calculations (2 + 1 = 3) in games or during other daily activities?"]. Responses were on a five-point Likert scale, from "never" to "everyday." Sums of scores of each subscale (home literacy and home numeracy) were used in the analyses. Maximum score for each subscale was 20. Reliability for each scale was sufficient for the present sample (Home numeracy: Cronbach's alpha = 0.69; Home literacy: Cronbach's alpha = 0.67).

## Children's Measures for the First Wave of Assessment (Second Year of Preschool)

### Language Skills

The following tasks taken from the Learning Difficulties Indexes (IDA; Bonifacci et al., 2015) were used in the present study:

1. Vocabulary. Children were asked to name 36 images disposed on three grids with 12 images each selected for decreasing frequency in spoken language (Burani et al., 2001). The accuracy score, ranging from 0 to 36 (1 point for each correct answer), was considered. The Cronbach's alpha of the scale was 0.85, according to the test manual.
2. Morpho-syntactic comprehension. Children were presented with three pictures representing three different scenarios. For each picture, they were asked to identify or manipulate elements of the scene by comprehending different types of sentences pronounced by the examiner (e.g., the child had to correctly place a card depicting a book after hearing a sentence such as "The book is under the pillow"). The morpho-syntactic structures investigated were: singular/plurals, locatives, active/passive, and relative clauses. A total of 18 sentences were presented, and for each of them,

a score of 2 (correct answer at first attempt), 1 (correct answer at the second attempt), or 0 (wrong answer) was given. The total score, ranging from 0 to 36, was considered. The scale's Cronbach's alpha was 0.70, according to the test manual.

### Non-symbolic Numeracy Skills

The tasks used were taken from the battery Number Sense: Prerequisites (Tobia et al., 2018), which assesses early numeracy skills in preschoolers.

1. Quantity comparison. Children were shown two illustrated baskets and were asked to quickly choose the one with a greater number of fruits in it, without counting, therefore relying on estimation processes. The number of fruits varied from 3 to 20, and the difference in quantity between sets ranged from 1 to 6 units. A total of 12 items was presented. A score of 1 (correct answer) or 0 (wrong answer) was given for each item, for a maximum total score of 12. There was a Cronbach's alpha of 0.64, according to the test manual.
2. Seriation. This subtest included two tasks: (a) First, children were asked to put in ascending order a set of four pictures of the same object drawn in different dimensions (seriation with perceptual cues); (b) second, a fifth picture was given to the child, who was asked to put it in the correct place in the ordered composition (insertion). For each object placed in the correct position, a score of 1 was assigned. The total score, ranging from 0 to 20, was considered. The size seriation subtest's KR-20 is 0.89, according to the test manual.

## Children's Measures for the Second Wave of Assessment

### Early Literacy Skills

1. Phonological awareness. This task was taken from the IDA battery (Bonifacci et al., 2015). It was a task of first syllable recognition (4 items). Children were given the image of an object (dog, bubble, sea, and pear) and four images amongst which the child was required to recognize the one whose name begins with the same sound [e.g., *ca*ne (dog), and *ca*sa (house)]. Each item received a score of 1 for correct responses and a score of 0 for incorrect answers, for a maximum total score of 4. The reliability score (KR-20) was 0.78, according to the test manual.
2. Letter knowledge. This task was adapted from the IDA battery (Bonifacci et al., 2015). Children were presented with a picture of a train with one letter (from a to z) in each coach. The experimenter said the sound of five letters (two vowels and three consonants), and the child was required to mark the correct letters on the sheet. A score of 1 was given for each correct response for a maximum score of 5. The Cronbach's alpha of the scale calculated on the study's sample was 0.77.
3. Early writing. This task was developed for the purpose of the present study. Children were asked to pretend to be writers, and they were asked to write five words: their first name, *ape* (bee), *serpente* (snake), *coccinella* (ladybug), and *treno* (train). A score from 0 (absence of signs) to 9 (all letters are correct and in proper order) was given for each word according to how the writing approximates the correct writing of the word. Scores ranged from 0 to 45, and Cronbach alpha calculated on the study's sample was 0.87.

### Symbolic Numeracy Skills

For being administered collectively, these tasks were adapted from the battery Number Sense: Prerequisites (Tobia et al., 2018).

1. Number recognition: Children receive a card with the digits 1 to 9 randomly distributed on a grid among blank squares. It is similar to a bingo card. Children are required to sign the number read aloud by the experimenter with a different colored pencil for each number. The examiner named five different numbers, and the score ranged from 0 to 5. Cronbach alpha was 0.89, according to the test manual.
2. Biunivocal correspondence. Children were provided with a card similar to the previous task, but boxes represented sets of elements (little stars ranging from 1 to 9). The examiner named five different numbers, requesting the child choose the set with the corresponding number of stars. For each digit correctly associated with a quantity, a score of 1 was given (score range: 0–5). Cronbach alpha was 0.77, according to the test manual.

## Procedure

Questionnaires on SES and home literacy/numeracy were given to parents during the first wave of assessment. Tasks in the first wave of assessment were administered individually by trained psychologists in a quiet room at the children's school, in a single session lasting about 30 min. In the second wave, tasks were administered collectively in small groups of around 10–12 children in a single session lasting about 30 min. Breaks were allowed if the child showed signs of fatigue. Special attention was given to ascertaining that children had correctly understood the instructions; verbal instructions were minimized, and examples for each task were provided.

## Data Analysis

Preliminary analysis on outliers evidenced that few participants scored over the absolute value of 3 SDs on some tasks. These were less than 5% of the data, and we were allowed to proceed with the Winsorizing method (Duan, 1997; Wilcox, 2010), which suggests modifying outliers at the end of the tails of the distribution to the highest/lowest value within the distribution that are not suspected to be outliers. Then we checked the distribution, and due to a high level of negative skewness for some variables, we used the ln-transformation on these variables. The normality of the data improved and finally resulted normally distributed, particularly with skewness and kurtosis ranging in the limits of $\pm 2$ (acceptable values according to Trochim and Donnelly, 2006); these values are now reported in **Table 1**.

We did not find any issues of non-linear relationships between dependent and independent variables using the scatter plot graphic builder in SPSS v26. We also checked the plot of the standardized residuals errors by the regression standardized predicted values and found that all the residuals were distributed randomly around zero, meeting the homoscedasticity in our data.

**TABLE 1** | Descriptive statistics of measures included in the study.

| | Measure | Mean | SD | Min–max | Skewness | Kurtosis |
|---|---|---|---|---|---|---|
| First wave | Vocabulary* | 32.42 | 2.54 | 11–36 | 0.48 | 0.17 |
| | Morpho-syntactic comprehension* | 29.46 | 4.37 | 2–36 | 0.21 | –0.49 |
| | Quantity comparison* | 10.10 | 1.46 | 0–12 | 0.46 | –0.56 |
| | Seriation* | 15.46 | 4.73 | 0–20 | –0.3 | –1.13 |
| Second wave | Letter knowledge* | 3.91 | 1.47 | 0–5 | –0.64 | –1.10 |
| | Phonological awareness* | 3.59 | 0.88 | 0–4 | –1,53 | 0.85 |
| | Early writing* | 33.68 | 10.96 | 6–45 | –0,15 | –1.27 |
| | Number recognition* | 4.67 | 0.86 | 0–5 | –1.92 | 1.95 |
| | Biunivocal correspondence* | 4.72 | 0.61 | 0–5 | –1.49 | 0.45 |
| Parents | Children's SES* | 47.04 | 10.60 | 13.5–61 | 0.10 | –0.93 |
| | Home Literacy | 11.73 | 3.28 | 5–20 | 0.14 | –0.6 |
| | Home Numeracy | 10.63 | 2.95 | 5–19 | 0.34 | –0.37 |

*Skewness and kurtosis for ln-transformed values.*

Therefore, we concluded that parametric tests were suitable for these data, also considering the increased chance of Type II error when applying non-parametric analysis to (close to) normally distributed data (e.g., Hodges and Lehmann, 1956).

Pearson correlations between the main variables included in the study were performed.

A structural equation model (SEM; e.g., Kline, 2010), including CFA and path analysis, was applied using Amos software version 26.0 (Arbuckle, 2016) after transforming the variables into standardized scores. In this model, four latent variables were identified: Language, Early Literacy, Non-symbolic Numeracy, and Symbolic Numeracy, which include respectively: (1) vocabulary and morpho-syntactic comprehension, (2) early writing, letter knowledge and phonological awareness, (3) quantity comparison, size seriation, and (4) number recognition and biunivocal correspondence. A path analysis was used to examine the relationship between these latent dependent variables and SES as the independent variable through possible mediation of Home Literacy and Home Numeracy variables.

We also included directional paths from language to literacy and from non-symbolic to symbolic numeracy skills. This choice was supported either by the longitudinal design and by previous research that supported these developmental pathways for language to literacy (Foorman et al., 2015; Hulme et al., 2015) and from non-symbolic to symbolic (von Aster and Shalev, 2007).

The second model provides the same four latent variables, but in this case, the independent variables were Home Literacy and Home Numeracy, and we included the Home Literacy × Home Numeracy interaction. The SES variable was included as a mediator between the independent and dependent variables.

The SEM, including CFA, was run using Maximum Likelihood as the estimator method; for testing the mediation patterns, the Specific Indirect Effect Amos plugin was used (Gaskin et al., 2020). In order to reach a good fit, some adjustments were made following the suggestion of modification indexes without changing the key structure of the models (Kenny, 2011).

Multiple indices were used to evaluate models' fit: Chi-square test of model fit ($\chi^2$); Root Mean Square Error of Approximation (RMSEA), Comparative Fit Index (CFI), Tucker-Lewis Index (TLI). A non-significant Chi-square test of model fit, TLI and CFI values equal to or higher than 0.90 indicate an acceptable model fit; RMSEA close to 0.08 or lower, indicate an acceptable fit (Marsh et al., 1988; Browne and Cudeck, 1993; Hu and Bentler, 1999). Cut-off values for both the RMSEA (0.01, 0.05, 0.08, and 0.10) and the CFI/TLI (0.99, 0.95, 0.92, and 0.90) have been commonly used to distinguish between excellent, close, fair, and mediocre or poor models, respectively (Hu and Bentler, 1999). In our study, the models' indexes suggest a close fit to the data (see **Table 3**). Considering the new approach of the equivalence testing (Yuan et al., 2016), we interpreted our model fit indices more carefully. We can say that our models are sufficiently acceptable for describing our data.

## RESULTS

Descriptive statistics and correlations among the observed variables are reported in **Tables 1**, **2**, respectively. SES was significantly related to both home literacy and numeracy and with all measures in the linguistic domain. It was also related to numeracy skills, except biunivocal correspondence and quantity comparison. Home literacy and numeracy were significantly related between each other [$r(308) = 0.568$, $p < 0.01$], although not overlapping. Home literacy was further related to all language and literacy measures except vocabulary and, although to a lesser degree, with numeracy task of biunivocal correspondence. Home numeracy was related to all measures in the numeracy domain and with all language measures except vocabulary. Then, there were significant intra-domain relationships for all language measures. For numeracy measures, there were significant relationships between seriation and number recognition and between quantity comparison and biunivocal correspondence but not between quantity comparison and number recognition and between seriation and biunivocal correspondence. Considering inter-domain relationships, the highest correlations index was

**TABLE 2 |** Pearson correlations coefficients (*r*) between SES, home literacy and numeracy, and children's skills.

| | SES | Home Literacy | Home Numeracy | Vocabulary | Morpho-syntactic comprehension | Quantity comparison | Seriation | Early writing | Letter knowledge | Phonological awareness | Number recognition |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Home Literacy | 0.175** | | | | | | | | | | |
| Home Numeracy | 0.139* | 0.568** | | | | | | | | | |
| Vocabulary | 0.129* | 0.106 | 0,089 | | | | | | | | |
| Morpho-syntactic comprehension | 0.182** | 0.215** | 0.214** | 0.385** | | | | | | | |
| Quantity comparison | 0.072 | 0.094 | 0.137* | 0.183** | 0.190** | | | | | | |
| Seriation | 0.173** | 0.109 | 0.159** | 0.173** | 0.377** | 0.166** | | | | | |
| Early writing | 0.231** | 0.289** | 0.259** | 0.178** | 0.161** | 0.001 | 0.129* | | | | |
| Letter knowledge | 0.193** | 0.144* | 0.138* | 0.241** | 0.188** | 0.042 | 0.125* | 0.345** | | | |
| Phonological awareness | 0.196** | 0.263** | 0.240** | 0.228** | 0.208** | 0.017 | 0.166** | 0.512** | 0.355** | | |
| Number recognition | 0.138* | 0.077 | 0.254** | 0.051 | 0.151** | −0.032 | 0.148** | 0.318** | 0.293** | 0.393** | |
| Biunivocal correspondence | 0.073 | 0.130* | 0.114* | 0.125* | 0.131* | 0.135* | 0.107 | 0.224** | 0.225** | 0.304** | 0.270** |

*$^{**}p < 0.01$; $^{*}p < 0.05$ (two-tailed).*

found between phonological awareness and number recognition [$r(308) = 0.393, p < 0.01$].

To better understand the predictive power of SES on children's early literacy and numeracy skills and on home literacy and numeracy, a SEM was performed (**Figure 1**), which included home literacy and home numeracy as potential mediators. The SEM's fit indexes were all acceptable (see **Table 3**).

The hypothesized path from the observed variable (SES) to the latent variables Language, Literacy, and Non-symbolic number was significant ($p < 0.01$), but the path from SES to Symbolic number was not ($p > 0.05$). All the other paths in the model were significant; see **Figure 1** for the summary.

The mediation effect from SES and latent variables by Home Literacy and Home Numeracy were all significantly different from zero (see **Table 3** for the results), concluding that Home Numeracy and Home literacy have a significant mediation effect in the relationships between SES and children's skills. In particular, we have a partial mediation over Language, Literacy, and Non-symbolic numeracy and a full mediation over the Symbolic numeracy due to the significance of the indirect path only. Finally, language skills at age four predicted early literacy skills at age five ($p < 0.01$), and non-symbolic numeracy predicted symbolic numeracy from age four to age five ($p < 0.05$). All the other paths were significant, and the model's fit was acceptable (see **Table 3**).

## Model 2

For testing the interaction effects between Home literacy and Home numeracy on the latent variables referred to children's skills (see **Figure 2**), we first standardized the scores and then used them in the models. In this case, we included SES as a mediator between the aforementioned variables. The SEM's fit indexes were all acceptable (see **Table 3**).

Results showed that the interaction effect is significant only on Symbolic-Numeracy (negative interaction, $p < 0.01$) and, therefore, the others interaction's paths were deleted from the model. The interaction effect of home literacy and home numeracy on symbolic numeracy is shown in **Figure 3** for a better understanding. The paths from Home Numeracy to SES and from SES to Symbolic Number were not significant ($p > 0.05$). All the other paths were significant; see the summary in **Figure 2**. Concerning the mediating role of SES, we found a significant mediation effect for both Early Literacy and Language, but we did not find a significant mediation effect on the numeracy skills.

## DISCUSSION

In the present study, we first aimed to evaluate if SES was a direct predictor of children's early language and literacy skills and symbolic and non-symbolic numeracy skills. We also tested if SES had a direct relationship with home literacy and numeracy and if these variables could mediate the relationship between SES and children's skills. Secondly, we tested if home literacy and numeracy directly predicted children's early literacy and numeracy skills. Finally, we evaluated the interaction's effect of home literacy and numeracy on children's skills through SES

**TABLE 3** | Models' parameters and statistics.

| | Indirect path | Unstandardized estimation | CI lower | CI upper | *p* | $\chi^2$ | df | *p* | CFI | TLI | RMSEA |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Model 1 | SES → HomeLiteracy → Language | 0.025 | 0.011 | 0.053 | 0.005 | 54.2 | 42.0 | 0.098 | 0.979 | 0.967 | 0.031 |
| | SES → HomeLiteracy → Literacy | 0.036 | 0.015 | 0.061 | 0.01 | | | | | | |
| | SES → HomeNumeracy → Non-symbolic number | 0.019 | 0.004 | 0.046 | 0.017 | | | | | | |
| | SES → HomeNumeracy → Symbolic number | 0.018 | 0.002 | 0.042 | 0.031 | | | | | | |
| Model 2 | HomeLiteracy → SES → Language | 0.002 | 0.001 | 0.004 | 0.032 | 61.0 | 50.0 | 0.137 | 0.982 | 0.971 | 0.027 |
| | HomeLiteracy → SES → Literacy | 0.002 | 0.001 | 0.006 | 0.026 | | | | | | |
| | HomeNumeracy → SES → Non-symbolic number | 0.001 | −0.001 | 0.004 | 0.258 | | | | | | |
| | HomeNumeracy → SES → Symbolic number | 0.000 | 0.000 | 0.002 | 0.322 | | | | | | |
| | Home Literacy × Home Numeracy → Symbolic Numeracy | | | | 0.007 | | | | | | |

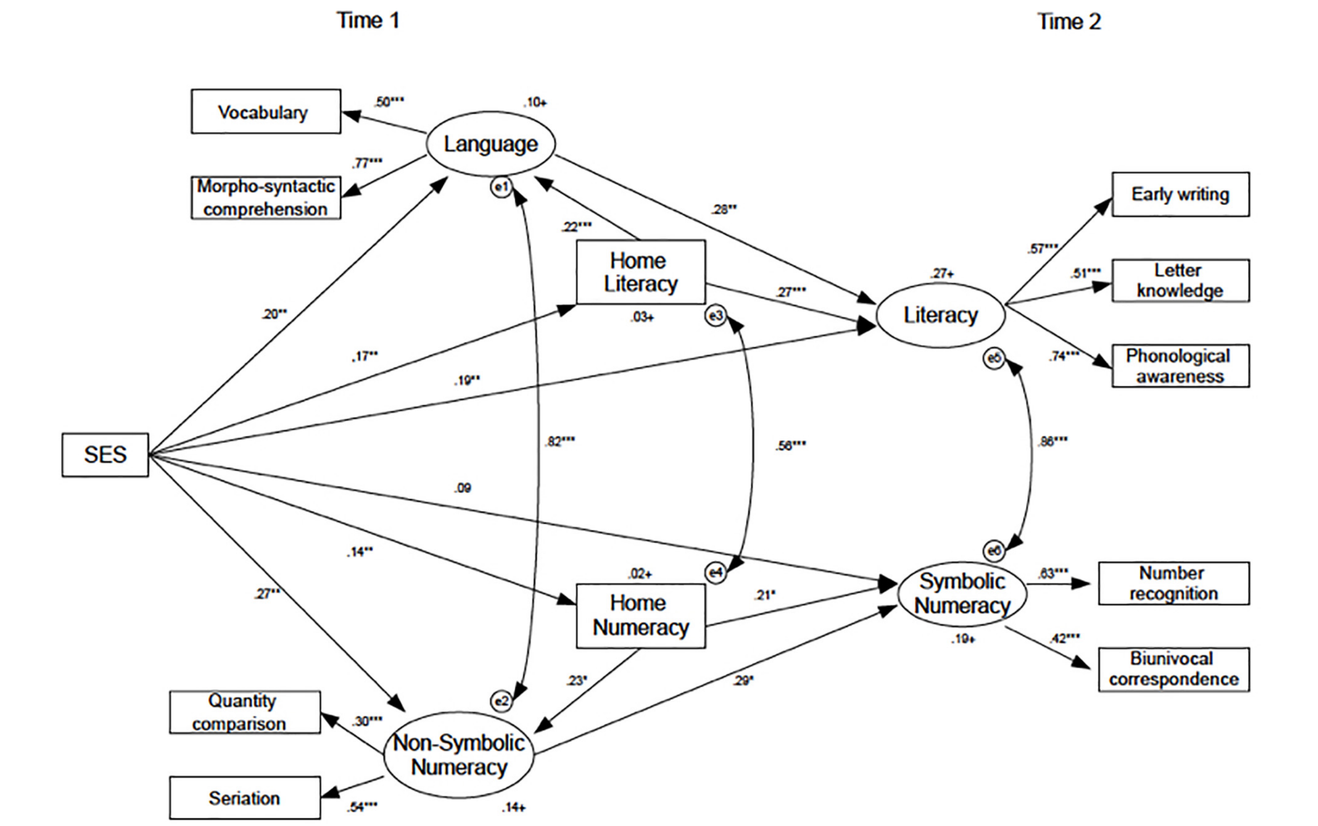


**FIGURE 1 |** Model 1 on the relationships between SES and children's early language/literacy and symbolic/non-symbolic numeracy skills with Home Literacy and Home Numeracy as mediators.

as a mediator. Importantly, this was a longitudinal study that included two waves of assessment, the first when children were in their second year of preschool and the second when they were in their final (third) year of preschool. SES, home literacy, and home numeracy were collected during the first wave of assessment.

We first explored correlations between the measures included in the study, and it emerged that SES was significantly related to all measures excluded biunivocal correspondence and quantity comparison. Then, there were domain-specific relationships between home literacy and language and literacy measures (except for a non-significant correlation between home literacy and vocabulary) and between home numeracy and all numeracy skills. Cross-domain relationships were found between home numeracy and all measures of language skills, but home literacy was related only with the numeracy task of biunivocal correspondence. Intra-domain relationships were found for all language measures but for the numeracy domain, there were only significant relationships between seriation and number recognition and between quantity comparison and biunivocal correspondence. There were also multiple cross-domain relationships amongst children's skills, with the highest value for the correlation between phonological awareness and number knowledge.

Taken together, these results suggest a complex pattern of relationships that reinforce the evidence reported in the literature about reciprocal interactions between SES, home literacy and numeracy, and children's early skills as well as cross-domain relationships between literacy and numeracy (Bonifacci et al., 2016; Cirino et al., 2018; Koponen et al., 2020; Bernabini et al., 2020a, 2021).

However, to better understand longitudinal causal pathways and cross-domain interactions, we developed two different SEM models.

In the first model, we considered SES to be a potential predictor of early language skills and early literacy skills, and symbolic and non-symbolic numeracy skills, including home literacy and numeracy as potential mediators. Results showed that SES had significant direct effects on early language and literacy skills. Home literacy significantly mediated the role of SES for language skills in the second year of preschool and early literacy skills at the end of preschool. Language skills were predictive of early literacy skills 1 year later. Concerning numeracy, it emerged that SES was predictive of non-symbolic skills but not of later symbolic skills. Home numeracy significantly mediated the role of SES on both waves of assessment. Also, early non-symbolic skills were significantly related to later numeracy skills. Considering the amount of variance explained in the model, this was higher for the second wave of assessment compared to the first and for early literacy (0.27) compared to symbolic numeracy (0.19).

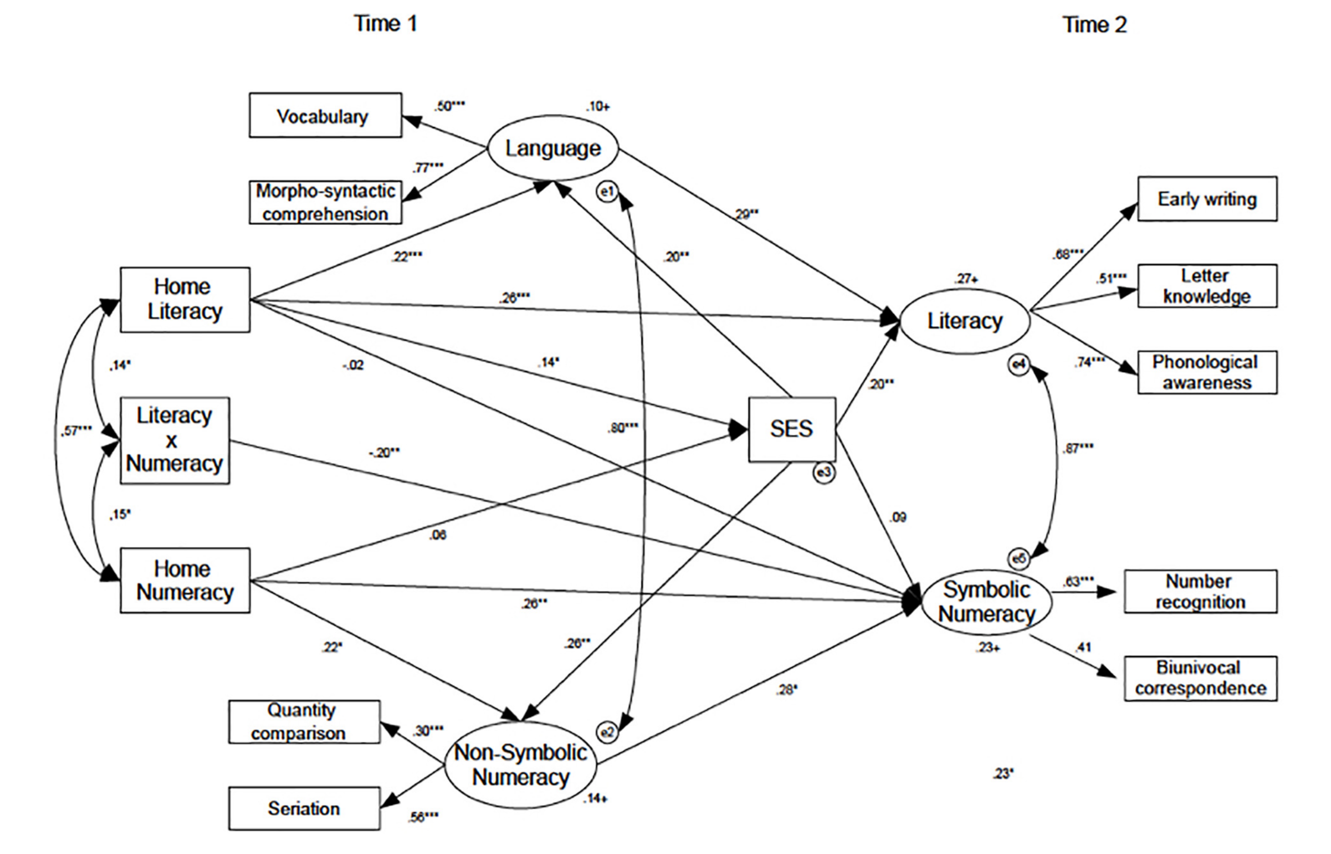


**FIGURE 2 |** Model 2 on the Home Literacy × Home Numeracy interaction on children's early language/literacy and symbolic/non-symbolic numeracy skills with SES as mediator.

This pattern of results reinforces some aspects of previous evidence and offers partially divergent results and new insights.

First of all, given the observed direct path from home literacy and numeracy to children's skills, this study reinforces the body of evidence that highlights the importance of home literacy on children's early language and literacy skills (e.g., Sénéchal et al., 1998) and that of home numeracy on early numeracy skills (e.g., Skwarchuk et al., 2014). Secondly, our results are in line with previous evidence of a direct relationship between SES and early language skills (Hoff, 2003). Although there was less evidence in this regard, we found that SES was also related to early literacy skills. Considering the relationship between home literacy and early language skills, these results diverge from those found in the Italian context by Bonifacci et al. (2021), where no direct path was observed from SES and home literacy to early literacy skills. The two studies, however, differ in some critical aspects. In Bonifacci et al. (2021), the authors also included measures of executive functions (inhibition and working memory) that may have dampened the influence of SES. Also, the present study involved a larger sample and considered home literacy and numeracy as mediators rather than as independent variables. However, it has to be underlined that also in the present study, in line with Bonifacci et al. (2021) and different from previous evidence (e.g., Hoff, 2013), we did not find, at a correlational level, significant relationships between SES and children's vocabulary. Therefore, it might be that some cultural differences between Italian and American/Canadian mothers (Richman et al., 1988; Girolametto et al., 2002; Hsu and Lavelli, 2005) intervene in the relationship between SES and early linguistic skills. We might suggest that more research is needed in different cultural contexts to better understand the stability of these relationships and the factors that might intervene.

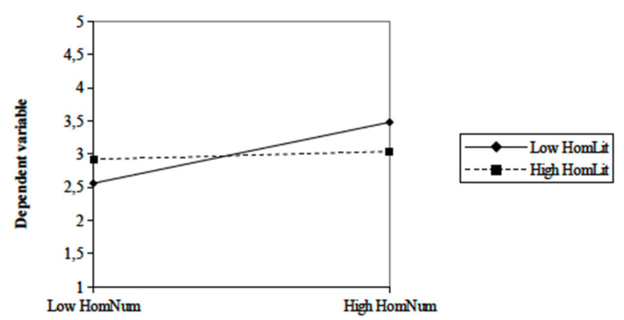


**FIGURE 3 |** Interaction effect of home literacy and home numeracy on symbolic numeracy.

Considering the relationship between SES and the numeracy domain, our results found that SES was significantly related to non-symbolic but not symbolic skills. These results contrast with some previous studies (Jordan and Levine, 2009), which found that SES disparities were differently related to subcomponents of numeracy skills, with higher gaps in the symbolic tasks and minor or no differences in performance in non-symbolic tasks. A reversed pattern was observed in the present study, with SES being related to non-symbolic skills but not to symbolic skills. Future studies will need to address this issue with more comprehensive measures of symbolic and non-symbolic skills. A potential explanation to the present pattern of results is linked to the hypotheses that parents with low SES might have had previous math difficulties and that intergenerational patterns might mediate the relationship between low-SES and early non-symbolic skills. In this regard, there is some evidence of intergenerational pathways in non-symbolic numeracy skills (Braham and Libertus, 2017; Navarro et al., 2018; Bernabini et al., 2020b). Since the absence of relationships of SES and symbolic numeracy skills, it might be that the school context might act as a protective factor. If children are exposed to proper early numeracy activities at school, this might reduce the impact of SES on symbolic numeracy skills. Future investigations should consider the quality and quantity of school activities in these domains.

Significantly, this study adds important new insights with respect to previous literature showing that, although SES predicted both home literacy and numeracy skills, home literacy partially mediates the effect of SES on language and literacy measures in addition to non-symbolic numeracy and fully mediates the relationship between SES and symbolic numeracy skills. Previous studies already suggested an influence of SES on home literacy (van Steensel, 2006) and home numeracy (DeFlorio and Beliakoff, 2015), although others reported opposite patterns, with more home activities in low-SES parents (Silinskas et al., 2010) or no effects of SES on home literacy and numeracy (de Keyser et al., 2020). To our knowledge, no previous study evaluated these mediation effects considering together different components of early language, literacy, and symbolic and non-symbolic aspects of numeracy skills. We found evidence that home literacy and home numeracy mediate the relationship between SES and children's skills. A previous study found similar results on first-grade children, but it focused on single measures of reading and math achievement and only considered mother's education as a proxy of SES (Zadeh et al., 2010). Also, in line with our study Galindo and Sonnenschein (2015) found that home numeracy mediated the relationship between SES and math skills. We, therefore, can conclude that all aspects of the home environment mediated to a certain degree the associations between SES and children's skills and that home environment during the preschool years might reduce the detrimental effects of low maternal education on children's ability, for both literacy and numeracy skills and particularly for symbolic numeracy skills.

As a second aim of the study, we also wanted to understand the cross-domain effects of home literacy and numeracy and children's skills. To this purpose, we developed a model of the interaction between home literacy and numeracy on the two different domains, including SES as a mediator. It emerged that the interaction of home literacy and home numeracy was not significant in language and literacy skills and non-symbolic numeracy measures. Instead, it was negatively significant for children's symbolic numeracy skills. The analysis revealed that if home literacy is high when home numeracy is low, this enhances numeracy skills (mainly symbolic ones). These results are partially in line with previous studies that found a relationship between home literacy and numeracy skills (LeFevre et al., 2009, 2010; Anders et al., 2012; Soto-Calvo et al., 2020) and reinforce the role of language on numeracy skills (Hauser et al., 2010). It contradicts previous evidence about the possibility that home numeracy predicts language and literacy skills (Huntsinger et al., 2016; Napoli and Purpura, 2018). This is a novel contribution of the present study since, to our knowledge, no previous study directly addressed this issue, considering literacy and numeracy skills considered at different time moments. Finally, Model 2 reinforces and enriches findings from Model 1 regarding the role of SES. In Model 2, SES was included as a mediator of the relationship between home literacy and numeracy, and children's skills. It was found that SES significantly mediates the role of home literacy on early language and literacy skills but not that of home numeracy on children's numeracy skills. These results suggest that SES might have a more prominent role in the language and literacy domains compared to the numeracy domain (Silinskas et al., 2010; Baird, 2012; de Keyser et al., 2020).

There are some limitations of the present study that need to be considered. First, we did not test specific relationships of SES and home literacy and numeracy with single literacy and numeracy factors, although this was partially considered in correlation analyses. In other words, it might be that SES might differently affect subdomains of literacy and numeracy, and this should be considered in forthcoming studies. In addition, measures of home literacy and numeracy did not distinguish between formal and informal activities. We opted for a short questionnaire to encourage greater adherence to the study, proposing a questionnaire that is easy to fill out by parents and in line with other studies that adopted a similar approach (Stephenson et al., 2008; Manolitsis et al., 2013). However, the absence of information about the differential role of formal and informal home literacy and numeracy activities might limit the generalizability of results and would require further investigation. Finally, the study was conducted on Italian monolingual children who showed considerable variation in SES scores but could not be considered a low-SES sample. Other studies should be performed on low-SES samples and on children from a migrant background where bilingual exposure in the home and family environment might differently interact with SES, home literacy and numeracy variables, and children's skills (Bonifacci et al., 2020).

Despite these limitations, the present study adds a significant contribution to the previous evidence regarding three main points. First, the study evidenced that home literacy and home numeracy partially or fully mediated the relationships between SES and children's skills, suggesting that home activities might dampen the detrimental effects of SES on children's skills. Secondly, the study highlighted a significant interaction of home literacy and home numeracy on symbolic numeracy skills, suggesting that home literacy might represent a protective factor when home numeracy is low. Finally, the present study was conducted on monolingual Italian children and their parents; Italian is a highly transparent language, and, since most studies were conducted on opaque language such as English, the study adds insights about the generalizability of results of previous studies to different linguistic and cultural contexts.

These results have potential implications for educational settings. Given the potential role of home literacy and home numeracy in mediating children's literacy and numeracy skills, the present study indirectly reinforces the importance of implementing parents' intervention programs to foster home literacy and numeracy practices. These interventions might reduce the negative impact of SES on children's early literacy and numeracy skills and possibly on future academic achievements. Particular attention should be given to low-SES populations for whom intervention programs might be of specific relevance and impact. This study also suggests that parents' intervention programs should focus on both literacy and numeracy activities.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Bioethics Committee of the University of Bologna. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

## AUTHOR CONTRIBUTIONS

BP and PB conceived the presented idea, developed the assessment protocol, and wrote a preliminary version of the manuscript. BP carried out the experiment and collected and analyzed the data. DC and PB performed the statistical analyses. AF and BP contributed to the interpretation of the results. AF, BP, and PB revised and significantly contributed to the final version of the manuscript. All authors discussed the results and contributed to the final manuscript.

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## REFERENCES


Adler, N. E., and Newman, K. (2002). Socio-economic disparities in health: pathways and policies. *Health Affairs* 21, 60–76. doi: 10.1377/hlthaff.21.2.60

Anders, Y., Rossbach, H. G., Weinert, S., Ebert, S., Kuger, S., Lehrl, S., et al. (2012). Home and preschool learning environments and their relations to the development of early numeracy skills. *Early Child. Res. Q.* 27, 231–244. doi: 10.1016/j.ecresq.2011.08.003

Arbuckle, J. L. (2016). *Amos (Version 26.0) [Computer Program]*. Chicago: IBM SPSS.

Baird, K. (2012). Class in the classroom: The relationship between school resources and math performance among low socio-economic status students in 19 rich countries. *Educ. Eco.* 20, 484–509. doi: 10.1080/09645292.2010.511848

Baker, C. E. (2014). Mexican mothers' English proficiency and children's school readiness: mediation through home literacy involvement. *Early Educ. Dev.* 25, 338–355. doi: 10.1080/10409289.2013.807721

Bellocchi, S., Tobia, V., and Bonifacci, P. (2017). Predictors of reading and comprehension abilities in bilingual and monolingual children: A longitudinal study on a transparent language. *Read. Writ.* 30, 1311–1334.

Benzies, K., and Mychasiuk, R. (2009). Fostering family resiliency: A review of the key protective factors. *Child Family Soc. Work* 14, 103–114. doi: 10.1111/j.1365-2206.2008.00586.x

Bernabini, L., Bonifacci, P., and de Jong, P. F. (2021). The relationship of reading abilities with the underlying cognitive skills of math: a dimensional approach. *Front. Psychol.* 12:577488. doi: 10.3389/fpsyg.2021.577488

Bernabini, L., Tobia, V., Guarini, A., and Bonifacci, P. (2020b). Predictors of children's early numeracy: environmental variables, intergenerational pathways, and children's cognitive, linguistic, and non-symbolic number skills. *Front. Psychol.* 11:505065. doi: 10.3389/fpsyg.2020.505065

Bernabini, L., Tobia, V., and Bonifacci, P. (2020a). Intergenerational features of math skills: symbolic and non-symbolic magnitude comparison and written calculation in mothers and children. *J. Cogn. Dev.* 22, 149–167. doi: 10.1080/15248372.2020.1844711

Blevins-Knabe, B., Austin, A. B., Musun, L., Eddy, A., and Jones, R. M. (2000). Family home care providers' and parents' beliefs and practices concerning mathematics with young children. *Early Child Dev. Care* 165, 41–58. doi: 10.1080/0300443001650104

Blevins-Knabe, B., and Musun-Miller, L. (1996). Number use at home by children and their parents and its relationship to early mathematical performance. *Infant Child Dev.* 5, 35–45. doi: 10.1002/(sici)1099-0917(199603)5:1<35::aid-edp113>3.0.co;2-0

Bollen, K. A., Glanville, J. L., and Stecklov, G. (2001). Socio-economic status and class in studies of fertility and health in developing countries. *Annu. Rev. Sociol.* 27, 153–185. doi: 10.1146/annurev.soc.27.1.153

Bonifacci, P., Lombardo, G., Pedrinazzi, J., Terracina, F., and Palladino, P. (2020). Literacy skills in bilinguals and monolinguals with different SES. *Read. Writ. Q.* 36, 243–259. doi: 10.1080/10573569.2019.1635057

Bonifacci, P., Pellizzari, C., Giuliano, P., and Serra, P. (2015). *IDA - Indicatori delle Difficoltà di Apprendimento*. Firenze: Hogrefe Editore.

Bonifacci, P., Tobia, V., Bernabini, L., and Marzocchi, G. M. (2016). Early literacy and numeracy skills in bilingual minority children: Toward a relative independence of linguistic and numerical processing. *Front. Psychol.* 7:1020. doi: 10.3389/fpsyg.2016.01020

Bonifacci, P., Trambagioli, N., Bernabini, L., and Tobia, V. (2021). Home activities and cognitive skills in relation to early literacy and numeracy: Testing a multifactorial model in preschoolers. *Eur. J. Psychol. Educ.* doi: 10.1007/s10212-021-00528-2 [Epub ahead of print].

Bradley, R. H., and Corwyn, R. F. (2002). Socio-economic status and child development. *Annu. Rev. Psychol.* 53, 371–399.

Braham, E. J., and Libertus, M. E. (2017). Intergenerational associations in numerical approximation and mathematical abilities. *Dev. Sci.* 20:desc.12436. doi: 10.1111/desc.12436

Braham, E. J., Libertus, M. E., and McCrink, K. (2018). Children's spontaneous focus on number before and after guided parent–child interactions in a children's museum. *Dev. Psychol.* 54:1492. doi: 10.1037/dev0000534

Brese, F., and Mirazchiyski, P. (2013). *Measuring students' family background in large-scale international education studies. Issues and methodologies in large-scale assessments. Special issue 2. IERI Monograph series*. Hamburg: IERI.

Broer, M., Bai, Y., and Fonseca, F. (2019). *Socio-economic inequality and educational outcomes: Evidence from twenty years of TIMSS*. Cham: Springer Open.

Browne, M. W., and Cudeck, R. (1993). "Alternative ways of assessing model fit," in *Testing Structural Equation Models,* eds K. A. Bollen, and J. S. Long (Newbury Park, CA: Sage), 136–162.

Buckingham, J., Beaman, R., and Wheldall, K. (2014). Why poor children are more likely to become poor readers: The early years. *Educ. Rev.* 66, 428–446.

Burani, C., Barca, L., and Arduino, L. S. (2001). Una base di dati sui valori di età di acquisizione, frequenza, familiarità, immaginabilità, concretezza, e altre variabili lessicali e sublessicali per 626 nomi dell'italiano [Dataset on age of acquisition, familiarity, imageability, concreteness, and other lexical and sublexical variables for 626 Italian words]. *G. Ital. Psicol.* 28, 839–856.

Caravolas, M., Lervåg, A., Defior, S., Seidlová Málková, G., and Hulme, C. (2013). Different patterns, but equivalent predictors, of growth in reading in consistent and inconsistent orthographies. *Psychol. Sci.* 24, 1398–1407. doi: 10.1177/0956797612473122

Case, A., Lubotsky, D., and Paxson, C. (2002). Economic status and health in childhood: The origins of the gradient. *Am. Econ. Rev.* 92, 1308–1334. doi: 10.1257/000282802762024520

Cirino, P. T., Child, A. E., and Macdonald, K. T. (2018). Longitudinal predictors of the overlap between reading and math skills. *Contemp. Educ. Psychol.* 54, 99–111. doi: 10.1016/j.cedpsych.2018.06.002

Clarke, B., and Shinn, M. R. (2004). A preliminary investigation into the identification and development of early mathematics curriculum-based measurement. *School Psychol. Rev.* 33:234. doi: 10.1080/02796015.2004.12086245

Davis-Kean, P. E. (2005). The influence of parent education and family income on child achievement: The indirect role of parental expectations and the home environment. *J. Family Psychol.* 19, 294–304. doi: 10.1037/0893-3200.19.2.294

de Keyser, L., Bakker, M., Rathé, S., Wijns, N., Torbeyns, J., Verschaffel, L., et al. (2020). No association between the home math environment and numerical and patterning skills in a large and diverse sample of 5-to 6-year-olds. *Front. Psychol.* 11:547626. doi: 10.3389/fpsyg.2020.547626

DeFlorio, L., and Beliakoff, A. (2015). Socio-economic status and preschoolers' mathematical knowledge: The contribution of home activities and parent beliefs. *Early Educ. Dev.* 26, 319–341. doi: 10.1080/10409289.2015.968239

Dehaene, S. (1992). Varieties of numerical abilities. *Cognition* 44, 1–42. doi: 10.1016/0010-0277(92)90049-n

Dehaene, S. (2001). Précis of the number sense. *Mind Lang.* 16, 16–36.

Duan, B. (1997). *The robustness of trimming and Winsorization when the population distribution is skewed*. Unpublished dissertation. New Orleans: Tulane University.

Duncan, G. J., and Magnuson, K. (2011). The nature and impact of early achievement skills, attention skills, and behavior problems. *Whither Opport.* 2011, 47–70.

Ehri, L. C., Nunes, S. R., Willows, D. M., Schuster, B. V., Yaghoub-Zadeh, Z., and Shanahan, T. (2001). Phonemic awareness instruction helps children learn to read: evidence from the national reading Panel's meta-analysis. *Read. Res. Q.* 36, 250–287. doi: 10.1598/rrq.36.3.2

Elliott, L. (2020). Sources of heterogeneity in the home learning environments of socioeconomically disadvantaged families. *J. Appl. Dev. Psychol.* 70:101190.

Elliott, L., and Bachman, H. J. (2018). SES disparities in early math abilities: The contributions of parents' math cognitions, practices to support math, and math talk. *Dev. Rev.* 49, 1–15. doi: 10.1016/j.dr.2018.08.001

Elliott, L., Braham, E. J., and Libertus, M. E. (2017). Understanding sources of individual variability in parents' number talk with young children. *J. Exp. Child Psychol.* 159, 1–15. doi: 10.1016/j.jecp.2017.01.011

Evans, M. A., Shaw, D., and Bell, M. (2000). Home literacy activities and their influence on early literacy skills. *Can. J. Exp. Psychol.* 54, 65–75.

Foorman, B. R., Herrera, S., Petscher, Y., Mitchell, A., and Truckenmiller, A. (2015). The structure of oral language and reading and their relation to comprehension in Kindergarten through Grade 2. *Read. Writ.* 28, 655–681.

Foy, J., and Mann, V. (2003). Home literacy environment and phonological awareness in preschool children: Differential effects for rhyme and phoneme awareness. *Appl. Psychol.* 24, 59–88. doi: 10.1017/s0142716403000043

Galindo, C., and Sonnenschein, S. (2015). Decreasing the SES math achievement gap: Initial math proficiency and home learning environments. *Contemp. Educ. Psychol.* 43, 25–38. doi: 10.1016/j.cedpsych.2015.08.003

Gallistel, C. R., and Gelman, R. (1992). Preverbal and verbal counting and computation. *Cognition* 44, 43–74. doi: 10.1016/0010-0277(92)90050-r

Gallistel, C. R., and Gelman, R. (2000). Non-verbal numerical cognition: From reals to integers. *Trends Cogn. Sci.* 4, 59–65. doi: 10.1016/s1364-6613(99)01424-2

Gaskin, J., James, M., and Lim, J. (2020). *"Indirect Effects", AMOS Plugin. Gaskination's StatWiki.* Available online at: http://statwiki.gaskination.com/index.php?title=Plugins

Girolametto, L., Bonifacio, S., Visini, C., Weitzman, E., Zocconi, E., and Pearce, P. (2002). Mother-child interactions in Canada and Italy: Linguistic responsiveness to late-talking toddlers. *Int. J. Lang. Commun. Disord.* 37, 153–171. doi: 10.1080/13682820110116794

Göbel, S. M., Watson, S. E., Lervåg, A., and Hulme, C. (2014). Children's arithmetic development: it is number knowledge, not the approximate number sense, that counts. *Psychol. Sci.* 25, 789–798. doi: 10.1177/0956797613516471

Guo, Y., Puranik, C., Kelcey, B., Sun, J., Dinnesen, M. S., and Breit-Smith, A. (2020). The role of home literacy practices in kindergarten children's early writing development: A one-year longitudinal study. *Early Educ. Dev.* 32, 1–19. doi: 10.1080/13670050.2021.1943304

Hannon, P., Nutbrown, C., and Morgan, A. (2020). Effects of extending disadvantaged families' teaching of emergent literacy. *Res. Papers Educ.* 35, 310–336. doi: 10.1080/02671522.2019.1568531

Hauser, M., Chomsky, N., and Fitch, W. (2010). "The faculty of language: What is it, who has it, and how did it evolve?," in *The Evolution of Human Language: Biolinguistic Perspectives*, eds R. Larson, V. Déprez, and H. Yamakido (Cambridge: Cambridge University Press), 14–42. doi: 10.1017/cbo9780511817755.002

Hecht, S. A., Torgesen, J. K., Wagner, R. K., and Rashotte, C. A. (2001). The relations between phonological processing abilities and emerging individual differences in mathematical computation skills: A longitudinal study from second to fifth grades. *J. Exper. Child Psychol.* 79, 192–227.

Hemmerechts, K., Agirdag, O., and Kavadias, D. (2017). The relationship between parental literacy involvement, socio-economic status, and reading literacy. *Educ. Rev.* 69, 85–101. doi: 10.1080/00131911.2016.1164667

Hodges, J., and Lehmann, E. L. (1956). The efficiency of some non-parametric competitors of the t-test. *Ann. Math. Stat.* 27, 324–335.

Hoff, E. (2003). "Causes and consequences of SES-related differences in parent-to-child speech," in *Monographs in parenting series. Socio-economic status, parenting, and child development*, eds M. H. Bornstein and R. H. Bradley (Mahwah, NJ: Lawrence Erlbaum Associates Publishers), 147–160.

Hoff, E. (2013). Interpreting the early language trajectories of children from low-SES and language minority homes: Implications for closing achievement gaps. *Dev. Psychol.* 49:4. doi: 10.1037/a0027238

Hofslundsengen, H., Gustafsson, J. E., and Hagtvet, B. E. (2019). Contributions of the home literacy environment and underlying language skills to preschool invented writing. *Scandinavian J. Educ. Res.* 63, 653–669. doi: 10.1080/00313831.2017.1420686

Hollingshead, A. B. (2011). Four factor index of social status. *Yale J. Sociol.* 8, 21–51.

Hood, M., Conlon, E., and Andrews, G. (2008). Preschool home literacy practices and children's literacy development: A longitudinal analysis. *J. Educ. Psychol.* 100:252. doi: 10.1037/0022-0663.100.2.252

Hsu, H. C., and Lavelli, M. (2005). Perceived and observed parenting behavior in American and Italian first time mothers across the first 3 months. *Infant Behav. Dev.* 28, 503–518.

Hu, L. T., and Bentler, P. M. (1999). Cutoff criteria for fit indexes in covariance structure analysis: Conventional criteria versus new alternatives. *Struc. Equation Model. Multidiscip. J.* 6, 1–55. doi: 10.1080/10705519909540118

Hulme, C., Nash, H. M., Gooch, D., Lervåg, A., and Snowling, M. J. (2015). The foundations of literacy development in children at familial risk of dyslexia. *Psychol. Sci.* 26, 1877–1886. doi: 10.1177/0956797615603702

Huntley-Fenner, G., and Cannon, E. (2000). Preschoolers' magnitude comparisons are mediated by a preverbal analog mechanism. *Psychol. Sci.* 11, 14 7–152.

Huntsinger, C. S., Jose, P. E., and Luo, Z. (2016). Parental facilitation of early mathematics and reading skills and knowledge through encouragement of home-based activities. *Early Child. Res. Q.* 37, 1–15. doi: 10.1016/j.ecresq.2016.02.005

Inoue, T., Manolitsis, G., de Jong, P. F., Landerl, K., Parrila, R., and Georgiou, G. K. (2020). Home literacy environment and early literacy development across languages varying in orthographic consistency. *Front. Psychol.* 11:1923. doi: 10.3389/fpsyg.2020.01923

Jordan, N. C., and Levine, S. C. (2009). Socio-economic variation, number competence, and mathematics learning difficulties in young children. *Dev. Disabil. Res. Rev.* 15, 60–68. doi: 10.1002/ddrr.46

Kenny, D. A. (2011). *Respecification of latent variable models*. Available online at: http://davidakenny.net/cm/respec.htm (accessed January, 2021).

Kleemans, T., Peeters, M., Segers, E., and Verhoeven, L. (2012). Child and home predictors of early numeracy skills in kindergarten. *Early Child. Res. Q.* 27, 471–477. doi: 10.1016/j.ecresq.2011.12.004

Kleemans, T., Segers, E., and Verhoeven, L. (2016). Relations between home numeracy experiences and basic calculation skills of children with and without specific language impairment. *Early Child. Res. Q.* 28, 415–423.

Kline, R. B. (2010). *Principles and Practice of Structural Equation Modeling,* 3rd Edn. New York, NY: Guilford Press.

Koponen, T., Eklund, K., Heikkilä, R., Salminen, J., Fuchs, L., Fuchs, D., et al. (2020). Cognitive correlates of the covariance in reading and arithmetic fluency: Importance of serial retrieval fluency. *Child Dev.* 91, 1063–1080. doi: 10.1111/cdev.13287

LeFevre, J. A., Polyzoi, E., Skwarchuk, S. L., Fast, L., and Sowinski, C. (2010). Do home numeracy and literacy practices of Greek and Canadian parents predict the numeracy skills of kindergarten children? *Int. J. Early Years Educ.* 18, 55–70. doi: 10.1080/09669761003693926

LeFevre, J. A., Skwarchuk, S. L., Smith-Chant, B. L., Fast, L., Kamawar, D., and Bisanz, J. (2009). Home numeracy experiences and children's math performance in the early school years. *Can. J. Behav. Sci.* 41:55. doi: 10.1037/a0014532

Levine, S. C., Jordan, N. C., and Huttenlocher, J. (1992). Development of calculation abilities in young children. *J. Exper. Child Psychol.* 53, 72–103. doi: 10.1016/s0022-0965(05)80005-0

Leyva, D., Tamis-LeMonda, C. S., Yoshikawa, H., Jimenez-Robbins, C., and Malachowski, L. (2017). Grocery games: How ethnically diverse low-income mothers support children's reading and mathematics. *Early Child. Res. Q.* 40, 63–76. doi: 10.1016/j.ecresq.2017.01.001

Linver, M. R., Brooks-Gunn, J., and Kohen, D. E. (2002). Family processes as pathways from income to young children's development. *Dev. Psychol.* 38, 719–734. doi: 10.1037/0012-1649.38.5.719

Manolitsis, G., Georgiou, G. K., and Tziraki, N. (2013). Examining the effects of home literacy and numeracy environment on early reading and math acquisition. *Early Child. Res. Q.* 28, 692–703. doi: 10.1016/j.ecresq.2013.05.004

Marsh, H. W., Balla, J. R., and McDonald, R. P. (1988). Goodness-of-fit indexes in confirmatory factor analysis: The effect of sample size. *Psychol. Bull.* 103:391. doi: 10.1037/0033-2909.103.3.391

Melhuish, E. C., Phan, M. B., Sylva, K., Sammons, P., Siraj-Blatchford, I., and Taggart, B. (2008). Effects of the home learning environment and preschool center experience upon literacy and numeracy development in early primary school. *J. Soc. Issues* 64, 95–114. doi: 10.1111/j.1540-4560.2008.00550.x

Mistry, R. S., Benner, A. D., Biesanz, J. C., and Clark, S. L. (2010). Family and social risk, and parental investments during the early childhood years as predictors of low-income children's school readiness outcomes. *Early Child. Res. Q.* 25, 432–449. doi: 10.1016/j.ecresq.2010.01.002

Mutaf Yildiz, B., Sasanguie, D., De Smedt, B., and Reynvoet, B. (2018). Investigating the relationship between two home numeracy measures: A questionnaire and observations during Lego building and book reading. *Br. J. Dev. Psychol.* 36, 354–370. doi: 10.1111/bjdp.12235

Mutaf- Yildiz, B., Sasanguie, D., De Smedt, B., and Reynvoet, B. (2020). Probing the relationship between home numeracy and children's mathematical skills: A systematic review. *Front. Psychol.* 11:2074.

Napoli, A. R., and Purpura, D. J. (2018). The home literacy and numeracy environment in preschool: Cross-domain relations of parent-child practices and child outcomes. *J. Exper. Child Psychol.* 166, 581–603. doi: 10.1016/j.jecp.2017.10.002

Navarro, M. G., Braham, E. J., and Libertus, M. E. (2018). Intergenerational associations of the approximate number system in toddlers and their parents. *Br. J. Dev. Psychol.* 36, 521–539. doi: 10.1111/bjdp.12234

Niklas, F., and Schneider, W. (2014). Casting the die before the die is cast: The importance of the home numeracy environment for preschool children. *Eur. J. Psychol. Educ.* 29, 327–345. doi: 10.1007/s10212-013-0201-6

Pan, Y., Gauvain, M., Liu, Z., and Cheng, L. (2006). American and Chinese parental involvement in young children's mathematics learning. *Cogn. Dev.* 21, 17–35. doi: 10.1016/j.cogdev.2005.08.001

Park, H. (2008). Home literacy environments and children's reading performance: A comparative study of 25 countries. *Educ. Res. Eval.* 14, 489–505. doi: 10.1080/13803610802576734

Payne, A. C., Whitehurst, G. J., and Angell, A. L. (1994). The role of home literacy environment in the development of language ability in preschool children from low-income families. *Early Child. Res. Q.* 9, 427–440. doi: 10.1016/0885-2006(94)90018-3

Puranik, C. S., Phillips, B. M., Lonigan, C. J., and Gibson, E. (2018). Home literacy practices and preschool children's emergent writing skills: An initial investigation. *Early Child. Res. Q.* 42, 228–238. doi: 10.1016/j.ecresq.2017.10.004

Purpura, D. J., and Logan, J. A. R. (2015). The non-linear relations of the approximate number system and mathematical language to early mathematics development. *Dev. Psychol.* 51, 1717–1724. doi: 10.1037/dev0000055

Reardon, S. F., and Portilla, X. A. (2016). Recent trends in income, racial, and ethnic school readiness gaps at kindergarten entry. *Aera Open* 2:233285841665734. doi: 10.1177/2332858416657343

Reutzel, D. R., Fawson, P. C., and Smith, J. A. (2005). Words to go!: Evaluating a first-grade parent involvement program for "making" words at home. *Literacy Res. Instruc.* 45, 119–159. doi: 10.1080/19388070609558445

Richman, A. L., LeVine, R. A., New, R. S., Howrigan, G. A., Welles-Nystrom, B., and LeVine, S. E. (1988). Maternal behavior to infants in five cultures. *New Dir. Child Dev.* 40, 81–97. doi: 10.1002/cd.23219884010

Roberts, J., Jergens, J., and Burchinal, M. (2005). The role of home literacy practices in preschool children's language and emergent literacy skills. *J. Speech. Lang. Hear. Res.* 48, 345–359. doi: 10.1044/1092-4388(2005/024)

Saint-Laurent, L., and Giasson, J. (2005). Effects of a family literacy program adapting parental intervention to first graders' evolution of reading and writing abilities. *J. Early Child. Literacy* 5, 253–278. doi: 10.1177/1468798405058688

Sénéchal, M. (2006). Testing the home literacy model: Parent involvement in kindergarten is differentially related to grade 4 reading comprehension, fluency, spelling, and reading for pleasure. *Sci. Stud. Read.* 10, 59–87. doi: 10.1207/s1532799xssr1001_4

Sénéchal, M., and LeFevre, J. A. (2002). Parental involvement in the development of children's reading skill: A five-year longitudinal study. *Child Dev.* 73, 4 45–460.

Sénéchal, M., LeFevre, J. A., Thomas, E. M., and Daley, K. E. (1998). Differential effects of home literacy experiences on the development of oral and written language. *Read. Res. Q.* 33, 96–116. doi: 10.1598/rrq.33.1.5

Sénéchal, M., Whissell, J., and Bildfell, A. (2017). Starting from home: Home literacy practices that make a difference. *Theor.Read. Dev.* 15:383.

Silinskas, G., Leppänen, U., Aunola, K., Parrila, R., and Nurmi, J. E. (2010). Predictors of mothers' and fathers' teaching of reading and mathematics during kindergarten and Grade 1. *Learn. Instruc.* 20, 61–71. doi: 10.1016/j.learninstruc.2009.01.002

Sim, F., Thompson, L., Marryat, L., Ramparsad, N., and Wilson, P. (2019). Predictive validity of preschool screening tools for language and behavioural difficulties: A PRISMA systematic review. *PloS One* 14:e0211409. doi: 10.1371/journal.pone.0211409

Sirin, S. R. (2005). Socio-economic status and academic achievement: a metanalytic review of research. *Rev. Educ. Res.* 75, 417–453. doi: 10.3102/00346543075003417

Skwarchuk, S. L., Sowinski, C., and LeFevre, J. A. (2014). Formal and informal home learning activities in relation to children's early numeracy and literacy skills: The development of a home numeracy model. *J. Exper. Child Psychol.* 121, 63–84. doi: 10.1016/j.jecp.2013.11.006

Soto-Calvo, E., Simmons, F. R., Adams, A. M., Francis, H. N., Patel, H., and Giofrè, D. (2020). Identifying the preschool home learning experiences that predict early number skills: Evidence from a longitudinal study. *Early Child. Res. Q.* 53, 314–328. doi: 10.1016/j.ecresq.2020.04.004

Stephenson, K. A., Parrila, R. K., Georgiou, G. K., and Kirby, J. R. (2008). Effects of home literacy, parents' beliefs, and children's task-focused behavior on emergent literacy and word reading skills. *Sci. Stud. Read.* 12, 24–50.

Suggate, S., Schaughency, E., McAnally, H., and Reese, E. (2018). From infancy to adolescence: The longitudinal links between vocabulary, early literacy skills, oral narrative, and reading comprehension. *Cogn. Dev.* 47, 82–95. doi: 10.1016/j.cogdev.2018.04.005

Tobia, V., Bonifacci, P., and Marzocchi, G. M. (2016). Concurrent and longitudinal predictors of calculation skills in preschoolers. *Eur. J. Psychol. Educ.* 31, 155–174. doi: 10.1007/s10212-015-0260-y

Tobia, V., Bonifacci, P., and Marzocchi, G. M. (2018). *SNUP - Senso del Numero: Prerequisiti*. Firenze: Hogrefe editore.

Torppa, M., Poikkeus, A. M., Laakso, M. L., Eklund, K., and Lyytinen, H. (2006). Predicting delayed letter name knowledge development and its relation to grade 1 reading achievement among children with and without familial risk for dyslexia. *Dev. Psychol.* 4, 1128–1142. doi: 10.1037/0012-1649.42.6.1128

Trochim, W. M., and Donnelly, J. P. (2006). *The Research Methods Knowledge Base*, 3rd Edn. Cincinnati, OH: Atomic Dog.

van Steensel, R. (2006). Relations between socio-cultural factors, the home literacy environment and children's literacy development in the first years of primary education. *J. Res. Read.* 29, 367–382. doi: 10.1111/j.1467-9817.2006.00301.x

von Aster, M. G., and Shalev, R. S. (2007). Number development and developmental dyscalculia. *Dev. Med. Child Neurol.* 49, 868–873. doi: 10.1111/j.1469-8749.2007.00868.x

Wagner, J. B., and Johnson, S. C. (2011). An association between understanding cardinality and analog magnitude representations in preschoolers. *Cognition* 119, 10–22. doi: 10.1016/j.cognition.2010.11.014

Westermann, G., Mareschal, D., Johnson, M. H., Sirois, S., Spratling, M. W., and Thomas, M. S. (2007). Neuroconstructivism. *Dev. Sci.* 10, 75–83.

Wilcox, R. R. (2010). *Fundamentals of Modern Statistical Methods: Substantially Improving Power and Accuracy*, 2nd Edn. New York: Springer.

Wollman-Bonilla, J. E. (2001). Family involvement in early writing instruction. *J. Early Child. Literacy* 1, 167–192. doi: 10.1177/14687984010012003

Xu, F., Spelke, E. S., and Goddard, S. (2005). Number sense in human infants. *Dev. Sci.* 8, 88–101. doi: 10.1111/j.1467-7687.2005.00395.x

Yuan, K.-H., Chan, W., Marcoulides, G. A., and Bentler, P. M. (2016). Assessing structural equation models by equivalence testing with adjusted fit indexes. *Struc. Equat. Model.* 23, 3 19–330.

Zadeh, Z. Y., Farnia, F., and Ungerleider, C. (2010). How home enrichment mediates the relationship between maternal education and children's achievement in reading and math. *Early Educ. Dev.* 21, 568–594. doi: 10.1080/10409280903118424

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# Anxiety, Motivation, and Competence in Mathematics and Reading for Children With and Without Learning Difficulties

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Knowledge of the relations among learners' socio-emotional characteristics and competencies as they engage in mathematics and reading is limited, especially for children with academic difficulties. This study examined the relations between anxiety, motivation, and competence in mathematics and reading, within and across domains, in an academically-diverse set of 8–13-year-old learners ($n = 146$). To measure anxiety and motivation across domains, we paired existing measures of math anxiety and reading motivation with researcher-developed analogs for reading anxiety and math motivation. Participants completed standardized assessments of mathematics and reading, anxiety and motivation surveys for math and reading, and a measure of nonverbal cognitive ability. Results showed high internal consistency for all anxiety and motivation scales (Cronbach's alpha = 0.76–0.91). Pearson correlations showed that within and across domains, participants with higher competence had lower anxiety and higher motivation. Higher anxiety was also associated with lower motivation. Regression analyses showed that for both math and reading, within-domain motivation was a stronger predictor of competence than anxiety. There was a unidirectional across-domain relation: socio-emotional characteristics for reading predicted math competence, after accounting for nonverbal cognitive ability, age, gender, and within-domain anxiety and motivation. Results contribute to knowledge of the socio-emotional characteristics of children with and without learning difficulties in association with reading and math activities. Implications of a unidirectional socio-emotional link between the two domains can advance research and theory of the relations among socio-emotional characteristics and competence for academically-diverse learners.

**Keywords: mathematics, reading, anxiety, motivation, competence, learning difficulties**

## INTRODUCTION

Socio-emotional characteristics, such as anxiety and motivation, are important for schooling and beyond. As examples, learners with high levels of math anxiety may avoid math during schooling (Hembree, 1990), postsecondary education, and career selection (e.g., Ashcraft, 2002). Learners with higher motivation to read tend to have higher reading performance in middle grades and secondary school (Retelsdorf et al., 2011; Froiland and Oros, 2014). Whether socio-emotional characteristics affect skill development across domains is also important, given that academic domains, such as math and reading, are interrelated (e.g., Duncan et al., 2007; Vanbinst et al., 2020b). Knowledge of the relations between anxiety, motivation, and competence in math and reading within and across domains is limited, especially for children who struggle in math, reading, or both. Such knowledge can illuminate important contextual factors for learners across domains, to help reduce barriers to learning, and to identify potential mechanisms of resilience. In this study, we examine elementary school children's anxiety, motivation, and competence within and across math and reading for those with and without learning disabilities.

The most well-studied socio-emotional construct in math is anxiety. Math anxiety is domain-specific apprehension, fear, or worry when engaging with math content (e.g., Ashcraft, 2002; Dowker, 2019a). Math anxiety manifests physiologically (Dowker et al., 2016; Suárez-Pellicioni et al., 2016; Ramirez et al., 2018), can be transmitted intergenerationally (Vanbinst et al., 2020a) and in the classroom (Beilock et al., 2010), and is higher in girls than in boys, on average, in as early as primary school (Dowker et al., 2016; Hill et al., 2016). There is a well-established link between higher levels of math anxiety and lower math competence across childhood, adolescence, and adulthood (Dowker et al., 2016; Foley et al., 2017; Dowker, 2019a) that begins in the early grades (Ma, 1999; Wu et al., 2012; Barroso et al., 2021; Szczygieł and Pieronkiewicz, 2021). This relation between math anxiety and math competence also holds for children with math disability, which is a difficulty in arithmetic and numerosity processing (Rubinsten and Tannock, 2010). While children with math disability may be more likely to have high math anxiety, most math anxious individuals are typically- or high-achieving (Devine et al., 2018), which underscores the importance of understanding math anxiety across a range of learners.

Compared to math anxiety, other socio-emotional characteristics of math, like motivation, have received less attention (see Dowker, 2019a). One reason may be that people may be more anxious about math than other subjects (Punaro and Reeve, 2012; Dowker et al., 2016; Dowker, 2019b). Math motivation has been operationalized in myriad and partially-overlapping ways, such as interest, engagement, enjoyment, self-perceived abilities, and self-efficacy (Kriegbaum et al., 2015; Baten et al., 2019). Generally, higher math motivation or attitudes toward math have been associated with lower math anxiety (Hembree, 1990; Zakaria and Nordin, 2008; Jain and Dowson, 2009; Jameson, 2014; Luttenberger et al., 2018). Math anxiety and positive attitudes may show an inverse relation generally, but they are not opposite ends of the same spectrum. One framework offers that math attitudes can be considered a cognitive factor, while math anxiety can be considered an emotional factor (Dowker et al., 2016). In other words, positive attitudes are not the mere absence of anxiety. For instance, research has shown positive relations between math attitudes and math achievement that persist when controlling for anxiety (Villavicencio and Bernardo, as cited in Dowker, 2019b). Higher math motivation or attitudes toward math are also associated with higher math competence (Zakaria and Nordin, 2008; Krinzinger et al., 2009; Seaton et al., 2014; Kriegbaum et al., 2015; Arens et al., 2017; Lohbeck, 2018) in adults and children (but see Wang et al., 2015). Math motivation may mediate the relation between math anxiety and competence (Justicia-Galiano et al., 2017). Math anxiety and motivation may be reciprocally related across time (e.g., Gunderson et al., 2018). Additional research is needed to inform how math anxiety and motivation relate to math competence across children with and without learning disabilities.

The reading domain has an opposite story: a growing but limited body of literature on reading anxiety and a more developed body of literature on reading motivation. Reading anxiety—negative emotional, cognitive, and physiological reactions to reading (Jalongo and Hirsh, 2010; Piccolo et al., 2017)—has received little attention (Piccolo et al., 2017). Prior research has mostly focused on relations between reading and general or trait anxiety, with higher levels of anxiety among adults and children with reading disabilities compared to typical readers (Casey et al., 1992; Carroll et al., 2005; Carroll and Iles, 2006; Grills-Taquechel et al., 2012; Grills et al., 2014; Elgendi et al., 2021; Hossain et al., 2021). Other socio-emotional characteristics of reading, including motivation, have received comparatively more attention. Reading motivation has been conceptualized in various ways such as self-concept; beliefs about reading, reading attitudes, or interest (see Conradi et al., 2014); or engagement and persistence (Urdan and Schoenfelder, 2006). Generally, higher reading motivation has been associated with better reading competence (e.g., Chapman and Tunmer, 2003). Reading attitudes and perceptions have been positively associated with reading skills in adolescents (Conlon et al., 2006) and higher self-concept has been associated with higher reading competence for children (Chapman and Tunmer, 1995).

With so few studies on reading anxiety, knowledge of the relations among reading anxiety, motivation, and competence is limited, but emerging. Katzir et al. (2018) examined the relations among reading anxiety, reading self-concept, and reading competence in 7–9-year-old Israeli children. The authors found that higher reading anxiety was associated with lower reading self-concept. They also found differences by gender, in which girls had higher reading anxiety and lower reading self-concept than boys, despite having higher reading accuracy. In another study, Ramirez et al. (2019) examined the relations among reading anxiety, reading affect (i.e., enjoyment), and reading competence for first and second grade U.S. children (roughly ages 6–8). They found that higher levels of reading anxiety were associated with lower reading competence, on average, and that reading anxiety was more strongly related to reading competence than positive reading affect. In contrast to Katzir et al. (2018), Ramirez et al. (2019) found that boys were more susceptible to the effects of reading anxiety compared to girls. Scale, construct, and cross-cultural differences may contribute to a lack of convergence of findings across studies. Together, these studies illustrate that relations among reading anxiety, motivation, and competence in children need further examination.

Beyond further clarification of the relations between socio-emotional characteristics and competence within domain, the interrelation of math and reading suggests the need for research across domains. Math and reading skills are already interrelated for young children. Vanbinst et al. (2020b) found that phonological awareness and numeral recognition correlated with both early arithmetic and early reading skills in 5-year-old children. The authors concluded that phonological awareness and numeral recognition were shared cognitive correlates of math and reading. Cui et al. (2019) found that visual form perception of geometric shapes related to both reading and arithmetic skills in elementary school children. Neuroimaging research suggests shared functional neural correlates for arithmetic and phonological processing in children (Pollack and Ashby, 2018; Kersey et al., 2019). This cross-domain relation between math and reading also holds for children with learning disabilities. Children with reading disabilities (e.g., dyslexia) struggle with aspects of math, especially arithmetic fact fluency (Simmons and Singleton, 2008; Boets and De Smedt, 2010; De Smedt and Boets, 2010; Vukovic et al., 2010; Evans et al., 2014; Koerte et al., 2016). Even with a normal range of math performance, children with dyslexia are less accurate and slower with fact retrieval than their typically-developing peers (Boets and De Smedt, 2010). Added to these interrelations is a substantial comorbidity of math and reading learning disabilities (Barbaresi et al., 2005; Kovas et al., 2007; Dirks et al., 2008; Landerl and Moll, 2010). These interrelations suggest that socio-emotional characteristics in one domain may relate to competence in another, especially across academically-diverse learners.

The mechanisms through which domain-specific anxiety, motivation, and competence affect each other are not fully understood. Experiences doing math may affect socio-emotional characteristics toward math, which in turn may affect subsequent math experiences (e.g., Jansen et al., 2013; Dowker et al., 2016). Alternatively, higher anxiety in math may lead to math avoidance or reduced working memory, either of which may lead to lower math performance (for reviews see Carey et al., 2016; Dowker et al., 2016; Dowker, 2019b). Or, these relations may be bidirectional over time (e.g., Carey et al., 2016). The same potential mechanisms may operate in the reading domain (e.g., Katzir et al., 2018). We speculate that these mechanisms may also apply across math and reading for academically-diverse learners due to the relation of skills across domains. For instance, children who struggle with reading may have higher math anxiety and/or lower math motivation, which could be because phonological processing is related to math fact retrieval and because reading skills are used in other areas of math, like reading word problems.

In sum, within-domain relations among anxiety, motivation, and competence in math and in reading are already present for children in elementary (or primary) school. Yet, there are substantial differences in knowledge of the within-domain relations between socio-emotional characteristics and competence in math and reading across a range of learners. These differences make it difficult to understand their interrelation, particularly in young learners who may have math or reading disabilities, or both. Further, to the best of our knowledge, there are no existing studies focused on the relations among these socio-emotional characteristics and competencies across domains in academically-diverse learners.

We address these gaps by examining the relations among anxiety, motivation, and competence across math and reading for children with and without learning disabilities in math, reading, or both. To evaluate comparable factors in both reading and math in the same sample, we developed analogs to existing scales to create pairs of parallel measures for anxiety and motivation in math and reading. We then administered standardized measures of math and reading and the anxiety and motivation scales to an academically-diverse sample of children. We used multiple regression to examine whether socio-emotional characteristics within and across domain predicted academic competence and whether these relations persisted when controlling for nonverbal cognitive ability, age, and gender. We hypothesized that there would be relations among anxiety, motivation, and competence within each domain that would persist after controlling for nonverbal cognitive ability, age, and gender. Based on the interrelation of math and reading skills, we hypothesized that anxiety and motivation would relate to competence across domains, though within-domain relations would be stronger.

## MATERIALS AND METHODS

### Participants

Participants were 146 academically-diverse children 8–13 years old ($M = 10.8$, $SD = 1.1$; 47% male) who in the U.S were part of a larger study on math and reading disabilities. As part of the larger study, we used purposeful recruiting to seek an overrepresentation of children with learning disabilities compared to the general population (see section Group Characterizations). We wanted to examine the relations among anxiety, motivation, and competence within and across domains for the full range of learners. That is, we were interested in whether relations would apply across a large performance spectrum, with children who are lower performers, average performers, and higher performers across math and reading. With a sample of about 145, a representative sample of 15% with learning disabilities would result in only about 20 children, which seemed to us to be too small to examine the full range of achievement across both math and reading. Participants' racial and ethnic identities, based on the U.S. Census categories, were 73% White, 6% Asian, 4% Black/African American, 1% Hispanic/Latino, 13% more than one race, and 3% undisclosed.

To the best of our knowledge, there is a dearth of studies that simultaneously examine the relations of anxiety and motivation with competence across domain, which precluded an *a priori* power analysis based on existing effect sizes. Related studies on the relations between socio-emotional characteristics and competence within math and reading domains had sample sizes ranging from 115 to 167 (Krinzinger et al., 2009; Justicia-Galiano et al., 2017; Katzir et al., 2018), suggesting that the sample size of the present study was generally in line with prior research.

Participants were recruited through flyers in the community, online posting, a database of participants from prior studies, and through cross-promotion with other studies. The Committee on the Use of Humans as Experimental Subjects (COUHES) at the Massachusetts Institute of Technology approved the study. Parents or guardians provided consent and children provided assent to participate.

## Measures

Participants completed a comprehensive battery of language, reading, math, cognitive, and socio-emotional assessments as part of the larger study. The present study includes socio-emotional measures in math and reading, standardized assessments of math and reading, and a measure of nonverbal cognitive ability.

### Socio-Emotional Measures

#### *Anxiety*

Participants completed the Math Anxiety Scale for Young Children, Revised (i.e., MASYC-R; Ganley and McGraw, 2016). The MASYC-R is a 13-item scale that measures math anxiety overall and on three subscales: negative reactions (items 1–4), confidence (items 5–7), and worry (items 8–13). To measure reading anxiety, we created the Reading Anxiety Scale for Young Children (i.e., RASYC) using Ganley and McGraw's (2016) MASYC-R. To create the RASYC, we modified item language to reflect reading anxiety. As examples, we changed "Math gives me a stomach ache" to "Reading gives me a stomach ache" and "I like to raise my hand in math class" to "I like to raise my hand in reading/English class." Importantly, the math anxiety scale did not include questions that involved reading and the reading anxiety scale did not include questions that involved math. For example, the math anxiety scale did not include any questions about word problems. Scoring for the RASYC followed Ganley and McGraw's (2016) scoring for the MASYC-R. Scores for the negative reactions and worry subscales were scored as Yes = 4, Sometimes = 3, Not really = 2, No = 1. Confidence subscale items have reverse scoring (e.g., Yes = 1), such that a higher score is associated with lower confidence and for overall scores, a higher score is associated with greater anxiety.

#### *Motivation*

Participants completed the Motivation to Read Profile-Revised (i.e., MRP-R; Malloy et al., 2013). The MRP-R is a 20-item scale that measures motivation to read. The survey contains two subscales: self-concept (odd-numbered items) and value (even-numbered items). Each item has four answer choices (scored 1–4), with higher scores representing higher self-concept or value. Prior studies have operationalized math motivation in varied ways. In line with conceptualizations of reading motivation (Urdan and Schoenfelder, 2006; Malloy et al., 2013), we define math motivation as the willingness for children to engage and persist with math, measured by children's value of math and self-concept in math. To measure motivation, we created the Motivation for Math Profile (i.e., MMP) using Malloy et al.'s (2013) MRP-R. We modified item wording to reflect math instead of reading. As an example, for the self-concept item "My friends think I am ____" with response options of "a very good reader; a good reader; an OK reader; a poor reader," we changed the answer choices to "very good at math; good at math; OK at math; bad at math." As an example of a value item, we changed the stem "Reading is something I like to do" to "Doing math problems is something I like to do." The math motivation scale did not include questions that involved reading and the reading motivation scale did not include questions that involved math. Scoring for the MMP followed Malloy et al.'s (2013) scoring guide (p. 279) for overall motivation, and subscale scores for self-concept and value.

To standardize administration across children of different reading levels, we administered the scales orally in a quiet location. A researcher read each item stem and answer choices aloud to the child, while the researcher and child both looked at the scale on a computer screen. The researcher selected each answer that the child chose.

### Math and Reading Competence

We measured mathematical competence with two composites. The Broad Mathematics composite of the Woodcock Johnson-IV (Schrank et al., 2014) includes three subtests. Math Fluency is a timed 3-min test of addition, subtraction, and multiplication fact fluency. The Calculation subtest is an untimed written test of calculation problems from single-digit arithmetic through calculus. The Applied Problems subtest is an untimed test in which participants analyze and solve math problems. The Math Fluency composite of the Wechsler Individual Achievement Test-III (WIAT-III, Psychological Corporation, 2009) measures fact fluency with separate 1-min timed addition, subtraction, and multiplication tests.

We measured reading competence with two composites. The Total Word Reading Efficiency composite of the TOWRE-2 (Torgesen et al., 2012) is comprised of timed measures of sight word reading and pseudoword reading. The Basic Skills composite of the WRMT-III (Woodcock, 2011) includes untimed measures of word reading (Word Identification) and pseudoword reading (Word Attack). Analyses include age-adjusted standard scores for all competence measures (based on a mean of 100 and a standard deviation of 15).

### Nonverbal Cognitive Ability

We measured nonverbal cognitive ability using the Kaufman Brief Intelligence Test (KBIT-2; Kaufman and Kaufman, 2004) Matrices subtest, in which participants select which image fits into a matrix. We used a measure of nonverbal cognitive ability because scores on measures of verbal cognitive ability may be artificially lower for children with reading disability due to differences in exposure and background knowledge related to reading. To be included in the study, participants had to have a standard score of 80 or greater. Analyses include standard scores.

# Analyses

## Group Characterizations

To examine whether the sample was academically diverse with a relatively high prevalence of children with learning disabilities, we screened participants for having math and/or reading disability using the standard math and reading competence measures. Participants in the math disability only group had a history or diagnosis of math disability, scored below 90 on at least two of the math subtests, and scored at or above 90 on all reading subtests. Participants in the reading disability only group had a history or diagnosis of reading disability, scored below 90 on at least two of the reading subtests, and scored at or about 90 on all math subtests. Participants in the comorbid math and reading disability group had some history of math and reading disability, and scored below 90 on at least two math subtests and at least two reading subtests.

We also characterized participants without learning disabilities. These participants had no personal or family history of math or reading disability. They had standard scores at or above 90 on all math and reading subtests. Participants who did not fit any set of criteria did not belong to a group. As we show in section Group Characterizations: Incidence of Learning Disabilities below, group characterizations revealed sample sizes that were too small for group comparisons. Therefore, all analyses used a multiple regression approach with the full sample as we describe in section Socio-Emotional Measures and Competence Within and Across Domains.

## Socio-Emotional Measures and Competence Within and Across Domains

To examine reliability of the new and existing scales, we calculated Cronbach's alpha for each full scale and all subscales.

We used multiple regression to examine whether socio-emotional measures predicted competence within and across domain, while accounting for nonverbal cognitive ability, age, and gender. Because our research questions focus on anxiety and motivation, rather than specific aspects like value or worry, and due to the number of subscales across the four outcomes and four measures, analyses include full scale scores for socio-emotional and competence measures.

Equation (1) describes the model:

$$Y_i = \beta_0 + \beta_1 A_{1i} + \beta_2 A_{2i} + \beta_3 M_{1i} + \beta_4 M_{2i} + \beta_5 \boldsymbol{X}_i + e_i \quad (1)$$

In Equation (1), $Y_i$ refers to each outcome (i.e., Broad Mathematics, Math Fluency, Total Word Reading Efficiency, Basic Skills) for each participant $i$. $A_{1i}$ refers to the within-domain anxiety scale associated with $Y_i$. $A_{2i}$ refers to the across-domain anxiety scale for outcome $Y_i$ for participant $i$. $M_{1i}$ refers to the within-domain motivation scale associated with $Y_i$ and $M_{2i}$ refers to the across-domain motivation scale. $\boldsymbol{X}_i$ refers to a set of three covariates that include nonverbal cognitive ability, age, and gender for each participant $i$. We individually include standard scores for nonverbal cognitive ability, age in years, and a dichotomous variable (1 = Boy) for gender. For each outcome, we fit a taxonomy of models in which we sequentially add predictors as Equation (1) specifies.

**TABLE 1** | Descriptive statistics for reading and mathematics competence, and reading and mathematics motivation and anxiety ($n$ = 146).

| Measure | Mean | SD | Minimum | Maximum |
|---|---|---|---|---|
| **Math competence** | | | | |
| Broad mathematics | 101.15 | 16.82 | 58 | 139 |
| Math fluency | 98.92 | 16.61 | 62 | 142 |
| **Reading competence** | | | | |
| Total Word Reading Efficiency | 97.47 | 16.39 | 58 | 130 |
| Basic Skills | 97.86 | 17.00 | 55 | 136 |
| **Anxiety and motivation** | | | | |
| Math anxiety | 23.60 | 7.74 | 13 | 49 |
| Math motivation | 57.83 | 9.97 | 29 | 77 |
| Reading anxiety | 22.15 | 6.67 | 13 | 44 |
| Reading motivation | 58.64 | 9.16 | 29 | 76 |
| Nonverbal cognitive ability | 112.30 | 14.09 | 82 | 143 |

# RESULTS

## Group Characterizations: Incidence of Learning Disabilities

Group characterizations show that the sample was academically diverse, with 34% (49/146) of participants having a learning disability. Three participants met the criteria for math-only disability. Thirteen participants met the criteria for reading-only disability and 33 participants met the criteria for comorbid math and reading disability. Sixty-eight participants met criteria for having no learning disability and the remaining 29 did not have a group. These participants had heterogeneous score patterns and may have, for example, scored below the cutoff for only one of the measures in one or both domains and may or may not have had a history of learning disabilities. **Supplementary Table 1** shows age and performance on the competence and socio-emotional measures by group, excluding the math disability only group due to small sample size. Due to the small sample sizes by group, we are unable to conduct group comparisons. Instead, we provide descriptive statistics to illustrate the academically-diverse nature of the sample.

## Preliminary Analyses

**Table 1** presents descriptive statistics for competence and socio-emotional measures for each domain, for the full sample ($n$ = 146). **Table 2** presents Cronbach's alpha for each full scale and subscale for the four socio-emotional measures. Scales showed good to high internal consistency (α = 0.76–0.91).

In **Table 3**, we present bivariate correlations and significance levels among competence, anxiety, and motivation measures for math and reading, nonverbal cognitive ability, and age. As the table shows, competence measures had strong, positive, statistically significant correlations within domain and across domains. Competence was correlated with socio-emotional measures within and across domains. Higher math competence was associated with lower math anxiety and higher math motivation; both correlations were statistically significant and moderate. Across domains, higher math competence

**TABLE 2 |** Cronbach's alpha for each full scale and subscale ($n = 146$).

| | Construct | |
|---|---|---|
| | **Math Anxiety[b] (MASYC-R)** | **Reading Anxiety[a] (RASYC)** |
| Full scale | 0.88 | 0.84 |
| Negative reactions | 0.69 | 0.73 |
| Confidence | 0.85 | 0.83 |
| Worry | 0.83 | 0.76 |
| | **Motivation for Math[a] (MMP)** | **Motivation to Read[b] (MRP-R)** |
| Full scale | 0.91 | 0.89 |
| Self-confidence | 0.89 | 0.82 |
| Value | 0.87 | 0.84 |

[a]*New scale;* [b]*Existing scale.*

was associated with higher reading motivation and lower reading anxiety; all correlations were statistically significant and were small-to-moderate. Similarly, reading competence had a moderate positive correlation with reading motivation and moderate negative association with reading anxiety, and both were statistically significant. Across domains, higher reading competence was associated with lower math anxiety and higher math motivation. Correlations were small and statistically significant.

As **Table 3** shows, all socio-emotional measures were statistically significantly correlated with one another. Correlations were strong and negative between anxiety and motivation within domain. Across domain, higher math anxiety was associated with higher reading anxiety and higher math motivation was associated with higher reading motivation. Higher nonverbal cognitive ability was associated with higher competence in both domains, higher motivation in both domains, lower anxiety in both domains, and younger age. Finally, older children had lower math and reading competence, greater math and reading anxiety, and lower reading motivation. All of these correlations were statistically significant. The correlation between age and math motivation was not statistically significant at the 0.05 level.

## Within- and Across-Domain Socio-Emotional Characteristics Predict Math Competence

### Predictors of Broad Mathematics

Socio-emotional characteristics in both math and reading predict math competence across both math measures. In **Table 4**, we present a taxonomy of models including parameter estimates, standard errors, and significance levels that illustrate the relation between Broad Mathematics, socio-emotional characteristics, and nonverbal cognitive ability. Model B1 shows the statistically significant, negative relation between Broad Mathematics and math anxiety, in which a one-point increment in math anxiety is associated with a 0.92-point decrement in Broad Mathematics score, on average. As Model B2 shows, both math anxiety and reading anxiety have statistically significant relations with Broad Mathematics, controlling for each other, in which higher anxiety predicts lower math competence, on average. Model B3 shows that when math motivation is a predictor, the relation between reading anxiety and Broad Mathematics is essentially unchanged, while the relation between math anxiety and Broad Mathematics is no longer statistically significant. In this model, math motivation has a statistically significant relation with Broad Mathematics, in which a one-point increment in math motivation predicts a 0.81-point increment in Broad Mathematics score, on average. Because math anxiety does not predict math competence when controlling for math motivation, we removed math anxiety from subsequent models in this taxonomy.

We next examined whether the relation between Broad Mathematics and reading anxiety and math motivation would remain when controlling for reading motivation. As Model B4 shows, reading motivation does not have a statistically significant relation with Broad Mathematics, and when controlling for reading motivation, the relation between reading anxiety and Broad Mathematics is no longer statistically significant. Due to the correlation between reading anxiety and reading motivation (**Table 3**), we examined whether they have a joint effect on Broad Mathematics. Using a general linear hypothesis test, we tested the null hypothesis that reading anxiety and reading motivation jointly have no effect on Broad Mathematics. We rejected the null hypothesis [$F_{(2,142)} = 7.68$, $p = 0.0007$], concluding that reading anxiety and reading motivation jointly predict Broad Mathematics.

Model B5 in **Table 4** shows that relations between Broad Mathematics and socio-emotional characteristics within and across domain remain essentially unchanged when controlling for nonverbal cognitive ability. The statistically significant joint effect of reading anxiety and reading motivation was also unchanged [$F_{(2, 141)} = 4.59$, $p = 0.012$]. This joint effect persisted in all subsequent models for Broad Mathematics.

In subsequent models, we did not find statistically significant interactions between nonverbal cognitive ability and math motivation [$\beta = -0.003$, $SE = 0.007$, and $p = 0.678$] or nonverbal cognitive ability and reading anxiety ($\beta = 0.009$, $SE = 0.011$, and $p = 0.395$). There were also no statistically significant main effects of age ($\beta = -0.640$, $SE = 0.966$, and $p = 0.509$) or gender ($\beta = 3.937$, $SE = 2.067$, and $p = 0.059$), controlling for socio-emotional characteristics and nonverbal cognitive ability. For the final model Model B5, we used a Shapiro–Wilk $W$-test to test the null hypothesis that the residuals from Model B5 are normally distributed in the population. We did not reject the null hypothesis ($W = 0.989$, $p = 0.293$) and concluded that there was not a violation of normality.

In sum, math motivation, the joint effect of reading anxiety and reading motivation, and nonverbal cognitive ability predict Broad Mathematics, controlling for the other predictors in the model. In **Supplementary Figure 1A**, we illustrate the relation between predicted Broad Mathematics and math motivation for children of lower (25th percentile) and higher (75th percentile)

**TABLE 3 |** Bivariate correlations among competence (1–4), socio-emotional characteristics (5–8), KBIT scores, and age ($n = 146$).

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
|---|---|---|---|---|---|---|---|---|---|---|
| (1) Broad Math | 1.000 | | | | | | | | | |
| (2) Math Fluency | 0.916*** | 1.000 | | | | | | | | |
| (3) Total Word Reading Efficiency | 0.711*** | 0.682*** | 1.000 | | | | | | | |
| (4) Basic Skills | 0.648*** | 0.620*** | 0.890*** | 1.000 | | | | | | |
| (5) Math anxiety | −0.423*** | −0.408*** | −0.211* | −0.216** | 1.000 | | | | | |
| (6) Math motivation | 0.533*** | 0.490*** | 0.285*** | 0.252** | −0.711*** | 1.000 | | | | |
| (7) Reading anxiety | −0.387*** | −0.357*** | −0.495*** | −0.452*** | 0.439*** | −0.297*** | 1.000 | | | |
| (8) Reading motivation | 0.392*** | 0.326*** | 0.608*** | 0.546*** | −0.184* | 0.316*** | −0.652*** | 1.000 | | |
| (9) Nonverbal cognitive ability | 0.606*** | 0.500*** | 0.498*** | 0.497*** | −0.271** | 0.310*** | −0.251** | 0.301*** | 1.000 | |
| (10) Age | −0.330*** | −0.351*** | −0.397*** | −0.459*** | 0.178* | −0.156~ | 0.259** | −0.295*** | −0.406*** | 1.000 |

*~p = 0.06, *p < 0.05, **p < 0.01, and ***p < 0.001.*

**TABLE 4 |** Taxonomy of models showing the relation between Broad Mathematics skills and within and across domain anxiety and motivation, and nonverbal cognitive ability ($n = 146$).

| | B1 | B2 | B3 | B4 | B5 |
|---|---|---|---|---|---|
| Intercept | 122.805*** | 131.118*** | 67.329*** | 51.127*** | 8.347 |
| | (4.072) | (4.807) | (13.659) | (14.676) | (13.840) |
| Math anxiety | −0.918*** | −0.680*** | 0.067 | | |
| | (0.164) | (0.178) | (0.224) | | |
| Reading anxiety | | −0.628** | −0.651*** | −0.401† | −0.330† |
| | | (0.206) | (0.191) | (0.226) | (0.193) |
| Math motivation | | | 0.807*** | 0.740*** | 0.542*** |
| | | | (0.163) | (0.121) | (0.107) |
| Reading motivation | | | | 0.275† | 0.138† |
| | | | | (0.166) | (0.143) |
| Nonverbal cognitive ability | | | | | 0.541*** |
| | | | | | (0.074) |
| $R^2$ | 0.179 | 0.229 | 0.342 | 0.354 | 0.532 |

**p < 0.05, **p < 0.01, and ***p < 0.001. †Reading anxiety and reading motivation jointly predict Broad Mathematics. Standard errors in parentheses.*

reading anxiety who have average nonverbal cognitive ability and reading motivation. The difference between the two lines in **Supplementary Figure 1A** is not statistically significant, since the joint effect of reading anxiety and reading motivation predicts Broad Mathematics. However, we illustrate this relation at higher and lower levels of math anxiety to facilitate visual comparison with the statistically significant relation in **Supplementary Figure 1B**.

## Predictors of Math Fluency

In **Table 5**, we show a taxonomy of models of the relation of Math Fluency with socio-emotional measures of math and reading, and nonverbal cognitive ability. Model F1 shows the statistically significant negative relation with Math Fluency, in which a one-point increment in math anxiety is associated with a 0.88-point decrement in Math Fluency, on average. Model F2 shows Math Fluency has statistically significant relations with math anxiety and reading anxiety, controlling for the other. Model F3 shows a positive, statistically significant relation between Math Fluency and math motivation, controlling for math and reading anxiety. However, with the addition of math motivation, math anxiety no longer has a statistically significant relation with Math Fluency. In a subsequent model, we tested whether these relations would remain when controlling for reading motivation. Reading motivation did not predict Math Fluency ($\beta = 0.136$, $SE = 0.171$, and $p = 0.430$) and its inclusion in the model did not substantively change results from Model F3. In Model F4, we added nonverbal cognitive ability as a predictor. Relations between Math Fluency and reading anxiety, math motivation, and nonverbal cognitive ability were each statistically significant, controlling for the other predictors in the model. Subsequent models did not show statistically significant interactions between reading anxiety and math motivation ($\beta = 0.0005$, $SE = 0.014$, and $p = 0.973$), or relations between Math Fluency and age ($\beta = -1.940$, $SE = 1.056$, and $p = 0.068$) or Math Fluency and gender ($\beta = 2.732$, $SE = 2.239$, and $p = 0.225$), all else equal. A Shapiro–Wilk test of the residuals from Model F4 showed no violation of normality ($W = 0.988$, $p = 0.225$). In **Supplementary Figure 1B**,

**TABLE 5 |** Taxonomy of models examining the relation between Math Fluency, math and reading anxiety, math motivation, and nonverbal cognitive ability ($n$ = 146).

| | F1 | F2 | F3 | F4 |
|---|---|---|---|---|
| Intercept | 119.592*** | 126.859*** | 72.867*** | 30.274* |
| | (4.052) | (4.819) | (14.024) | (11.619) |
| Math anxiety | −0.876*** | −0.668*** | −0.036 | |
| | (0.163) | (0.178) | (0.230) | |
| Reading anxiety | | −0.549** | −0.569** | −0.434* |
| | | (0.207) | (0.196) | (0.172) |
| Math motivation | | | 0.683*** | 0.533*** |
| | | | (0.168) | (0.118) |
| Nonverbal cognitive ability | | | | 0.423*** |
| | | | | (0.082) |
| $R^2$ | 0.167 | 0.206 | 0.289 | 0.402 |

*$p$ < 0.05, **$p$ < 0.01, and ***$p$ < 0.001. Standard errors in parentheses.

**TABLE 6 |** Taxonomy of models examining the relation between Total Word Reading Efficiency, reading anxiety, reading motivation, and nonverbal cognitive ability ($n$ = 146).

| | T1 | T2 | T3 | T4 |
|---|---|---|---|---|
| Intercept | 124.423*** | 54.679*** | 17.082 | −0.657 |
| | (4.115) | (12.685) | (13.595) | (8.986) |
| Reading anxiety | −1.217*** | −0.421* | −0.337 | |
| | (0.178) | (0.212) | (0.195) | |
| Reading motivation | | 0.889*** | 0.758*** | 0.914*** |
| | | (0.155) | (0.144) | (0.113) |
| Nonverbal cognitive ability | | | 0.387*** | 0.397*** |
| | | | (0.073) | (0.073) |
| $R^2$ | 0.245 | 0.387 | 0.489 | 0.478 |

*$p$ < 0.05, **$p$ < 0.01, and ***$p$ < 0.001. Standard errors in parentheses.

we illustrate the relation between predicted Math Fluency and math motivation for children of lower (25th percentile) and higher (75th percentile) reading anxiety and of average nonverbal cognitive ability. The figure shows that children with lower reading anxiety have higher Math Fluency at every level of math motivation, on average.

Taken together, analyses show that, controlling for nonverbal cognitive ability, both within- and across-domain socio-emotional characteristics predict math competence, on average.

## Within-Domain Socio-Emotional Characteristics Predict Reading Competence

### Predictors of Total Word Reading Efficiency

**Table 6** shows a taxonomy of models of the relation between Total Word Reading Efficiency (i.e., timed word and pseudoword reading) and reading anxiety, motivation to read, and nonverbal cognitive ability. Model T1 shows the statistically significant relation between Total Word Reading Efficiency and reading anxiety, in which a one-point increment in reading anxiety is associated with a 1.2-point decrement in Total Word Reading Efficiency, on average. The addition of math anxiety to the model did not yield a statistically significant relation ($\beta$ = 0.015, $SE$ = 0.171, and $p$ = 0.929). In Model T2, we show that reading anxiety and reading motivation each predict Total Word Reading Efficiency, on average, controlling for the other. In a subsequent model, we found that math motivation did not have a statistically significant relation with Total Word Reading Efficiency, controlling for reading anxiety and reading motivation ($\beta$ = 0.144, $SE$ = 0.114, and $p$ = 0.209). These results suggest that when considered together, within-domain anxiety and motivation predict reading competence, while across-domain anxiety and motivation do not.

Model T3 in **Table 6** shows that nonverbal cognitive ability has a statistically significant relation with Total Word Reading Efficiency, controlling for reading anxiety and reading motivation. Further, this model shows that when controlling for nonverbal cognitive ability, the relation between Total Word Reading Efficiency and reading anxiety is no longer statistically significant. We refit the model, removing reading anxiety (Model T4). In subsequent models, we did not find a statistically significant interaction between reading motivation and nonverbal cognitive ability ($\beta$ = −0.0004, $SE$ = 0.009, and $p$ = 0.958), or main effects of age ($\beta$ = −1.890, $SE$ = 0.973, and $p$ = 0.054) or gender ($\beta$ = 2.961, $SE$ = 2.016995, and $p$ = 0.144). A Shapiro–Wilk test of the residuals from Model T4 showed no violation of normality ($W$ = 0.993, $p$ = 0.682). **Supplementary Figure 1C** displays predicted Total Word Reading Efficiency by reading motivation for children of average nonverbal cognitive ability.

### Predictors of Basic Skills

Lastly, **Table 7** shows a selection of models of the relation between Basic Skills and reading anxiety, reading motivation, nonverbal cognitive ability, age, and gender. Model S1 shows the negative, statistically significant relation between reading anxiety and Basic Skills. In a subsequent model, we did not find a statistically significant relation between math anxiety and Basic Skills ($\beta$ = −0.048, $SE$ = 0.182, and $p$ = 0.792) and therefore we excluded math anxiety from subsequent models. Model S2 shows the statistically significant relation between reading motivation and Basic Skills, controlling for reading anxiety. However, controlling for reading motivation, the relation between Basic Skills and reading anxiety was no longer statistically significant. Similar to math anxiety, math motivation did not have a statistically significant relation with Basic Skills ($\beta$ = 0.150, $SE$ = 0.125, and $p$ = 0.233). Model S3 shows that the statistically significant relation between reading motivation and Basic Skills persists when controlling for nonverbal cognitive ability. In Models S4 and S5, respectively, we add the effects of age and gender, which both have statistically significant relations with Basic Skills, all else equal. Model S5 also shows that, controlling for age, gender, and nonverbal cognitive ability, reading motivation maintains a statistically significant relation with Basic Skills. There were no statistically significant interactions (all $ps$ > 0.35). A Shapiro–Wilk test of the residuals

**TABLE 7 |** Taxonomy of models examining the relation between Basic Skills, reading anxiety, reading motivation, nonverbal cognitive ability, age, and gender ($n$ = 146).

| | S1 | S2 | S3 | S4 | S5 |
|---|---|---|---|---|---|
| Intercept | 123.359*** | 59.558*** | −0.352 | 50.147** | 48.818** |
| | (4.383) | (13.915) | (9.768) | (18.540) | (18.328) |
| Reading anxiety | −1.151*** | −0.424 | | | |
| | (0.190) | (0.233) | | | |
| Reading motivation | | 0.813*** | 0.817*** | 0.738*** | 0.789*** |
| | | (0.170) | (0.123) | (0.121) | (0.122) |
| Nonverbal cognitive ability | | | 0.449*** | 0.354*** | 0.341*** |
| | | | (0.079) | (0.082) | (0.082) |
| Age | | | | −3.281** | −3.491*** |
| | | | | (1.036) | (1.028) |
| Boy | | | | | 4.483* |
| | | | | | (2.119) |
| $R^2$ | 0.204 | 0.314 | 0.427 | 0.465 | 0.481 |

*$p < 0.05$, **$p < 0.01$, and ***$p < 0.001$. Standard errors in parentheses.*

from Model S5 showed no violation of normality ($W = 0.989$, $p = 0.307$). **Supplementary Figure 1D** shows the relation between predicted Basic Skills and reading motivation, on average. The graph shows the 4.5-point predicted difference in Basic Skills between boys and girls of average nonverbal cognitive ability and average age.

In sum, reading motivation predicted Basic Skills, controlling for nonverbal cognitive ability, age, and gender. There were no across-domain relations between Basic Skills and math socio-emotional characteristics.

## DISCUSSION

In this study, we provide an examination of the within and across-domain relations among anxiety, motivation, and competence for math and reading for an academically-diverse group of children. We leveraged existing math anxiety and reading motivation scales to create novel parallel measures of reading anxiety and math motivation to measure socio-emotional characteristics across domains. We found within domain relations among anxiety, motivation, and competence for both math and reading. We also found a unidirectional across-domain relation between reading socio-emotional characteristics and math competence, which persisted when accounting for math motivation, nonverbal cognitive ability, age, and gender.

This study contributes to burgeoning research focused on an individual differences approach to studying children with and without learning disabilities across domains. The multiple regression approach we use facilitates the inclusion of children who do not fit into group criteria. This provides a sample that more accurately represents a continuum of learners. As Peters and Ansari (2019) discuss, an individual differences approach avoids several challenges inherent to group comparisons. Group comparisons may include arbitrary score cut-offs, which does not produce groups with "specific and separable deficits," (p. 5). Group comparisons may also mask variation within groups and may lead to an inadequate examination of comorbidities across domains, such as math and reading. Indeed, the notion that characteristics of math and reading disabilities are related dimensions along a continuum may better describe struggling learners (Branum-Martin et al., 2013) and thus can better illuminate relations among cognitive and socio-emotional factors within and across domains.

### Socio-Emotional Predictors of Math Competence Are Within and Across Domain

We found that math anxiety correlated with both measures of math competence. However, this relation was no longer statistically significant controlling for math motivation. Rather, math motivation was a stronger predictor of math competence than math anxiety. Together with prior studies showing a reciprocal link between math anxiety and math motivation across time (Ahmed et al., 2012; Seaton et al., 2014; Gunderson et al., 2018) and math self-concept as a mediator between math anxiety and achievement (Justicia-Galiano et al., 2017), results underscore the need to attend to math motivation as an important socio-emotional predictor of mathematics skills. This in turn raises questions about how math motivation may have factored into the robust negative correlations between math anxiety and math achievement found in prior studies (for meta-analyses, see Hembree, 1990; Ma, 1999; and Barroso et al., 2021). Given the disproportionate research focus on math anxiety, results suggest the need for greater emphasis on math motivation and its interplay with math anxiety as they relate to math competence. In line with studies that have included measures of math anxiety and motivation (e.g., Lai et al., 2015; Justicia-Galiano et al., 2017), future studies should likewise include measures of both math anxiety and math motivation to more comprehensively illuminate socio-emotional factors that impact math achievement.

In line with our hypotheses, reading anxiety and reading motivation each were correlated with math competence. These socio-emotional characteristics jointly predicted math competence controlling for math motivation and nonverbal cognitive ability. This finding suggests that interrelations among math and reading domains include socio-emotional dimensions, in addition to cognitive, neural, and genetic ones (e.g., Kovas et al., 2007; Pollack and Ashby, 2018; Vanbinst et al., 2020b). Indeed, just as good reading skills may facilitate math skills, but not necessarily the reverse (Erbeli et al., 2021), how learners feel about reading may not just facilitate reading skills, but math skills as well.

We found that reading anxiety and reading motivation related to math competence differently across math outcomes. The joint effect of reading anxiety and reading motivation predicted Broad Mathematics, while reading anxiety (but not reading motivation) predicted Math Fluency, all else equal. What might account for this difference? We speculate that relations between socio-emotional characteristics of reading and math skills may be dependent on the ways in which math tasks involve reading or reading-related skills. Broad Mathematics is a measure of fact retrieval, procedural knowledge, and applications and problem solving that involve written language (Schrank et al., 2014). This broader conceptualization of math may therefore engage both reading anxiety and motivation, through the connection between written language and math problems (e.g., Lewis and Mayer, 1987; Hegarty et al., 1995; van der Schoot et al., 2009). In contrast, Math Fluency narrowly focuses on timed math fact retrieval across addition, subtraction, and multiplication (Schrank et al., 2014), and so may engage socio-emotional characteristics of reading differently. Reading anxiety, but not reading motivation, predicted Math Fluency controlling for socio-emotional characteristics for math. One potential explanation may be shared underlying mechanisms for arithmetic fact fluency and reading skills, such as retrieval fluency (Willburger et al., 2008; Koponen et al., 2020). Difficulty with retrieval fluency that may contribute to higher levels of reading anxiety may likewise relate to performance on math tasks that heavily engage retrieval, such as fact fluency, even when accounting for socio-emotional characteristics for math. Together, results suggest that across-domain relations between math competence and reading anxiety and reading motivation may vary by math task, according to associated cognitive mechanisms.

## Socio-Emotional Predictors of Reading Competence Are Within Domain

The present study adds to a nascent body of literature on the relations among reading anxiety, reading motivation, and reading competence. Across both reading outcomes, reading anxiety correlated with reading competence, but did not predict reading competence controlling for reading motivation. Rather, reading motivation predicted reading competence, controlling for nonverbal cognitive ability, age, and gender. These results align with Katzir et al. (2018), who reported more consistent relations between reading skills and reading self-concept than between reading skills and reading anxiety in children without learning disabilities. However, our results are in contrast to Ramirez et al. (2019), who found a stronger relation between reading competence and reading anxiety than reading competence and positive reading affect in children without learning disabilities. One potential reason for these differences may be that both our study and Katzir et al. (2018) included measures of reading self-concept, whereas Ramirez et al. (2019) measured positive reading affect. Additionally, we found a main effect of gender, such that boys had higher untimed reading skills than girls on average, but found no interaction between gender and reading motivation. This contrasts with related studies that have shown higher reading accuracy for girls, on average (Katzir et al., 2018) and an interaction between gender and reading anxiety and motivation (Katzir et al., 2018; Ramirez et al., 2019). Differences between samples, motivational and affective constructs, and analytic approach may account for the lack of convergence among studies. With so few studies of reading anxiety (and thus reading anxiety, motivation, and competence), additional research is needed to clarify these relations and discrepancies across studies.

Partially in line with our hypothesis, reading competence was negatively correlated with math anxiety and positively correlated with math motivation. However, these relations were not robust; neither math anxiety nor math motivation predicted reading competence when controlling for socio-emotional characteristics in reading. The correlation between math anxiety and reading competence may have been driven by the correlation of each with reading anxiety, with an analogous pattern for motivation. Similar to our speculation above, one possibility may be that timed and untimed word and pseudoword reading does not sufficiently engage math-related content to trigger math anxiety. Rather, feelings of anxiety that are associated with cognitive processes like automaticity may impact math and reading domains, and may be accounted for by reading anxiety when reading.

## Limitations and Next Steps

The correlational analyses in this study do not support causal interpretations of within or across-domain relations between socio-emotional characteristics and competence. Similarly, prior research on relations among socio-emotional characteristics and between those characteristics and competence suggests reciprocal relations (e.g., Foley et al., 2017; Gunderson et al., 2018; Ramirez et al., 2019). With one wave of data, we are unable to speak to how relations may change over time or impact students differently in other age bands. Future studies can build on the cross-sectional analyses in the present study to examine how socio-emotional characteristics may reciprocally relate to each other and interact with math and reading performance, within and across domains. In addition, future studies can test these relations cross-sectionally and longitudinally by also incorporating measures of general anxiety and motivation. Additionally, younger children in our sample had higher math and reading competence, on average, than older children, as evidenced by the zero-order correlations between competence and age. However, results show that for most outcomes, age was not a statistically significant predictor of competence and in all sets of models, the inclusion of age did not substantially change results, suggesting this relation did not drive the results.

Our results raise several considerations for future research. As one example, approaches to alleviate math anxiety have spanned cognitive therapy, task reappraisal, pre-task expressive writing, noninvasive brain stimulation, and skill improvement (for a review, see Dowker, 2019b). The stronger relation of within-domain motivation for both math and reading raises the question of whether efforts to reduce anxiety and raise competence should also incorporate the improvement of motivational factors that include self-concept and value for math or reading. As anxiety and motivation are not opposite ends of the same spectrum (Dowker et al., 2016; Dowker, 2019b), interventions that combine strategies to reduce anxiety and encourage motivation may be an avenue for future research.

The unidirectional link from reading anxiety and reading motivation to math competence may likewise have implications for interventions that target socio-emotional characteristics related to math and reading. Future research should further probe the mechanisms that underlie across-domain relations between socio-emotional characteristics for reading and math competence. In turn, such research could open the door to testing whether efforts to boost reading motivation and reduce reading anxiety may have primary effects on reading competence and secondary effects on math competence.

## CONCLUSION

The present study suggests that the ways in which socio-emotional factors relate to competence within and across domain vary between math and reading. There is a need for greater attention to the roles that socio-emotional factors may play across math and reading for children with and without learning disabilities. Researchers and practitioners alike know that socio-emotional characteristics like anxiety and motivation matter for learning. This study contributes to an expanded view of these relations, suggesting that connections across domain may also be important to support children with and without learning disabilities.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Committee on the Use of Humans as Experimental Subjects (COUHES) at the Massachusetts Institute of Technology. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

## AUTHOR CONTRIBUTIONS

JG and JAC contributed to project conceptualization, management of funding, and project supervision, management, and organization. JG, JAC, and TC contributed to grant writing. TC, KH, and JAC created the surveys. DW, TC, and KH contributed to project set-up, organization, and management. DW and KH recruited participants. CP, DW, TC, KH, AI, KW, RR, JC, IF, AD, and NA collected data. CP and JAC conceptualized the study and managed data. CP conducted statistical analysis and wrote the manuscript. TC, JG, and JAC edited the manuscript. All authors read and approved the manuscript.

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## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2021.704821/full#supplementary-material

**Supplementary Figure 1 |** Predicted mathematics competence (top panel) and reading competence (bottom panel) from the regression models. **(A)** shows the relation between predicted Broad Mathematics and math motivation for participants with lower reading anxiety (25th percentile) and higher reading anxiety (75th percentile) (see **Table 4**, Model B5). **(B)** shows the analogous relation for predicted Math Fluency (see **Table 5**, Model F4). **(C)** shows the relation between predicted Total Word Reading Efficiency and reading motivation (see **Table 6**, Model T4). **(D)** shows the relation of predicted Basic Skills and reading motivation for boys and girls (see **Table 7**, Model S5). For all graphs, KBIT2 is set to the sample mean. In **(D)**, participant age is also set to the sample mean ($n = 146$).

**Supplementary Table 1 |** Descriptive statistics for age, math and reading competence, and socio-emotional measures, by group (n = 143). Note, we exclude the three participants who had math disability only due to insufficient sample size.

## REFERENCES

Ahmed, W., Minnaert, A., Kuyper, H., and van der Werf, G. (2012). Reciprocal relationships between math self-concept and math anxiety. *Learn. Individ. Differ.* 22, 385–389. doi: 10.1016/j.lindif.2011.12.004

Arens, A. K., Marsh, H. W., Pekrun, R., Lichtenfeld, S., Murayama, K., and vom Hofe, R. (2017). Math self-concept, grades, and achievement test scores: Long-term reciprocal effects across five waves and three achievement tracks. *J. Educ. Psychol.* 109, 621–634. doi: 10.1037/edu0000163

Ashcraft, M. H. (2002). Math anxiety: personal, educational, and cognitive consequences. *Curr. Dir. Psychol. Sci.* 11, 181–185. doi: 10.1111/1467-8721.00196

Barbaresi, W. J., Katusic, S. K., Colligan, R. C., Weaver, A. L., and Jacobsen, S. J. (2005). Math learning disorder: incidence in a population-based birth cohort, 1976-82, Rochester, Minn. *Ambul. Pediatr.* 5, 281–289. doi: 10.1367/A04-209R.1

Barroso, C., Ganley, C. M., McGraw, A. L., Geer, E. A., Hart, S. A., and Daucourt, M. C. (2021). A meta-analysis of the relation between math anxiety and math achievement. *Psychol. Bull.* 147, 134–168. doi: 10.1037/bul0000307

Baten, E., Pixner, S., and Desoete, A. (2019). "Motivational and math anxiety perspective for mathematical learning and learning difficulties," in *International Handbook of Mathematical Learning Difficulties*, eds. A. Fritz, V. G. Haase, and P. Räsänen (Cham: Springer International Publishing), 457–467.

Beilock, S. L., Gunderson, E. A., Ramirez, G., and Levine, S. C. (2010). Female teachers' math anxiety affects girls' math achievement. *Proc. Natl. Acad. Sci. U. S. A.* 107, 1860–1863. doi: 10.1073/pnas.0910967107

Boets, B., and De Smedt, B. (2010). Single-digit arithmetic in children with dyslexia. *Dyslexia* 16, 183–191. doi: 10.1002/dys.403

Branum-Martin, L., Fletcher, J. M., and Stuebing, K. K. (2013). Classification and identification of reading and math disabilities: the special case of comorbidity. *J. Learn. Disabil.* 46, 490–499. doi: 10.1177/0022219412468767

Carey, E., Hill, F., Devine, A., and Szücs, D. (2016). The chicken or the egg? The direction of the relationship between mathematics anxiety and mathematics performance. *Front. Psychol.* 6:1987. doi: 10.3389/fpsyg.2015.01987

Carroll, J. M., and Iles, J. E. (2006). An assessment of anxiety levels in dyslexic students in higher education. *Br. J. Educ. Psychol.* 76, 651–662. doi: 10.1348/000709905X66233

Carroll, J. M., Maughan, B., Goodman, R., and Meltzer, H. (2005). Literacy difficulties and psychiatric disorders: evidence for comorbidity. *J. Child Psychol. Psychiatry* 46, 524–532. doi: 10.1111/j.1469-7610.2004.00366.x

Casey, R., Levy, S. E., Brown, K., and Brooks-Gunn, J. (1992). Impaired emotional health in children with mild reading disability. *J. Dev. Behav. Pediatr*. 13, 256–260. doi: 10.1097/00004703-199208000-00003

Chapman, J. W., and Tunmer, W. E. (1995). Development of young children's reading self-concepts: an examination of emerging subcomponents and their relationship with reading achievement. *J. Educ. Psychol*. 87, 154–167. doi: 10.1037/0022-0663.87.1.154

Chapman, J. W., and Tunmer, W. E. (2003). Reading difficulties, reading-related self-perceptions, and strategies for overcoming negative self-beliefs. *Read. Writ. Q*. 19, 5–24. doi: 10.1080/10573560308205

Conlon, E. G., Zimmer-Gembeck, M. J., Creed, P. A., and Tucker, M. (2006). Family history, self-perceptions, attitudes and cognitive abilities are associated with early adolescent reading skills. *J. Res. Read*. 29, 11–32. doi: 10.1111/j.1467-9817.2006.00290.x

Conradi, K., Jang, B. G., and McKenna, M. C. (2014). Motivation terminology in reading research: a conceptual review. *Educ. Psychol. Rev*. 26, 127–164. doi: 10.1007/s10648-013-9245-z

Cui, J., Zhang, Y., Wan, S., Chen, C., Zeng, J., and Zhou, X. (2019). Visual form perception is fundamental for both reading comprehension and arithmetic computation. *Cognition* 189, 141–154. doi: 10.1016/j.cognition.2019.03.014

De Smedt, B., and Boets, B. (2010). Phonological processing and arithmetic fact retrieval: evidence from developmental dyslexia. *Neuropsychologia* 48, 3973–3981. doi: 10.1016/j.neuropsychologia.2010.10.018

Devine, A., Hill, F., Carey, E., and Szucs, D. (2018). Cognitive and emotional math problems largely dissociate: Prevalence of developmental dyscalculia and mathematics anxiety. *J. Educ. Psychol*. 110, 431–444. doi: 10.1037/edu0000222

Dirks, E., Spyer, G., van Lieshout, E. C. D. M., and de Sonneville, L. (2008). Prevalence of combined reading and arithmetic disabilities. *J. Learn. Disabil*. 41, 460–473. doi: 10.1177/0022219408321128

Dowker, A. (2019a). "Math anxiety and performance," in *Mathematics Anxiety: What Is Known, and What is Still Missing*, eds. I. C. Mammarella, S. Caviola, and A. Dowker (New York, NY: Routledge), 62–76.

Dowker, A. (2019b). "'Maths doesn't like me anymore': the role of attitudes and emotions – implications for helping children with their arithmetical difficulties," in *Individual Differences in Arithmetic: Implications for Psychology, Neuroscience and Education* (Abingdon; New York, NY: Routledge), 260–285.

Dowker, A., Sarkar, A., and Looi, C. Y. (2016). Mathematics anxiety: what have we learned in 60 years? *Front. Psychol*. 7:508. doi: 10.3389/fpsyg.2016.00508

Duncan, G. J., Dowsett, C. J., Claessens, A., Magnuson, K., Huston, A. C., Klebanov, P., et al. (2007). School readiness and later achievement. *Dev. Psychol*. 43, 1428–1446. doi: 10.1037/0012-1649.43.6.1428

Elgendi, M. M., Stewart, S. H., MacKay, E. J., and Deacon, S. H. (2021). Two aspects of psychological functioning in undergraduates with a history of reading difficulties: anxiety and self-efficacy. *Ann. Dyslexia* 71, 84–102. doi: 10.1007/s11881-021-00223-3

Erbeli, F., Shi, Q., Campbell, A. R., Hart, S. A., and Woltering, S. (2021). Developmental dynamics between reading and math in elementary school. *Dev. Sci*. 24:e13004. doi: 10.1111/desc.13004

Evans, T. M., Flowers, D. L., Napoliello, E. M., Olulade, O. A., and Eden, G. F. (2014). The functional anatomy of single-digit arithmetic in children with developmental dyslexia. *Neuroimage* 101, 644–652. doi: 10.1016/j.neuroimage.2014.07.028

Foley, A. E., Herts, J. B., Borgonovi, F., Guerriero, S., Levine, S. C., and Beilock, S. L. (2017). The math anxiety-performance link: a global phenomenon. *Curr. Dir. Psychol. Sci*. 26, 52–58. doi: 10.1177/0963721416672463

Froiland, J. M., and Oros, E. (2014). Intrinsic motivation, perceived competence and classroom engagement as longitudinal predictors of adolescent reading achievement. *Educ. Psychol*. 34, 119–132. doi: 10.1080/01443410.2013.822964

Ganley, C. M., and McGraw, A. L. (2016). The development and validation of a revised version of the math anxiety scale for young children. *Front. Psychol*. 7:1181. doi: 10.3389/fpsyg.2016.01181

Grills, A. E., Fletcher, J. M., Vaughn, S., Barth, A., Denton, C. A., and Stuebing, K. K. (2014). Anxiety and response to reading intervention among first grade students. *Child Youth Care Forum* 43, 417–431. doi: 10.1007/s10566-014-9244-3

Grills-Taquechel, A. E., Fletcher, J. M., Vaughn, S. R., and Stuebing, K. K. (2012). Anxiety and reading difficulties in early elementary school: evidence for unidirectional- or bi-directional relations? *Child Psychiatry Hum. Dev*. 43, 35–47. doi: 10.1007/s10578-011-0246-1

Gunderson, E. A., Park, D., Maloney, E. A., Beilock, S. L., and Levine, S. C. (2018). Reciprocal relations among motivational frameworks, math anxiety, and math achievement in early elementary school. *J. Cogn. Dev*. 19, 21–46. doi: 10.1080/15248372.2017.1421538

Hegarty, M., Mayer, R. E., and Monk, C. A. (1995). Comprehension of arithmetic word problems: A comparison of successful and unsuccessful problem solvers. *J. Educ. Psychol*. 87, 18–32. doi: 10.1037/0022-0663.87.1.18

Hembree, R. (1990). The nature, effects, and relief of mathematics anxiety. *J. Res. Math. Educ*. 21:33. doi: 10.2307/749455

Hill, F., Mammarella, I. C., Devine, A., Caviola, S., Passolunghi, M. C., and Szucs, D. (2016). Maths anxiety in primary and secondary school students: Gender differences, developmental changes and anxiety specificity. *Learn. Individ. Differ*. 48, 45–53. doi: 10.1016/j.lindif.2016.02.006

Hossain, B., Bent, S., and Hendren, R. (2021). The association between anxiety and academic performance in children with reading disorder: a longitudinal cohort study. *Dyslexia*. 27, 342–354. doi: 10.1002/dys.1680

Jain, S., and Dowson, M. (2009). Mathematics anxiety as a function of multidimensional self-regulation and self-efficacy. *Contemp. Educ. Psychol*. 34, 240–249. doi: 10.1016/j.cedpsych.2009.05.004

Jalongo, M. R., and Hirsh, R. A. (2010). Understanding reading anxiety: new insights from neuroscience. *Early Child. Educ. J*. 37, 431–435. doi: 10.1007/s10643-010-0381-5

Jameson, M. M. (2014). Contextual factors related to math anxiety in second-grade children. *J. Exp. Educ*. 82, 518–536. doi: 10.1080/00220973.2013.813367

Jansen, B. R. J., Louwerse, J., Straatemeier, M., Van der Ven, S. H. G., Klinkenberg, S., and Van der Maas, H. L. J. (2013). The influence of experiencing success in math on math anxiety, perceived math competence, and math performance. *Learn. Individ. Differ*. 24, 190–197. doi: 10.1016/j.lindif.2012.12.014

Justicia-Galiano, M. J., Martín-Puga, M. E., Linares, R., and Pelegrina, S. (2017). Math anxiety and math performance in children: the mediating roles of working memory and math self-concept. *Br. J. Educ. Psychol*. 87, 573–589. doi: 10.1111/bjep.12165

Katzir, T., Kim, Y.-S. G., and Dotan, S. (2018). Reading self-concept and reading anxiety in second grade children: the roles of word reading, emergent literacy skills, working memory and gender. *Front. Psychol*. 9:1180. doi: 10.3389/fpsyg.2018.01180

Kaufman, A. S., and Kaufman, N. L. (2004). *Kaufman Brief Intelligence Test Second Edition (KBIT-2)*. Pearson. Available online at: https://www.pearsonassessments.com/store/usassessments/en/Store/Professional-Assessments/Cognition-%26-Neuro/Non-Verbal-Ability/Kaufman-Brief-Intelligence-Test-%7C-Second-Edition/p/100000390.html (accessed March 27, 2021).

Kersey, A. J., Wakim, K.-M., Li, R., and Cantlon, J. F. (2019). Developing, mature, and unique functions of the child's brain in reading and mathematics. *Dev. Cogn. Neurosci*. 39:100684. doi: 10.1016/j.dcn.2019.100684

Koerte, I. K., Willems, A., Muehlmann, M., Moll, K., Cornell, S., Pixner, S., et al. (2016). Mathematical abilities in dyslexic children: a diffusion tensor imaging study. *Brain Imaging Behav*. 10, 781–791. doi: 10.1007/s11682-015-9436-y

Koponen, T., Eklund, K., Heikkil,ä, R., Salminen, J., Fuchs, L., Fuchs, D., et al. (2020). Cognitive correlates of the covariance in reading and arithmetic fluency: importance of serial retrieval fluency. *Child Dev*. 91, 1063–1080. doi: 10.1111/cdev.13287

Kovas, Y., Haworth, C. M. A., Harlaar, N., Petrill, S. A., Dale, P. S., and Plomin, R. (2007). Overlap and specificity of genetic and environmental influences on mathematics and reading disability in 10-year-old twins. *J. Child Psychol. Psychiatry* 48, 914–922. doi: 10.1111/j.1469-7610.2007.01748..x

Kriegbaum, K., Jansen, M., and Spinath, B. (2015). Motivation: a predictor of PISA's mathematical competence beyond intelligence and prior test achievement. *Learn. Individ. Differ*. 43, 140–148. doi: 10.1016/j.lindif.2015.08.026

Krinzinger, H., Kaufmann, L., and Willmes, K. (2009). Math anxiety and math ability in early primary school years. *J. Psychoeduc. Assess*. 27, 206–225. doi: 10.1177/0734282908330583

Lai, Y., Zhu, X., Chen, Y., and Li, Y. (2015). Effects of mathematics anxiety and mathematical metacognition on word problem solving in children with and without mathematical learning difficulties. *PLoS One* 10:e0130570. doi: 10.1371/journal.pone.0130570

Landerl, K., and Moll, K. (2010). Comorbidity of learning disorders: prevalence and familial transmission. *J. Child Psychol. Psychiatry* 51, 287–294. doi: 10.1111/j.1469-7610.2009.02164.x

Lewis, A. B., and Mayer, R. E. (1987). Students' miscomprehension of relational statements in arithmetic word problems. *J. Educ. Psychol*. 79, 363–371. doi: 10.1037/0022-0663.79.4.363

Lohbeck, A. (2018). Self-concept and self-determination theory: math self-concept, motivation, and grades in elementary school children. *Early Child Dev. Care* 188, 1031–1044. doi: 10.1080/03004430.2016.1241778

Luttenberger, S., Wimmer, S., and Paechter, M. (2018). Spotlight on math anxiety. *Psychol. Res. Behav. Manag*. 11, 311–322. doi: 10.2147/PRBM.S141421

Ma, X. (1999). A meta-analysis of the relationship between anxiety toward mathematics and achievement in mathematics. *J. Res. Math. Educ*. 30, 520–540. doi: 10.2307/749772

Malloy, J. A., Marinak, B. A., Gambrell, L. B., and Mazzoni, S. A. (2013). Assessing motivation to read: the motivation to read profile-revised. *Read. Teach*. 67, 273–282. doi: 10.1002/trtr.1215

Peters, L., and Ansari, D. (2019). Are specific learning disorders truly specific, and are they disorders? *Trends Neurosci. Educ*. 17:100115. doi: 10.1016/j.tine.2019.100115

Piccolo, L. R., Giacomoni, C. H., Julio-Costa, A., Oliveira, S., Zbornik, J., Haase, V. G., et al. (2017). Reading anxiety in L1: reviewing the concept. *Early Child. Educ. J*. 45, 537–543. doi: 10.1007/s10643-016-0822-x

Pollack, C., and Ashby, N. C. (2018). Where arithmetic and phonology meet: the meta-analytic convergence of arithmetic and phonological processing in the brain. *Dev. Cogn. Neurosci*. 30, 251–264. doi: 10.1016/j.dcn.2017.05.003

Psychological Corporation (2009). *WIAT III: Wechsler Individual Achievement Test*. San Antonio, TX.: Psychological Corp.

Punaro, L., and Reeve, R. (2012). Relationships between 9-year-olds' math and literacy worries and academic abilities. *Child Dev. Res.* (2012). 2012:e359089. doi: 10.1155/2012/359089

Ramirez, G., Fries, L., Gunderson, E., Schaeffer, M. W., Maloney, E. A., Beilock, S. L., et al. (2019). Reading anxiety: an early affective impediment to children's success in reading. *J. Cogn. Dev*. 20, 15–34. doi: 10.1080/15248372.2018.1526175

Ramirez, G., Shaw, S. T., and Maloney, E. A. (2018). Math anxiety: past research, promising interventions, and a New Interpretation Framework. *Educ. Psychol.* 53, 145–164. doi: 10.1080/00461520.2018.1447384

Retelsdorf, J., Köller, O., and Möller, J. (2011). On the effects of motivation on reading performance growth in secondary school. *Learn. Instr*. 21, 550–559. doi: 10.1016/j.learninstruc.2010.11.001

Rubinsten, O., and Tannock, R. (2010). Mathematics anxiety in children with developmental dyscalculia. *Behav. Brain Funct*. 6:46. doi: 10.1186/1744-9081-6-46

Schrank, F. A., Mather, N., and McGrew, K. S. (2014). *Woodcock-Johnson IV Tests of Achievement*. Rolling Meadows, IL: Riverside Publishing.

Seaton, M., Parker, P., Marsh, H. W., Craven, R. G., and Yeung, A. S. (2014). The reciprocal relations between self-concept, motivation and achievement: juxtaposing academic self-concept and achievement goal orientations for mathematics success. *Educ. Psychol*. 34, 49–72. doi: 10.1080/01443410.2013.825232

Simmons, F. R., and Singleton, C. (2008). Do weak phonological representations impact on arithmetic development? A review of research into arithmetic and dyslexia. *Dyslexia Chichester Engl*. 14, 77–94. doi: 10.1002/dys.341

Suárez-Pellicioni, M., Núñez-Peña, M. I., and Colomé, À. (2016). Math anxiety: a review of its cognitive consequences, psychophysiological correlates, and brain bases. *Cogn. Affect. Behav. Neurosci*. 16, 3–22. doi: 10.3758/s13415-015-0370-7

Szczygieł, M., and Pieronkiewicz, B. (2021). Exploring the nature of math anxiety in young children: Intensity, prevalence, reasons. *Math. Think. Learn*. 1–19. doi: 10.1080/10986065.2021.1882363

Torgesen, J. K., Rashotte, C. A., and Wagner, R. K. (2012). *TOWRE 2: Test of Word Reading Efficiency*. Available online at: https://www.proedinc.com/Products/13910/towre2-test-of-word-reading-efficiencysecond-edition-complete-kit.aspx (accessed January 3, 2021).

Urdan, T., and Schoenfelder, E. (2006). Classroom effects on student motivation: goal structures, social relationships, and competence beliefs. *J. Sch. Psychol*. 44, 331–349. doi: 10.1016/j.jsp.2006.04.003

van der Schoot, M., Bakker Arkema, A. H., Horsley, T. M., and van Lieshout, E. C. D. M. (2009). The consistency effect depends on markedness in less successful but not successful problem solvers: an eye movement study in primary school children. *Contemp. Educ. Psychol*. 34, 58–66. doi: 10.1016/j.cedpsych.2008.07.002

Vanbinst, K., Bellon, E., and Dowker, A. (2020a). Mathematics anxiety: an intergenerational approach. *Front. Psychol*. 11:1648. doi: 10.3389/fpsyg.2020.01648

Vanbinst, K., van Bergen, E., Ghesquière, P., and De Smedt, B. (2020b). Cross-domain associations of key cognitive correlates of early reading and early arithmetic in 5-year-olds. *Early Child. Res. Q*. 51, 144–152. doi: 10.1016/j.ecresq.2019.10.009

Vukovic, R. K., Lesaux, N. K., and Siegel, L. S. (2010). The mathematics skills of children with reading difficulties. *Learn. Individ. Differ*. 20, 639–643. doi: 10.1016/j.lindif.2010.08.004

Wang, Z., Lukowski, S. L., Hart, S. A., Lyons, I. M., Thompson, L. A., Kovas, Y., et al. (2015). Is Math Anxiety Always Bad for Math Learning? The Role of Math Motivation. *Psychol. Sci*. 26, 1863–1876. doi: 10.1177/0956797615602471

Willburger, E., Fussenegger, B., Moll, K., Wood, G., and Landerl, K. (2008). Naming speed in dyslexia and dyscalculia. *Learn. Individ. Differ*. 18, 224–236. doi: 10.1016/j.lindif.2008.01.003

Woodcock, R. W. (2011). *Woodcock Reading Mastery Test, 3rd Edn*. Bloomington, MN: Pearson.

Wu, S. S., Barth, M., Amin, H., Malcarne, V., and Menon, V. (2012). Math anxiety in second and third graders and its relation to mathematics achievement. *Front. Psychol*. 3:162. doi: 10.3389/fpsyg.2012.00162

Zakaria, E., and Nordin, N. M. (2008). The effects of mathematics anxiety on matriculation students as related to motivation and achievement. *Eurasia J. Math. Sci. Technol. Educ*. 4, 27–30. doi: 10.12973/ejmste/75303

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# Inferencing Skill and Attentional Control Account for the Connection Between Reading Comprehension and Mathematics

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We examined the relations of inference, vocabulary, decoding, short-term memory, and attentional control to reading comprehension and mathematics performance for first-grade students in the US ($N = 83$). The students were composed of 75% Hispanics, 15% Whites, and 6% Asian Americans. Students' performance on mathematics and reading comprehension were very strongly related ($r = 0.88$). Results from path analysis showed that inference ($0.27 \leq s \leq 0.38$) was independently and positively related to both reading comprehension and mathematics performance after accounting for short-term memory, attentional control, decoding, and vocabulary. Decoding was independently related to reading comprehension, but not mathematics, whereas vocabulary was independently related to mathematics, but not to reading comprehension. Attentional control was directly related to mathematics, and indirectly related to reading comprehension and mathematics via inference, vocabulary, and decoding, with a substantial total effect on reading comprehension and mathematics (0.56 respectively). Short-term memory was not directly nor indirectly related to reading comprehension and mathematics. Overall these results show that language and cognitive skills are shared resources of reading comprehension and mathematics, and highlight the roles of attentional control and inference skill in reading comprehension and mathematics.

**Keywords: mathematics, reading, inference, attentional control, vocabulary**

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## INTRODUCTION

By now, there is robust evidence that reading and mathematics skills are related. Studies have consistently shown moderate to fairly strong relations between reading and mathematics (Aunola et al., 2004; Duncan et al., 2007; Grimm, 2008; Vilenius-Tuohimaa et al., 2008; Hart et al., 2010; Bailey et al., 2014; Korpipää et al., 2017, 2019; Erbeli et al., 2020; Koponen et al., 2020; Rinne et al., 2020; Vanbinst et al., 2020). For example, word reading and mathematics performances were moderately related with correlations ranging from 0.44 to 0.55 for first graders (Bailey et al., 2014). Another study showed that reading (composed of word reading and reading comprehension) and mathematics skills had fairly strong relations with correlations ranging from 0.65 to 0.67 for 7-to 12-year-olds (Hart et al., 2010). A recent meta-analysis also showed that students who experience a mathematics disability are two times more likely to have a reading disability (Joyner and Wagner, 2020). In the present study, we investigated sources of the relation between reading and mathematics, using data from first graders in the US.

## SOURCES OF THE RELATION BETWEEN READING AND MATHEMATICS SKILLS

Extant literature suggests several sources for the shared variance between reading and mathematics skills, including domain-general cognitive skills such as working memory and attentional control, and oral language skills such as vocabulary. According to theoretical models of reading (Kim, 2020) and mathematics (e.g., Geary, 1993; Geary and Hoard, 2005), domain-general cognitive skills or executive functions such as working memory and attentional control are foundational for reading and mathematics, respectively. Reading and mathematics both rely on holding and processing visual, phonological, and semantic information, and encoding and retrieving this information (Dehaene and Cohen, 1995; Geary and Hoard, 2005; Kim, 2020), for which working memory and attentional control are necessary. Indeed, a large number of studies have shown that working memory is related to mathematics (e.g., Bull and Scerif, 2001; Alloway et al., 2005; Koponen et al., 2007, 2020; Willcutt et al., 2013; Fuchs et al., 2016; Wang et al., 2016; Korpipää et al., 2017, 2019; Caviola et al., 2020; Rinne et al., 2020) and reading (e.g., Barnes et al., 1996; Swanson and Howell, 2001; Cain et al., 2004; Kim, 2017, 2020; Kim et al., 2018; Peng et al., 2018). Studies also showed the relation of inhibitory and attentional control to mathematics (e.g., Bull and Scerif, 2001; Fuchs et al., 2005, 2006; Gold et al., 2013; Rinne et al., 2020) and reading (e.g., Conners, 2009; Arrington et al., 2014; Kim, 2020). In addition, sustained attention was associated with comorbidity of math and reading difficulties (Barnes et al., 2020).

Another widely recognized source of the relation between reading and mathematics is oral language skills. For word reading, phonological processing is essential for mapping phonological representations with orthographic representations (e.g., Adams, 1990; Wagner et al., 1997; National Reading Panel., 2000). For reading comprehension, one must understand the words in a text to construct propositions of the given text (Anderson and Freebody, 1979), and quality lexical representation of a word allows efficient access to semantic information and successful reading comprehension (Perfetti, 2007). Therefore, vocabulary knowledge is important to reading comprehension (e.g., National Reading Panel., 2000; Perfetti and Hart, 2002; Elleman et al., 2009; Quinn et al., 2020). However, vocabulary knowledge is not sufficient for comprehension. Discourse comprehension of oral texts, listening comprehension, is also needed for reading comprehension (Gough and Tunmer, 1986; Hoover and Gough, 1990; Florit and Cain, 2011; Joshi et al., 2012; Kim, 2017, 2020).

Oral language skills are also important to mathematics. Verbal code is necessary for the development of number concepts because it connects the visual Arabic number code with the magnitude representation code (Geary, 1993; Dehaene and Cohen, 1995). Furthermore, much of mathematical knowledge and problems inherently relies on oral language skills such as vocabulary (both general and math-specific vocabulary) and listening comprehension. Not surprisingly, a rich body of studies indicates the relations of oral language skills to mathematics, including phonological processing (Hecht et al., 2001; Swanson and Sachse-Lee, 2001; Durand et al., 2005; Simmons et al., 2008; LeFevre et al., 2010; Koponen et al., 2020; Vanbinst et al., 2020), vocabulary (Durand et al., 2005; Fuchs et al., 2006; LeFevre et al., 2010; Purpura et al., 2011; Hornburg et al., 2018; Rinne et al., 2020), and listening comprehension (Aunola et al., 2004; Durand et al., 2005; Willcutt et al., 2013; Wang et al., 2016). For example, children's vocabulary and phonological awareness in preschool and kindergarten predicted their early numeracy skills (i.e., number naming), and their language skill composed of phonological awareness, vocabulary, and rapid automatized naming consistently predicted conventional mathematics skills 2 years later (e.g., numeration, measurement, number line; LeFevre et al., 2010). In a study of co-occurrence between reading and mathematics difficulties, Willcutt et al. (2013) found that verbal comprehension composed of vocabulary and comprehension explained reading and mathematics difficulties.

Another important source of the relation between mathematics and reading—reading comprehension in particular—is reasoning. Reasoning has long been considered important for mathematics skill (Russell, 1919; Piaget, 1952). Perhaps not surprisingly, reasoning is one of the eight standards for mathematical practice in the Common Core State Standards for mathematics (National Governors Association Center for Best Practices Council of Chief State School Officers., 2010), which are widely adopted in US schools. Reasoning is a broad, multi-dimensional, higher order construct that taps inferential skills, and includes deductive, inductive, causal, visual/spatial or non-verbal, and verbal reasoning. Studies have investigated and shown the roles of deductive, inductive, and non-verbal reasoning in mathematics skills (e.g., Handley et al., 2004; Cowan et al., 2005; Fuchs et al., 2005, 2016; Inglis and Simpson, 2008, 2009; Barkl et al., 2012; Morsanyi et al., 2013, 2017; Davidse et al., 2014; Wang et al., 2016).

Reasoning is also crucial for reading comprehension. Reading comprehension involves constructing propositions and integrating them to build a coherent mental representation of the text called the situation model (Kintsch, 1988). The text does not always explicitly provide all the information necessary for successful comprehension. Therefore, it is important for readers to make inferences to fill in the gaps, integrate information in the text, and integrate information in the text with prior knowledge (Kintsch, 1988; McNamara and Magliano, 2009). A rich body of studies has shown that inference skill is important to reading comprehension (e.g., Yuill and Oakhill, 1988; Barnes et al., 1996; Cain and Oakhill, 1999; Cain et al., 2004; Kim, 2020). Cain et al. (2004) showed that children's inferencing skill was related to reading comprehension after controlling for word reading, vocabulary, and working memory. Inference was also related to reading comprehension after accounting for working memory, attentional control, vocabulary, grammatical knowledge, comprehension monitoring, and perspective taking (Kim, 2020). Furthermore, poor comprehenders differed from their age-and skill-matched peers in their inferencing skill (Cain and Oakhill, 1999).

# PRESENT STUDY

Previous studies indicated that language and cognitive skills make contributions to both reading and mathematics skills. In the present study, we build on and expand prior work by investigating the relations of oral language (vocabulary), domain-general cognitions (working memory and attentional control), decoding, and inference to reading comprehension and mathematics for students in Grade 1. The question that guided the present study was as follows: How are working memory, attentional control, vocabulary, decoding, and inference related to reading comprehension and mathematics for students in Grade 1?

Note that short-term memory was included as part of working memory (e.g., Davidson et al., 2006). We hypothesized that all the included skills would be related to reading comprehension and mathematics based on prior evidence. The role of decoding in reading comprehension is well-established (Gough and Tunmer, 1986; Hoover and Gough, 1990; Florit and Cain, 2011). Although previous studies did not focus on the role of decoding in mathematics, we hypothesized its role as decoding is necessary for mathematics tasks that include written texts beyond numerals.

Of the language and cognitive skills, we were particularly interested in the role of inference to reading comprehension and mathematics over and above the other skills. As stated above, evidence from the reading literature and mathematics literature, respectively, clearly indicates that reasoning is important to both reading comprehension and mathematics. However, slightly different aspects of reasoning were investigated in reading and mathematics fields, respectively. In mathematics, prior investigations focused on inductive reasoning (Barkl et al., 2012), transitive deductive reasoning (e.g., Handley et al., 2004; Morsanyi et al., 2013, 2017), and conditional deductive reasoning (e.g., Inglis and Simpson, 2008, 2009). In reading, prior investigations focused on causal inference such as making inferences using prior knowledge (i.e., elaborative inference) or making inferences using information in the text (i.e., bridging inference). In this study, we investigated whether students' elaborative inference skill is related to mathematics as well as reading comprehension. Elaborative inference captures skill in inferring information and relations using explicitly stated or provided information and extrapolating beyond the information provided. As such, underlying causal elaborative inference, and deductive and inductive reasoning are inferential processes, and therefore, elaborative inference skill would be relevant to various dimensions of mathematics (e.g., estimation, numeration, computation, word problems).

# METHOD

## Participants

The sample included 83 students in Grade 1 (55% females; $M_{age}$ = 6.83) from eight classrooms in four schools in the Southwestern part of the US. The sample was composed of 75% Hispanics, 15% Whites, and 6% Asian Americans. All children in the participating classrooms were invited, and only consented children were included. The only exclusion criterion was students with identified intellectual disabilities, but no consented students were excluded based on this criterion. ∼67% of the students were eligible for the free and reduced lunch program, a proxy for poverty. ∼52% of students were classified as English learners (or limited English proficiency) according to the school district records.

## Measures

Students were assessed on reading comprehension, mathematics, inference, vocabulary, decoding, short-term memory, and attentional control. Unless otherwise noted, all the items were scored dichotomously, and reliability estimates are from the present sample. Reliability estimates were good to excellent and are reported in **Table 1**. Any questions from students regarding the task were addressed in the beginning of each task where the task was explained, and practice items were provided.

### Reading Comprehension

A standardized, nationally normed measure, the Reading task of the Measures of Academic Progress (MAP; Northwest Evaluation Association [NWEA], 2019) was used. MAP reading comprehension is a computer-adaptive, multiple-choice test. Students read literary and informational texts and answered questions about them; for vocabulary items, students also matched sentences to pictures or diagrams.

### Mathematics

A standardized, nationally normed measure, the Mathematics task of Measures of Academic Progress (MAP, North West Evaluation Association [NWEA], 2011) was used. Like the reading task, MAP mathematics is a computer-adaptive, multiple-choice test. The items assessed students' understanding of place value, counting, cardinality, number and operations, representing and solving problems, and representing and interpreting data (Northwest Evaluation Association, 2011).

### Inference

The Inference subtask of the Comprehensive Assessment of Spoken Lanauge-2nd Edition (CASL-2; Carrow-Woolfolk, 2017) was used. In this task, the student was presented with a brief scenario, then asked a question that required inference to answer correctly. For instance, the student heard "*Mandy wanted to wear last year's dress to school 1 day, but when she tried it on, she could not wear it. Why?*" The correct responses must reference the fact that Mandy has grown or the dress does not fit anymore. There were two practice items.

### Vocabulary

The Inference subtask of the Clinical Evaluation of Language Fundamentals-4th Edition (CELF-4; Semel et al., 2003) was used. In this task, the student was shown illustrations of people, objects, and actions, and was asked to name them. There was one demonstration item (demonstrating naming of a pictured object) and two practice items.

**TABLE 1** | Descriptive statistics.

| Variable | Reliability | Mean | SD | Min–Max | Skewness | Kurtosis |
|---|---|---|---|---|---|---|
| MAP reading SS | 0.97+ | 150.58 | 13.16 | 118–194 | −0.04 | 1.15 |
| MAP reading percentile rank | NA | 32.12 | 24.48 | 1–99 | 0.67 | −0.16 |
| MAP math SS | 0.97+ | 152.44 | 15.92 | 121–216 | 0.58 | 2.03 |
| MAP math percentile rank | NA | 33.35 | 28.36 | 1–99 | 0.62 | −0.73 |
| CASL-2 inference raw | 0.93 | 12.15 | 6.98 | 0–22 | −0.58 | −1.07 |
| CASL-2 inference SS | NA | 83.01 | 16.15 | 54–125 | −0.42 | −0.70 |
| CELF-4 vocabulary raw | 0.87 | 17.05 | 9.57 | 2–44 | 0.36 | −0.58 |
| CELF-4 vocabulary SS | NA | 5.63 | 3.34 | 1–15 | 0.42 | −0.49 |
| TOWRE-2 decoding raw | 0.92++ | 9.74 | 8.81 | 0–52 | 2.43 | 8.43 |
| TOWRE-2 decoding SS | NA | 91.00 | 13.93 | 68–145 | 1.43 | 3.83 |
| CTOPP-2 digit Span raw | 0.88 | 11.31 | 4.36 | 0–18 | −1.55 | 2.08 |
| CTOPP-2 digit Span SS | NA | 6.58 | 2.86 | 1–12 | −0.39 | −0.38 |
| SWAN attentional control | 0.98 | 26.83 | 11.69 | 3–54 | 0.32 | −0.31 |

*+ Northwest Evaluation Association, 2011; ++Torgesen et al. (2012). MAP = Measures of Academic Progress; SS = Standard Score; CASL-2 = Comprehensive Assessment of Spoken Lanauge-2nd Edition; CELF-4 = Clinical Evaluation of Language Fundamentals-4th Edition; TOWRE-2 decoding = Phonological Decoding Efficiency subtask of the Test of Word Reading Efficiency-2nd Edition; CTOPP-2 = Comprehensive Test of Phonological Processing-2; SWAN = Strengths and Weaknesses of ADHD Symptoms and Normal Behavior Scale.*

### Decoding

The Phonological Decoding Efficiency subtask of the Test of Word Reading Efficiency-2nd Edition (TOWRE-2; Torgesen et al., 2012) was used. In this task, the student was asked to read a list of words, which were listed in order of increasing difficulty, within 45 seconds. The number of correctly read words within the time was their score. Practice included reading aloud eight words.

### Short-Term Memory

The Digit Span subtask of the Comprehensive Test of Phonological Processing-2 (CTOPP-2; Wagner et al., 2013) was used. In this task, the student was presented with a sequence of digits and had to correctly recall the given sequence. Sequences increased in length, and administration discontinued after three consecutive incorrect responses. Correct answers were provided to students for Items one to four, following the protocols of CTOPP-2.

### Attentional Control

The Strengths and Weaknesses of ADHD Symptoms and Normal Behavior Scale (SWAN; Swanson et al., 2012) was used. SWAN is a behavioral checklist that includes 30 items rated on a seven-point scale, ranging from a score of one (*far below average*) to seven (*far above average*) to allow for ratings of relative strengths (above average) as well as weaknesses (below average). In the present study, we used the first nine items (e.g., "sustain attention on tasks or play activities," and "follow through on instructions and finish school work/chores."), which were shown to capture the respondent's ability to regulate attention (Sáez et al., 2012). Higher scores represent greater attentional control. Participating students' teachers completed the SWAN checklist.

## Procedures

The measures were administered individually in a quiet space in the schools. The order of assessment was as follows: short-term memory, vocabulary, inference, and decoding, which were administered ∼1 week apart by trained research assistants. MAP Reading and Mathematics tasks were administered by teachers as part of district practices. SWAN and MAP tasks administration intervals varied depending on teachers.

# RESULTS

## Descriptive Statistics

**Table 1** shows descriptive statistics. The sample students' mean performances on the MAP Reading and Mathematics tasks were in the low average range compared to the norm sample. Similar low average performance was found in the CASL-2 Inference task. The mean standard score of the TOWRE-2 decoding task was in the average range whereas mean standard scores on the CELF-4 Vocabulary and CTOPP-2 Digit Span tasks were in the low range. Note, however, these results should be taken with caution because many students in the sample were English learners and these tasks were not normed for English learners. What is important for the analysis in this study is that there was sufficient variability among students in the measured skills, and distributional properties were all adequate.

**Table 2** shows bivariate correlations. Reading comprehension and mathematics were very strongly related ($r = 0.88$). Inference, vocabulary, decoding, and attentional control were moderately to fairly strongly related to reading comprehension and mathematics ($0.50 \leq r\text{s} \leq 0.64$) whereas short-term memory was weakly related to reading comprehension and mathematics ($0.22 \leq r\text{s} \leq 0.23$).

**TABLE 2 |** Correlations between measures.

| | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| 1. MAP reading comprehension | – | | | | | |
| 2. MAP mathematics | 0.88 | – | | | | |
| 3. CASL-2 inference | 0.55 | 0.64 | – | | | |
| 4. CELF-4 vocabulary | 0.59 | 0.64 | 0.50 | – | | |
| 5. TOWRE-2 decoding | 0.58 | 0.50 | 0.29 | 0.44 | – | |
| 6. CTOPP digit span | 0.23 | 0.22 | 0.27 | 0.20+ | 0.11+ | – |
| 7. Attentional control | 0.58 | 0.59 | 0.42 | 0.51 | 0.57 | 0.11+ |

*All correlations are statistically significant ($p < 0.05$) unless marked by +. + $p > 0.05$. MAP = Measures of Academic Progress; SS = Standard Score; CASL-2 = Comprehensive Assessment of Spoken Lanauge-2nd Edition; CELF-4 = Clinical Evaluation of Language Fundamentals-4th Edition; TOWRE-2 decoding = Phonological Decoding Efficiency subtask of the Test of Word Reading Efficiency-2nd Edition; CTOPP-2 = Comprehensive Test of Phonological Processing-2; SWAN = Strengths and Weaknesses of ADHD Symptoms and Normal Behavior Scale.*

## Relations of Language and Cognitive Skills to Reading Comprehension and Mathematics

The path model shown in **Figure 1** was fitted to the data using the maximum likelihood estimator, and model fit was excellent: $\chi^2$ (1) = 0.50, $p$ = 0.48; CFI = 1.00; RMSEA = 0.00 [90% CI = 0.00, 0.26]; SRMR = 0.01. We used bootstrapping to estimate 95% confidence intervals. Standardized path coefficients and confidence intervals are shown in **Figure 1**. Reading comprehension was independently predicted by inference (0.27, $p$ = 0.003) and decoding skill (0.28, $p$ = 0.002). Vocabulary had a positive and statistically significant unique relation to reading comprehension when using a point estimate (0.22, $p$ = 0.02), but confidence intervals included a zero and therefore was considered non-significant (see **Figure 1**). Mathematics was independently predicted by inference (0.38, $p$ < 0.001), vocabulary (0.27, $p$ = 0.002), and attentional control (0.21, $p$ = 0.03). Attentional control was related to inference (0.39, $p$ < 0.001), vocabulary (0.49, $p$ < 0.001), and decoding (0.57, $p$ < 0.001). The relation of attentional control to reading comprehension was marginally significant (0.19, $p$ = 0.06) after controlling for short-term memory, decoding, vocabulary, and inference. Short-term memory was marginally related to inference after controlling for attentional control (0.19, $p$ = 0.06). (Note that given the relatively small sample size, we have noted paths that were just shy of the conventional statistical significance of 0.05.) Indirect and total effects of attentional control and short-term memory were estimated. The indirect effects of attentional control on reading comprehension and mathematics were 0.37 (s.e. = 0.07, $p$ < 0.001; 95% CI = 0.21, 0.53) and 0.36 (s.e. = 0.07, $p$ < 0.001; 95% CI = 0.23, 0.50), respectively, and its total effects were 0.56 for both (95% CI for reading comprehension = 0.36, 0.71; 95% CI for mathematics = 0.38, 0.71). For short-term memory, indirect effect and total effect were 0.08 (s.e. = 0.05, $p$ = 0.11; 95% CI = −0.01, 0.19) and 0.15 (s.e. = 0.09, $p$ = 0.08; 95% CI = −0.04, 0.31), respectively, for reading comprehension, and 0.10 (s.e. = 0.06, $p$ = 0.07; 95% CI = −0.01, 0.23) and 0.15 (s.e. = 0.09, $p$ = 0.10; 95% CI = −0.07, 0.30), respectively, for mathematics. Approximately 55% and 60% of total variance in reading comprehension and mathematics, respectively, were explained by the included predictors.

# DISCUSSION

In this study, we were interested in identifying sources of shared variance between reading comprehension and mathematics for students in Grade 1. Based on theory and prior evidence, we included language and cognitive skills, such as short-term memory, attentional control, decoding, vocabulary, and inference in our investigation.

Our findings revealed that inference was a common predictor of reading comprehension and mathematics for students in Grade 1 over and above short-term memory, attentional control, decoding, and vocabulary. Elaborative inference is part of a larger construct, reasoning, and is one of the necessary skills for establishing coherence and successful comprehension (Kintsch, 1988; Cain et al., 2004; Kim, 2020). Previous studies showed that different types of reasoning skills such as deductive and inductive reasoning and non-verbal reasoning skills contribute to mathematics (e.g., Handley et al., 2004; Cowan et al., 2005; Inglis and Simpson, 2009; Barkl et al., 2012; Morsanyi et al., 2013, 2017; Fuchs et al., 2016; Wang et al., 2016). In the present study, we used an inference task that requires students to infer information drawing on their background knowledge (i.e., elaborative inference). We hypothesized that elaborative inference would be important to mathematics because it captures one's skill in identifying and inferring relations, which is important to mathematical functions such as identifying and inferring patterns and relations (e.g., understanding how two or more items or numbers are related to each other) and deriving solutions. This hypothesis was supported as inference was independently related to both reading comprehension and mathematics even after accounting for the other language and cognitive skills. The results for reading comprehension are convergent with a large body of literature (e.g., Yuill and Oakhill, 1988; Cain and Oakhill, 1999; Cain et al., 2004; Kim, 2020) and theoretical models (e.g., van den Broek et al., 2005; Perfetti and Stafura, 2014; Kim, 2020). The findings for mathematics are in line with the importance of reasoning in mathematics performance. However, the relation of elaborative inference, a specific aspect of reasoning, to mathematics is novel in this study. These results suggest that primary grade students' skill in inferring unstated information using their background knowledge is a shared resource for reading comprehension and mathematics performance.

We also found that vocabulary was independently related to mathematics, but not to reading comprehension. Studies have shown that vocabulary knowledge, both general vocabulary knowledge and mathematical vocabulary words, is important to mathematics performance (Durand et al., 2005; LeFevre et al., 2010; Purpura et al., 2011; Hornburg et al., 2018; Rinne et al., 2020). The non-significant result for the unique relation of vocabulary to reading comprehension may appear inconsistent

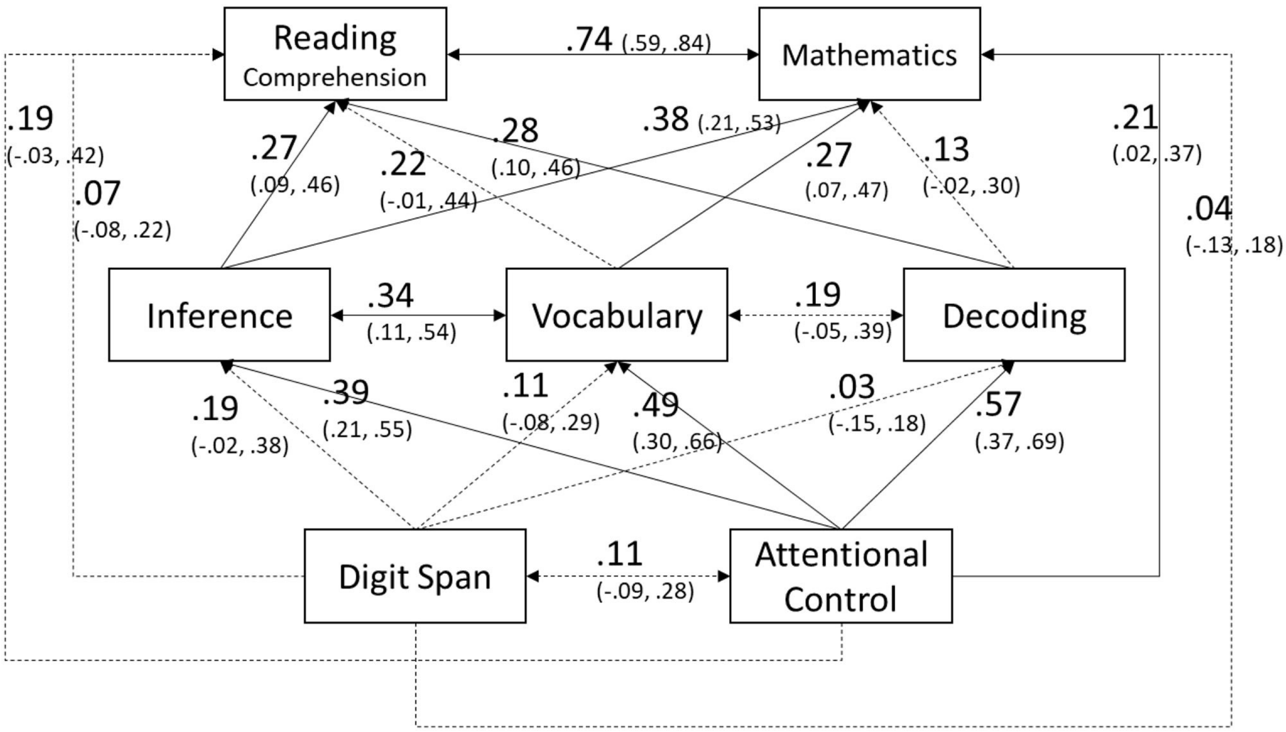


**FIGURE 1 |** Standardized path coefficients (95% confidence intervals) where language and cognitive skills predict reading comprehension and mathematics. Solid lines represent statistically significant paths ($p < 0.05$) whereas dashed lines represent non-significant paths.

with theoretical models of reading (Perfetti and Stafura, 2014; Kim, 2020) and a large body of empirical evidence (e.g., Perfetti and Hart, 2002; Elleman et al., 2009; Quinn et al., 2020). However, the results are likely due to shared variance of vocabulary with inference ($r = 0.50$) and decoding ($r = 0.44$, see **Table 2**). The moderate relations of vocabulary with inference and decoding are in line with previous work (e.g., for inference, see Lepola et al., 2012; Tompkins et al., 2013; Currie and Cain, 2015; Kim, 2016, 2017; for decoding, see Ouellette, 2006; Ricketts et al., 2007). Vocabulary learning requires deriving or inferring meaning from context using meaning cues, and inferencing unstated meaning in a text relies on knowledge of vocabulary words (Currie and Cain, 2015; Kim, 2016). Furthermore, vocabulary knowledge is also hypothesized to be related to decoding via its relation with phonological awareness (e.g., Metsala, 1999) and irregular word reading (Ricketts et al., 2007). Therefore, the lack of an independent relation of vocabulary to reading comprehension over and above inference, decoding, short-term memory, and attentional control should not be taken as a lack of its contribution.

With regard to domain-general cognitions, attentional control and short-term memory, different patterns were found. Attentional control made a direct contribution to mathematics while it was marginally related to reading comprehension after controlling for the other skills. The relations of attentional control to reading comprehension and mathematics are in line with prior work (e.g., Bull and Scerif, 2001; Fuchs et al., 2005; Arrington et al., 2014; Barnes et al., 2020; Kim, 2020), and the present study extends prior work by showing the pathways of its contributions. That is, the present study revealed not only a direct relation of attentional control to mathematics and reading comprehension, but also the indirect relations of attentional control via inference and vocabulary (see **Figure 1**). In fact, indirect effects of attentional control on reading comprehension and mathematics were substantial. Studies have shown that attentional control is necessary for reading comprehension and mathematics (see above), and for vocabulary and inference skill (Saldert and Ahlsen, 2007; Smith et al., 2010; Nicolay and Poncelet, 2013; Kim, 2016, 2020), which contribute to reading comprehension and mathematics (see above). Therefore, it is important to recognize not only direct effects but also indirect effects of attentional control on reading comprehension and mathematics. This is in line with a recent theoretical model of reading, which explicitly articulated direct and indirect relations of skills to reading comprehension (Kim, 2020).

Unlike attentional control, short-term memory was not independently related to any of the predictors nor reading comprehension and mathematics. An exception is its marginally significant relation to inference. Note that short-term memory was related to reading comprehension, mathematics, and inference in the zero order correlations (**Table 2**), but it was not after accounting for attentional control. In other words, the present findings may be due to the moderate relation of attentional control to the other skills ($0.42 \leq r\text{s} \leq 0.59$, see

**Table 2**) such that although short-term memory is related to inference, reading comprehension, and mathematics, it no longer has a unique relation over and above attentional control.

We found that decoding was uniquely related to reading comprehension but not mathematics. This is convergent with theoretical models of reading and a large body of evidence about the necessary role of decoding in reading comprehension (e.g., Hoover and Gough, 1990; Florit and Cain, 2011; Kim, 2017, 2020). Similar to the relation of vocabulary to reading comprehension, these results do not entail that decoding skill is not important for mathematics because decoding is necessary for any mathematics tasks that require students to read texts. What the present findings suggest is that although decoding skill was moderately related to mathematics (see **Table 2**), once the other predictors in the model were accounted for, it did not add a unique explanation of mathematics performance.

Taken together, these results indicate that the connection between early reading comprehension and mathematics is partly explained by and built on shared reliance on inferencing skill, general vocabulary knowledge, and attentional control. In other words, these are not specific to reading or mathematics performance. This implies that instruction on these skills would improve performance and development of reading comprehension *and* mathematics. Future experimental work is needed to test this hypothesis.

## LIMITATIONS AND FUTURE DIRECTIONS

The generalizability of the present findings is limited to populations that share similar characteristics with the present sample, that is, first-grade students many of whom were English learners and from low socio-economic backgrounds. Theoretically the included language, cognitive, and decoding skills are expected to be important for students from various backgrounds, including L1 vs. L2 learners. However, the relative weight of their roles might differ as a function of language learner status (e.g., vocabulary may play a greater constraining role for L2 learners than for L1 learners; See Kim, 2020). Future replications with students from different demographic backgrounds are warranted. Furthermore, in this study, relations were estimated using observed variables which suffer from measurement error. Therefore, future replications are needed using latent variables for the included constructs.

Another important future direction is replication with a larger sample size. Given a relatively small sample size in the present study, some of the path coefficients in this study (i.e., short-term memory to inference; attentional control and vocabulary to reading comprehension) would have reached conventional statistical significance with a larger sample size. Despite this limitation, however, we believe the patterns found in the present study provide a good starting point for future exploration of shared language and cognitive sources of reading and math, and the nature of their relations.

Future studies should also explore other predictors of shared variance between reading comprehension and mathematics. For example, in the present study, we included elaborative inference, and future work can include other types of reasoning/inference skills such as deductive reasoning and non-verbal reasoning (Cowan et al., 2005; Pimperton and Nation, 2010) in conjunction with elaborative inference. This will reveal the relations among these different types of reasoning, and their shared and unique contributions to reading and mathematics.

Finally, the present study examined unidirectional relations, given cross-sectional data. However, bidirectional relations are hypothesized between language and cognitive (e.g., vocabulary) and reading comprehension according to theoretical models of reading (e.g., Kim, 2020). Such relations are also suggested between language and cognitive skills and mathematics (e.g., Cameron et al., 2019). Future longitudinal studies are warranted to investigate potential bidirectional relations.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the author upon request.

## ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Human Subjects Research in the Office of Research in the University of California Irvine. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

## AUTHOR CONTRIBUTIONS

Y-SGK conceived of the presented idea, collected and analysed data, and wrote the manuscript.

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## REFERENCES


Adams, M. (1990). *Beginning to Read: Thinking and Learning About Print*. Cambridge, MA: MIT Press.

Alloway, T. P., Gathercole, S. E., Adams, A., Willis, C., Eaglen, R., and Lamont, E. (2005). Working memory and phonological awareness as predictors of progress towards early learning goals at school entry. *Br. J. Dev. Psychol.* 23, 417–426. doi: 10.1348/026151005X26804

Anderson, R. C., and Freebody, P. (1979). *Vocabulary Knowledge (Tech. Rep. No. 136)*. University of Illinois, Center for the Study of Reading.

Arrington, C. N., Kulesz, P. A., Francis, D. J., Fletcher, J. M., and Barnes, M. A. (2014). The contribution of attentional control and working memory to reading comprehension and decoding. *Sci. Stud. Read.* 18, 325–346. doi: 10.1080/10888438.2014.902461

Aunola, K., Leskinen, E., Lekkanen, M.-K., and Nurmi, J.-E. (2004). Developmental dynamics of math performance from preschool to grade 2. *J. Educ. Psychol.* 96, 699–713. doi: 10.1037/0022-0663.96.4.699

Bailey, D. H., Watts, T. W., Littlefield, A. K., and Geary, D. C. (2014). State and trait effects on individual differences in children's mathematical development. *Psychol. Sci*. 25, 2017-2026. doi: 10.1177/0956797614547539

Barkl, S., Porter, A., and Ginns, P. (2012). Cognitive training for children: effects on inductive reasoning, deductive reasoning, and mathematics achievement in an Australian school setting. *Psychol. Sch.* 49, 828–842. doi: 10.1002/pits.21638

Barnes, M. A., Clemens, N. H., Fall, A.-M., Roberts, G., Klein, A., Starkey, P., et al. (2020). Cognitive predictors of difficulties in math and reading in pre-kindergarten children at high risk for learning disabilities. *J. Educ. Psychol.* 112, 685–700. doi: 10.1037/edu0000404

Barnes, M. A., Dennis, M., and Haefele-Kalvaitis, J. (1996). The effects of knowledge availability and knowledge accessibility on coherence and elaborative inferencing in children from 6 to 15 years of age. *J. Exp. Child Psychol.* 61, 216–241. doi: 10.1006/jecp.1996.0015

Bull, R., and Scerif, G. (2001). Executive functioning as a predictor of children's mathematics ability: inhibition, switching, and working memory. *Dev. Neuropsychol.* 19, 273–293. doi: 10.1207/S15326942DN1903_3

Cain, K., and Oakhill, J. (1999). Inference making ability and its relation to comprehension failure in young children. *Read. Writ.* 11, 489–503. doi: 10.1023/A:1008084120205

Cain, K., Oakhill, J., and Bryant, P. (2004). Children's reading comprehension ability: concurrent prediction by working memory, verbal ability, and component skills. *J. Educ. Psychol.* 96, 31–42. doi: 10.1037/0022-0663.96.1.31

Cameron, C. E., Kim, H., Duncan, R. J., Becker, D. R., and McClelland, M. M. (2019). Bidirectional and co-developing associations of cognitive, mathematics, and literacy skills during kindergarten. *J. Appl. Dev. Psychol.* 62, 135–144. doi: 10.1016/j.appdev.2019.02.004

Carrow-Woolfolk, E. (2017). *Comprehensive Assessment of Spoken Language (CASL-2), 2nd Edn*. Gladstone: Western Psychological Services.

Caviola, S., Collillng, L. J., Mammarella, I., and Szucs, D. (2020). Predictors of mathematics in primary school: magnitude comparison, verbal and spatial working memory measures. *Dev. Sci*. 23:e12957. doi: 10.1111/desc.12957

Conners, F. A. (2009). Attentional control and the simple view of reading. *Read Writ.* 22, 591–613. doi: 10.1007/s11145-008-9126-x

Cowan, R., Donlan, C., Newton, E. J., and Lloyd, D. (2005). Number skills and knowledge in children with specific language impairment. *J. Educ. Psychol.* 97, 732–744. doi: 10.1037/0022-0663.97.4.732

Currie, N. K., and Cain, K. (2015). Children's inference generation: the role of vocabulary and working memory. *J. Exp. Child Psychol.* 137, 57–75. doi: 10.1016/j.jecp.2015.03.005

Davidse, N. J., De Jong, M. T., and Bus, A. G. (2014). Explaining common variance shared by early numeracy and literacy. *Read. Writ.* 27, 631–648. doi: 10.1007/s11145-013-9465-0

Davidson, M. C., Amso, D., Anderson, L. C., and Diamond, A. (2006). Development of cognitive control and executive functions from 4 to 13 years: evidence from manipulations of memory, inhibition, and task switching. *Neuropsychologia* 44, 2037–2078. doi: 10.1016/j.neuropsychologia.2006.02.006

Dehaene, S., and Cohen, L. (1995). Towards an anatomical and functional model of number processing. *Math. Cogn.* 1, 83–120.

Duncan, G. J., Dowsett, C. J., Classens, A., Magnuson, K., Huston, A. C., Klebanov, P., et al. (2007). School readiness and later achievement. *Dev. Psychol.* 43, 1428-1446. doi: 10.1037/0012-1649.43.6.1428

Durand, M., Hulme, C., Larking, R., and Snowling, M. (2005). The cognitive foundations of reading and arithmetic skills in 7-to 10-year-olds. *J. Exp. Child Psychol.* 91, 113–136. doi: 10.1016/j.jecp.2005.01.003

Elleman, A. M., Lindo, E. J., Morphy, P., and Compton, D. L. (2009). The impact of vocabulary instruction on passage-level comprehension of school-age children: a meta-analysis. *J. Res. Educ. Eff.* 2, 1–44. doi: 10.1080/19345740802539200

Erbeli, F., Shi, Q., Campbell, A. R., Hart, S. A., and Woltering, S. (2020). Developmental dynamics between reading and math in elementary school. *Dev. Sci.* 24: e13004. doi: 10.1111/desc.13004

Florit, E., and Cain, K. (2011). The simple view of reading: is it valid for different types of alphabetic orthographies? *Educ. Psychol. Rev.* 23, 553–576. doi: 10.1007/s10648-011-9175-6

Fuchs, L. S., Compton, D. L., Fuchs, D., Paulsen, K., Bryant, J. D., and Hamlett, C. L. (2005). The prevention, identification, and cognitive determinants of math difficulty. *J. Educ. Psychol.* 97, 493–513. doi: 10.1037/0022-0663.97.3.493

Fuchs, L. S., Fuchs, D., Compton, D. L., Powell, S. R., Seethaler, P. M., Capizzi, A. M., et al. (2006). The cognitive correlates of third-grade skill in arithmetic, algorithmic computation, and arithmetic word problems. *J. Educ. Psychol.* 98, 29–43. doi: 10.1037/0022-0663.98.1.29

Fuchs, L. S., Geary, D., Fuchs, D., Compton, D. L., and Hamlett, C. L. (2016). Pathways to third-grade calculation vs. word-reading competence: are they more alike or different? *Child Dev.* 87, 558–567. doi: 10.1111/cdev.12474

Geary, D. C. (1993). Mathematical disabilities: cognitive, neuropsychological, and genetic components. *Psychol. Bull.* 114, 345–362. doi: 10.1037/0033-2909.114.2.345

Geary, D. C., and Hoard, M. K. (2005). Learning disabilities in arithmetic and mathematics: theoretical and empirical perspectives. in *Handbook of Mathematical Cognition*, ed J. I. D. Campbell (Hove: Psychology Press), 253-267.

Gold, A. B., Ewing-Cobbs, L., Cirino, P., Fuchs, L. S., Stuebing, K. K., and Fletcher, J. M. (2013). Cognitive and behavioral attention in children with math difficulties. *Child Neuropsychol.* 19, 420–437. doi: 10.1080/09297049.2012.690371

Gough, P. B., and Tunmer, W. E. (1986). Decoding, reading, and reading disability. *Remedial Spec. Educ.* 7, 6–10. doi: 10.1177/074193258600700104

Grimm, K. J. (2008). Longitudinal associations between reading and mathematics achievement. *Dev. Neuropsychol.* 33, 410–426. doi: 10.1080/87565640801982486

Handley, S. J., Capton, A., Beveridge, M., Dennis, I., and Evans, J., St,. B. T. (2004). Working memory, inhibitory control and the development of children's reasoning. *Think. Reason.* 10, 175-195. doi: 10.1080/13546780442000051

Hart, S. A., Petrill, S. A., and Thompson, L. A. (2010). A factorial analysis of timed and untimed measures of mathematics and reading abilities in school aged twins. *Learn. Individ. Differ.* 20, 63–69. doi: 10.1016/j.lindif.2009.10.004

Hecht, S. A., Torgesen, J. K., Wagner, R. K., and Rashotte, C. A. (2001). The relations between phonological processing abilities and emerging individual differences in mathematical computation skills: a longitudinal study from second to fifth grades. *J. Exp. Child Psychol.* 79, 192–227. doi: 10.1006/jecp.2000.2586

Hoover, W. A., and Gough, P. B. (1990). The simple view of reading. *Read. Writ.* 2, 127–160. doi: 10.1007/BF00401799

Hornburg, C. B., Schmitt, S. A., and Purpura, D. J. (2018). Relations between preschoolers' mathematical language understanding and specific numeracy skills. *J. Exp. Child Psychol.* 176, 84–100. doi: 10.1016/j.jecp.2018.07.005

Inglis, M., and Simpson, A. (2008). Conditional inference and advanced mathematical study. *Educ. Stud. Math.* 67, 187–204. doi: 10.1007/s10649-007-9098-9

Inglis, M., and Simpson, A. (2009). Conditional inference and advanced mathematical study: further evidence. *Educ. Stud. Math.* 72, 185–198. doi: 10.1007/s10649-009-9187-z

Joshi, R. M., Tao, S., Aaron, P. G., and Quiroz, B. (2012). Cognitive component of componential model of reading applied to different orthographies. *J. Learn. Disabil.* 45, 480–486. doi: 10.1177/0022219411432690

Joyner, R. E., and Wagner, R. K. (2020). Co-occurrence of reading disabilities and math disabilities: a meta-analysis. *Sci. Stud. Read.* 24, 14–22. doi: 10.1080/10888438.2019.1593420

Kim, Y.-S. G. (2016). Direct and mediated effects of language and cognitive skills on comprehension or oral narrative texts (listening comprehension) for children. *J. Exp. Child Psychol.* 141, 101-120. doi: 10.1016/j.jecp.2015.08.003

Kim, Y.-S. G. (2017). Why the simple view of reading is not simplistic: Unpacking the simple view of reading using a direct and indirect effect model of reading (DIER). *Sci. Stud. Read.* 21, 310–333. doi: 10.1080/10888438.2017.1291643

Kim, Y.-S. G. (2020). Hierarchical and dynamic relations of language and cognitive skills to reading comprehension: testing the direct and indirect effects model of reading (DIER). *J. Exp. Child Psychol.* 112, 667–684. doi: 10.1037/edu0000407

Kim, Y.-S. G., Cho, J.-R., and Park, S.-G. (2018). Unpacking direct and indirect relations of short term memory, RAN, phonological awareness, morphological awareness, and orthographic awareness to word reading. *J. Learn. Disabil.* 51, 473–481. doi: 10.1177/0022219417724817

Kintsch, W. (1988). The use of knowledge in discourse processing: a construction-integration model. *Psychol. Rev.* 95, 163–182. doi: 10.1037/0033-295X.95.2.163

Koponen, T., Aunola, K., Ahonen, T., and Nurmi, J.-E. (2007). Cognitive predictors of single-digit and procedural calculation skills and their covariation with reading skill. *J. Exp. Child Psychol.* 97, 220-241. doi: 10.1016/j.jecp.2007.03.001

Koponen, T., Eklund, K., Heikkila, R., Salminen, J., Fuchs, L., Fuchs, D., et al. (2020). Cognitive correlates of the covariance in reading and arithmetic fluency: importance of serial retrieval fluency. *Child Dev.* 91, 1063-1080. http://dx.doi.org/10.1111/cdev.13287 doi: 10.1111/cdev.13287

Korpipää, H., Koponen, T., Aro, M., Tolvanen, A., Aunola, K., Poikkeus, A., et al. (2017). Covariation between reading and arithmetic skills from grade 1 to grade 7. *Contemp. Educ. Psychol.* 51, 131-140. doi: 10.1016/j.cedpsych.2017.06.005

Korpipää, H., Niemi, P., Aunola, K., Koponen, T., Hannula-Sormunen, M., Stolt, S., et al. (2019). Prematurity and overlap between reading and arithmetic: the cognitive mechanism behind the association. *Contemp. Educ. Psychol.* 56, 171–179. doi: 10.1016/j.cedpsych.2019.01.005

LeFevre, J.-A., Fast, L., Skwarchuk, S.-L., Smith-Chant, B. L., Bisanz, J., Kamawar, D., et al. (2010). Pathways to mathematics: Longitudinal predictors of performance. *Child Dev.* 81, 1753-1767. doi: 10.1111/j.1467-8624.2010.01508.x

Lepola, J., Lynch, J., Laakkonen, E., Silvén, M., and Niemi, P. (2012). The role of inference making and other language skills in the development of narrative listening comprehension in 4-to 6-year-old children. *Read. Res. Q.* 47, 259–282. doi: 10.1002/rrq.020

McNamara, D. S., and Magliano, J. (2009). "Toward a comprehensive model for comprehension," in *The Psychology of Learning and Motivation,* ed B. Ross (Amsterdam: Elsevier), 297–384. doi: 10.1016/S0079-7421(09)51009-2

Metsala, J. L. (1999). Young children's phonological awareness and non-word repetition as a function of vocabulary development. *J. Educ. Psychol.* 91, 3–19. doi: 10.1037/0022-0663.91.1.3

Morsanyi, K., Devine, A., Nobes, A., and Szucs, D. (2013). The link between logic, mathematics and imagination. Evidence from children with developmental dyscalculia and mathematically gifted children. *Dev. Sci.* 16, 542–553. doi: 10.1111/desc.12048

Morsanyi, K., Kahl, T., and Rooney, R. (2017). "The link between math and logic in adolescence: the effect of argument form," in *Individual Differences in Judgment and Decision Making from a Developmental Context*, eds M. E. Toplak, and J. Weller (Hove: Psychology Press), 166–185.

National Governors Association Center for Best Practices and Council of Chief State School Officers. (2010). *Common Core State Standards for Mathematics*. Washington, DC: National Governors Association Center for Best Practices, Council of Chief State School Officers.

National Reading Panel. (2000). *Report of the National Reading Panel-Teaching children to Read: An Evidence-Based Assessment of the Scientific Research Literature on Reading and its Implications for Reading Instruction*. National Institute of Child Health and Human Development.

Nicolay, A.-C., and Poncelet, M. (2013). Cognitive abilities underlying second-language vocabulary acquisition in an early second-language immersion education context: a longitudinal study. *J. Exp. Child Psychol.* 115, 655-671. doi: 10.1016/j.jecp.2013.04.002

Northwest Evaluation Association (2011). *Technical manual for Measures of Academic Progress (MAP) and Measures of Academic Progress for Primary Grades (MPG)*. Portland: Northwest Evaluation Association.

Ouellette, G. P. (2006). What's meaning got to do with it: the role of vocabulary in word reading and reading comprehension. *J. Educ. Psychol.* 98, 554–566. doi: 10.1037/0022-0663.98.3.554

Peng, P., Barnes, M., Wang, C., Wang, W., Li, S., Swanson, H. L., et al. (2018). A meta-analysis on the relation between reading and working memory. *Psychol. Bull.* 144, 48–76. doi: 10.1037/bul0000124

Perfetti, C. (2007). Reading ability: lexical quality to comprehension. *Sci. Stud. Read.* 11, 357–383. doi: 10.1080/10888430701530730

Perfetti, C., and Stafura, J. (2014). Word knowledge in a theory of reading comprehension. *Sci. Stud. Read.* 18, 22-37. doi: 10.1080/10888438.2013.827687

Perfetti, C. A., and Hart, L. (2002). "The lexical quality hypothesis," in *Precursors of Functional Literacy*, ed L. Verhoeven (Amsterdam: John Benjamins Publishing Company), 189–313. doi: 10.1075/swll.11.14per

Piaget, J. (1952). *The Child's Conception of Number*. Oxfordshire: Routledge.

Pimperton, H., and Nation, K. (2010). Understanding words, understanding numbers: an exploration of the mathematical profiles of poor comprehenders. *Br. J. Educ. Psychol.* 80, 255–268. doi: 10.1348/000709909X477251

Purpura, D. J., Hume, L. E., Sims, D. M., and Lonigan, C. J. (2011). Early literacy and early numeracy: the value of including early literacy skills in the prediction of numeracy development. *J. Exp. Child Psychol.* 110, 647-658. doi: 10.1016/j.jecp.2011.07.004

Quinn, J. M., Wagner, R. K., Petscher, Y., Roberts, G., Menzel, A. J., and Schatschneider, C. (2020). Differential codevelopment of vocabulary knowledge and reading comprehension for students with and without learning disabilities. *J. Educ. Psychol.* 112, 608–627. doi: 10.1037/edu0000382

Ricketts, J., Nation, K., and Bishop, D. V. M. (2007). Vocabulary is important for some, but not all reading skills. *Sci. Stud. Read.* 11, 235–257. doi: 10.1080/10888430701344306

Rinne, L. F., Ye, A., and Jordan, N. C. (2020). Development of arithmetic fluency: a direct effect of reading fluency? *J. Educ. Psychol.* 112, 110–130. doi: 10.1037/edu0000362

Russell, B. (1919). *Introduction to Mathematical Philosophy*. Crows Nest: George Allen and Unwin.

Sáez, L., Folsom, J. S., Al Otaiba, S., and Schatschneider, C. (2012). Relations among student attention behaviors, teacher practices, and beginning word reading skill. *J. Learn. Disabil.* 45, 418–432. doi: 10.1177/0022219411431243

Saldert, C., and Ahlsen, E. (2007). Inference in right hemisphere damaged individuals' comprehension: the role of sustained attention. *Clin. Linguist. Phon.* 21, 637–655. doi: 10.1080/02699200701431056

Semel, E., Wiig, E. H., and Secord, W. A. (2003). *Clinical Evaluation of Language Fundamentals (CELF-4), $4^{th}$ Edn*. San Antonio, TX: The Psychological Corporation.

Simmons, F., Singleton, C., and Horne, J. (2008). Phonological awareness and visuo-spatial sketchpad functioning predict early arithmetic attainment: evidence from a longitudinal study. *Eur. J. Cognit. Psychol.* 20, 711–722. doi: 10.1080/09541440701614922

Smith, L. B., Colunga, E., and Yoshida, H. (2010). Knowledge as process: contextually cued attention and early word learning. *Cogn. Sci.* 34, 1287–1314. doi: 10.1111/j.1551-6709.2010.01130.x

Swanson, H. L., and Howell, M. (2001). Working memory, short-term memory, and speech rate as predictors of children's reading performance at different ages. *J. Educ. Psychol.* 93, 720-734. doi: 10.1037//0022-0663.93.4.720

Swanson, H. L., and Sachse-Lee, C. (2001). Mathematical problem solving and working memory in children with learning disabilities: both executive and phonological processes are important. *J. Exp. Child Psychol.* 79, 294–321. doi: 10.1006/jecp.2000.2587

Swanson, J. M., Schuck, S., Porter, M. M., Carlson, C., Hartman, K., Sergeant, J. A., et al. (2012). Categorical and dimensional definitions and evaluations of symptoms of ADHD: history of SNAP and SWAN rating scales. *Int. J. Educ. Psychol.Assess.* 10, 51-70.

Tompkins, V., Guo, Y., and Justice, L. M. (2013). Inference generation, story comprehension, and language in the pre-school years. *Read. Writ.* 26, 403–429. doi: 10.1007/s11145-012-9374-7

Torgesen, J. K., Wagner, R. K., and Rashotte, C. A. (2012). *Test of Word Reading Efficiency (TOWRE-2), 2nd Edn*. Austin, TX: Pro-Ed.

van den Broek, P., Rapp, D. N., and Kendeou, P. (2005). Integrating memory-based and constructionist processes in accounts of reading comprehension. *Discourse Process.* 39, 299–316. doi: 10.1080/0163853X.2005.9651685

Vanbinst, K., van Bergen, E., Ghesquière, P., and De Smedt, B. (2020). Cross domain associations of key cognitive correlates of early reading and early arithmetic in 5-year-olds. *Early Child. Res. Q.* 51, 144–152. doi: 10.1016/j.ecresq.2019.10.009

Vilenius-Tuohimaa, P. M., Aunola, K., and Nurmi, J. E. (2008). The association between mathematical word problems and reading comprehension. *Educ. Psychol.* 28, 409–426. doi: 10.1080/01443410701708228

Wagner, R. K., Torgesen, J. K., Rashotte, C. A., Hecht, S. A., Barker, T. A., Burgess, S. R., et al. (1997). Changing relations between phonological processing abilities and word-level reading as children develop from beginning to skilled readers: a 5-year longitudinal study. *Dev. Psychol.* 33, 468–479. doi: 10.1037/0012-1649.33.3.468

Wagner, R. K., Torgesen, J. K., Rashotte, C. A., and Pearson, N. A. (2013). *Comprehensive Test of Phonological Processing-(CTOPP-2), 2nd Edn.* Austin, TX: Pro-Ed. doi: 10.1037/t52630-000

Wang, A. Y., Fuchs, L. S., and Fuchs, D. (2016). Cognitive and linguistic predictors of mathematical word problems with and without irrelevant information. *Learn. Individ. Differ. 52*, 79-87. doi: 10.1016/j.lindif.2016.10.015

Willcutt, E. G., Petrill, S. A., Wu, S., Boada, R., DeFries, J. C., Olson, R. K., et al. (2013). Comorbidity between reading disability and math disability: Concurrent psychopathology, functional impairment, and neuropsychological functioning. *J. Learn. Disabil.* 46, 500–516. doi: 10.1177/0022219413477476

Yuill, N., and Oakhill, J. (1988). Effects of inference awareness training on poor reading comprehension. *Appl. Cogn. Psychol.* 2, 33–45. doi: 10.1002/acp.235000105

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# Cross- and Within-Domain Associations of Early Reading and Mathematical Skills: Changes Across the Preschool Years

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Existing research has mainly examined the role of cognitive correlates of early reading and mathematics from a stationary perspective that does not consider how these skills unfold and interact over time. This approach constraints the interpretation of cross-domain associations and the *specificity* of domain-specific covariates. In this study, we disentangle the role of these predictors and investigate cross-domain associations between reading, math, and two related domain-specific predictors (phonological awareness and fluency with number sets) over the kindergarten years ($n = 512$, Mage = 54 months, SDage = 3.5, 52% females). Results reveal that the overlap between reading and math skills changes over development. Reciprocal associations between reading and math abilities are observed at earlier stages; then, reading abilities become the lead force. Findings also show that phonological awareness and fluency with number sets are domain-specific predictors that do not contribute to cross-domain gains in academic skills. Indeed, there is a trend for domain-specific skills to be more strongly related to achievement at the beginning of formal education than at the beginning of kindergarten, which suggests an increasing differentiation of domains over the kindergarten years. Such findings have implications for the timing and nature of interventions that aim to support children's reading and mathematical development.

**Keywords: mathematics, reading, phonological awareness, preschool (kindergarten), longitudinal, number sets**



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## INTRODUCTION

The acquisition of basic reading and numerical skills prior to school is argued to be the bedrock for continued learning as children enter formal schooling. In an influential study that investigated several datasets from different large-scale studies, Duncan et al. (2007) found that early math and reading skills have the greatest predictive power in school readiness and later achievement. Indeed, beyond allowing engagement in formal academic learning, such skills are predictive of longer-term life outcomes, including income, leadership in critical occupational roles, and even life expectancy (Ritchie and Bates, 2013; Lubinski et al., 2014). Decades of research on the acquisition and development of reading and math skills have shaped policy recommendations regarding instructional practices, materials, and assessment of reading and math skills at both national and international levels. Nonetheless, the bulk of evidence supporting such policy recommendations comes from domain-specific studies that have focused on either math or reading. This study aims to extend the existing knowledge base by exploring cross-domain associations between reading, math, and two related domain-specific predictors (phonological awareness and fluency in identifying and processing quantities represented by numerals and object sets) over the kindergarten years. Clarifying the possible existence of bi-directional associations on the underlying influences of reading and mathematics ability in early childhood may carry significant implications in the refinement of pedagogy and policy.

## Co-development of Reading and Mathematics

There is clear evidence that math and reading abilities are closely related (Davis et al., 2014). Findings from correlational studies suggest that about 40–50% of the variance in reading and math is shared. This association between reading and mathematics emerges during early childhood (McClelland et al., 2007) and persists into the elementary school years (Hecht et al., 2001). The comorbidity between difficulties in reading and mathematics also highlights the strong link between the development of reading and mathematical skills (Landerl and Moll, 2010; Mann Koepke and Miller, 2013; Moll et al., 2015, 2019). Although the origins and reasons for comorbidity are not clear yet, rates of comorbidity of reading and mathematics difficulties have been found to be more than 10 times larger than if they were unrelated conditions (Wilson et al., 2015). Consistent with this, a recent meta-analysis reported that children with a mathematical disability were approximately two times more likely to possess a reading disability compared to children without a mathematical disability (Joyner and Wagner, 2020 for a review).

This reciprocity has been investigated in non-experimental studies that have looked at how reading and math abilities jointly unfold and affect each other during childhood, through intervention studies, and through neuroimaging and behavioral studies examining the co-occurrence of math and reading difficulties. While the findings are arguably consistent in highlighting the cross-domain association between reading and mathematics, some differences exist in terms of methodological approaches and directionality of effects. For instance, an examination of six longitudinal data sets by Duncan et al. (2007), found early math skills to be a stronger predictor of later reading achievement, compared to early reading in its ability to predict math proficiency. More recent work by Bailey et al. (2020) draws further attention to the possible impact of the choice of analytical method on the cross-domain estimates obtained. In their study, the use of the traditional cross-lagged panel model yielded results similar to Duncan et al. (2007); in contrast, use of more recently developed variations of this model—which account for potentially confounding unmeasured individual and environmental factors—yielded attenuated estimates of the cross-domain association between reading and mathematics, showing evidence of low (but larger) paths from reading to later math (see also, Erbeli et al., 2020). Intervention studies also add to the evidence for reciprocal cross-domain associations. Improvements in mathematics ability have been observed following reading-oriented learning activities (Purpura et al., 2017). Similarly, engagement with structured learning activities designed to facilitate acquisition of mathematics skills has been found to predict stronger language ability in preschool (Sarama et al., 2012; Napoli and Purpura, 2018; but see, Fuchs et al. (2013), for differential findings).

Findings from neuroimaging studies also suggest a substantial overlap between reading and math. Activation of the left inferior frontal gyrus has been observed during the performance of both reading- and mathematics-related tasks (Andin et al., 2015). The phonological network, involved during the performance of reading-related tasks, has also been found to be activated during tasks requiring direct retrieval of mathematics-related facts or procedures (Li et al., 2019). Parts of the left temporo-parietal cortex—in particular, the left angular gyrus—have been linked with both reading (e.g., Pugh et al., 2001; Schlaggar and McCandliss, 2007) and math (e.g., Dehaene et al., 2003). Studies that have looked at neural activations in children with different patterns of difficulties in reading and math suggest that such comorbidity of reading and math deficits may be explained by neural underpinnings. Recently, Peters et al. (2018) explored the neural activation in four distinct groups of children (dyslexia, dyscalculia, comorbid dyslexia/dyscalculia, and typically developing) during reading and arithmetic tasks. They found that children with dyslexia, dyscalculia, and comorbid dyslexia/dyscalculia had similar neural activation patterns.

Two main hypotheses have been put forward regarding cross-domain associations between reading and math. From a functional perspective—or how abilities in one domain contribute to development in another domain—it has been suggested that this association can be attributed to the role of reading skills as the medium by which mathematics skills are acquired (Hecht et al., 2001; Jordan et al., 2003; Fuchs et al., 2005, 2006; Shin et al., 2013). In a similar vein, Cameron et al. (2019) posited that the co-development of reading and mathematics might be explained by cognitive processes that are involved in both abilities; they noted that symbol recognition is particularly important for performing reading and mathematics tasks at the preschool and kindergarten levels. Indeed, numeral literacy or learning to associate the well-known sounds of spoken language with symbol numbers—i.e., symbol-speech sound correspondence—does not involve different cognitive architectures for letter and number naming (Vander Stappen and Reybroeck, 2018). In other words, accessing the ordinal and cardinal meaning of number words/symbols is not required. For instance, neuroscience evidence shows that children aged 5 years who can easily name letters and numbers, but who have not yet learned to read and operate with numbers at school, do not exhibit a neural dissociation between numbers and letters (Cantlon et al., 2011).

A complementary hypothesis is that co-development of reading and math abilities is explained by shared underlying factors (i.e., domain-general factors; Ferrer and McArdle, 2004; Purpura et al., 2019). This hypothesis does not preclude whether reading affects the development of math skills (or *vice versa*). Among the factors that may explain such co-development, there are several cognitive aspects (e.g., executive functions and intelligence). Cattell's (1987) investment theory has also provided support to this hypothesis—a general cognitive factor would underlie the development of academic outcomes. For instance, in a recent meta-analysis of the relationship between academic achievement and broad abilities of the Cattell-Horn-Carroll theory, Zaboski II et al. (2018) found that the mean effect size of that general cognitive factor across all achievement domains and ages was $r^2 = 0.54$. Other non-cognitive aspects, such as socioeconomic status, are known to affect both math and reading skills as well as the development of general cognitive abilities (e.g., Peng and Kievit, 2020).

Collectively, developmental, longitudinal, and neuroimaging studies provide distinct but converging evidence of the co-development of reading and mathematics before the formal schooling years. These findings underscore the importance of studying predictors of the development of both these abilities together rather than separately, to achieve a holistic understanding of how these skills mature during the early childhood years.

## Domain Specificity of Reading and Mathematics Predictors

Despite evidence of the co-development of reading and mathematics, research on early life predictors of these abilities has largely focused on examining them separately from each other. Notwithstanding, a handful of recent studies has examined the cross-domain overlaps between cognitive skills previously thought to be associated specifically with reading or mathematics ability at the preschool age. Some findings highlight the specificity of these within-domain associations. For example, Geary (2011) found that processing speed and the central executive component of working memory were predictors of both math and reading performance—domain-general predictors—with additional factors accounting for unique variance in each domain (i.e., phonological loop for reading, fluency in combining the cardinal value of collections of objects with the cardinal value of Arabic numerals for math)—domain-specific predictors. Similarly, Amland et al. (2021) and Fuhs et al. (2016) found that kindergartners and first graders' phonological memory and general language competencies predicted later reading but not arithmetic achievement.

Other studies highlight evidence of cross-domain impact of these "domain-specific" skills. For instance, phonological awareness explains a substantial amount of the variance in math during the first years of formal education (e.g., Krajewski and Schneider, 2009; De Smedt et al., 2010; Zhang and Lin, 2018; Child et al., 2019; Vanbinst et al., 2020). Studies that have specifically modeled the shared variance between reading and math have reported similar cross-domain associations. These studies have distinguished a set of core predictors, such as non-verbal reasoning, working memory, and processing speed, as well as several cross-domain influences between domain-specific aspects that have been traditionally associated to either reading or math. For instance, it has been found that both counting skills and letter knowledge (which are broadly acknowledged as domain-specific predictors of math and reading, respectively) account for the shared variance in reading and arithmetic fluency (Korpipää et al., 2017; Koponen et al., 2018). In another study exploring domain-specific and domain-general predictors of reading and math, symbolic naming, phonological awareness, and rapid automatized naming were found to predict both reading and mathematics skills in kindergarteners (Cirino et al., 2018).

It has been postulated that conversion of numbers and operators into a verbal code is the first step in solving mathematics problems (Dehaene, 1992; Hecht et al., 2001). A child must first transform the numbers and operators in the problem into a speech-based code to solve both simple and complex mathematics problems (Dehaene, 1992; Hecht et al., 2001). Following this Arabic-to-verbal conversion, the child must then process the phonological information using a specific task-solving strategy by retrieving the answer directly from long-term memory; the ability to solve such a problem is dependent on the storage of phonological information (Amland et al., 2021). Finally, the phonological system may also be employed when the child uses the phonological codes for the number names in counting. In summary, there are several ways in which phonological processing (and phonological awareness, in particular) may yield a causal influence on math. Phonological processing is likely important for both decoding and arithmetic since both tasks depend on mental processes that use sound-based representations. Interestingly, children with better working memory—a cognitive skill that is thought to affect both reading and math—also show better phonological awareness (e.g., Alloway et al., 2005). In other words, as suggested by Chu et al. (2016), "*domain-general cognitive and learning systems will influence the acquisition of domain-specific knowledge and thus may be correlated with achievement in unrelated domains*" (p. 3).

While perhaps a less obvious directional association, a similar scenario can be found in relation to the association between precursors of math abilities and reading skills. For instance, Chu et al. (2016) found that kindergarteners' sensitivity to the relative quantities of collections of objects and cardinal knowledge was predictors of reading skills. Counting skills are also among the precursors of math that usually correlate with reading skills (e.g., Koponen et al., 2013). Likewise, symbol recognition—a domain-specific predictor of mathematics ability—is significantly associated with reading development (Zemlock et al., 2018). From a functional perspective, it has been speculated that these skills contribute to strengthening visual-verbal associations in long-term memory, which are relevant for reading (Koponen et al., 2013). Nonetheless, as mentioned above, it is also possible that such association reflects the prior influence of domain-general systems and not the importance of content-specific knowledge *per se*—i.e., domain-specific skills as a proxy for individual differences in domain-general abilities that predict achievement across academic domains (Chu et al., 2016).

Taken together, these findings suggest that domain-specific predictors are not so specific in the sense that they are not uniquely associated with reading (or math) and that similar cross-domain associations (to those observed between math and reading) may emerge at the level of domain-specific predictors. Given the degree of association between same-domain variables (e.g., phonological awareness and reading) and that of reading and math skills, it is not surprising that cross-domain associations between domain-specific predictors and reading (and math) have been observed. Arguably, if an underlying factor explains variability in math and reading, then, the same factor should explain the development of other math- and reading-related aspects. Furthermore, although the magnitude of cross-domain associations between domain-specific skills and math and reading has been used to differentiate between prior influences of domain-general aspects and the influence of content-specific knowledge *per se,* it is not clear whether those cross-domain associations simply reflect differences in academic domains—reading and math (e.g., phonological awareness as a proxy for reading skills and counting skills as a proxy for math abilities).

Extant findings are inconclusive and there are multiple factors that may alter the *specificity and reciprocity* of domain-specific variables (e.g., adequacy of measures and control of confounding variables, research design, developmental stage, and methodological approach). For instance, the literature suggests that cross-domain associations of domain-specific skills and reading and math are more likely in early childhood. This is because domain-general aspects (i.e., a common underlying factor that also contributes to development in domain-specific predictors of reading and math abilities) are more relevant in younger children's reading and math. For instance, in a longitudinal study with children from first to eighth grade, Geary et al. (2017) found that the role of domain-specific knowledge on math increased over development and that the contribution of domain-general aspects was stronger for younger children's mathematics. This does not mean that within-domain associations are weak at earlier stages in development but that domain-specific aspects are not yet differentiated. For instance, correlations between different early numeracy skills in children (e.g., verbal counting, numeral identification, subitizing, number comparison, and number order) are usually moderate to high. Indeed, studies that have specifically investigated the factor structure of measures of early numeracy skills either have failed to identify more than one factor or have reported factor structures that are controversial due to high correlations between factors (e.g., Braeuning et al., 2020; Purpura and Lonigan, 2013). Similarly, the strength of the associations between skills related with early reading ability also suggests a higher degree of overlap in younger children (Schatschneider et al., 2002; Vukovic and Siegel, 2006). For instance, Poulsen et al. (2015) found that phonological awareness explained a significant proportion of the variance of the association between rapid automatized naming and reading in a large sample of children followed-up from kindergarten to Grade 1. As such, the extent to which phonological awareness and rapid automatized naming can be differentiated from each other, and the exact contributions of each skill on reading development are inconclusive at best (Van der Ven et al., 2012). Collectively, these findings underscore the complexity of unraveling the influence of various cognitive processes involved in early development of reading and mathematics.

Furthermore, it is not surprising that reading skills contribute substantially to variance in math achievement (and *vice versa*) at earlier stages in development given the role of numeral literacy in the set of math skills that young children are expected to master. For instance, Braeuning et al. (2020) investigated the multifactorial structure of the ECLS-K math assessment with a large sample of preschoolers and found that the largest factor loadings of indicators representing number sense (one of four factors that was identified) corresponded to number knowledge items—e.g., identifying a written Arabic number. Indeed, this raises additional questions regarding the adequacy or specificity of math and reading measures for younger children; is number naming different from letter naming in children who have not yet learned to read and operate with numbers at school?

## Present Study

The purpose of the present study is to further elucidate the role of two domain-specific predictors that have been broadly investigated in the literature—phonological awareness, one of the strongest cognitive correlates of learning to read (Melby-Lervåg et al., 2012) and of disabilities in reading (Snowling, 2001), and children's fluency in identifying and processing quantities represented by numerals and object sets, which is associated with math achievement (e.g., (Geary et al., 2007, 2009; Fuchs et al., 2010a,b; Geary, 2011), and may serve to identify children with mathematical learning difficulties (Geary et al., 2009). Specifically, in a path model, we examine whether these are indeed domain-specific predictors, or whether they show cross-domain associations (i.e., they represent shared cognitive correlates of reading and math development). Secondly, the study also examined the cross-domain association between early reading and mathematics. Lastly, the bi-direction longitudinal associations between reading and mathematics from preschool (age 5) to the first year of formal education (age 7) were examined.

# MATERIALS AND METHODS

## Participants

Data from the current study were drawn from a large-scale longitudinal study examining the impact of preschool education on children's development in Singapore (Singapore Kindergarten Impact Project; Ng and O'Brien, 2020). Recruitment for the main study followed a stratified sampling strategy to target mainstream preschool centers from a range of social strata. The sample for the current study was selected based on testing window (February to April of K1) and testing interval (12 months between each data collection point), resulting in a final sample of 512 children ($M_{\text{age at K1entry}} = 54$ months, SD = 3.5; 52% females). In terms of ethnicity, 324 children identified as Chinese, 59 as Malay, 94 as Indian, and 18 as others (17 children did not have ethnicity information). All children were attending kindergarten which provides half-day (2.5–4 h) care and education in the 2 years prior to formal schooling. Approximately 97% of children attend at least 1 year of preschool (kindergarten or full-day childcare) education (Bull and Bautista, 2018). The "Nurturing Early Learners" (NEL) Kindergarten Curriculum Framework sets out key knowledge, skills, and dispositions that children are expected to demonstrate by the end of kindergarten. For literacy, this includes demonstrating print awareness, alphabet knowledge, phonological awareness, and recognizing familiar and high frequency words (Ministry of Education, 2013). For early numeracy, skills include recognizing and using simple relationships and patterns, number recognition, counting to 10, understanding of counting principles, comparing quantities, representing quantity in different format and transcoding between them, part-whole relationships, shape recognition and manipulation, and use of position, direction, and distance referents (Ministry of Education, 2013). Literacy and numeracy are just two of six curriculum areas, and there is no specified amount of curriculum time that educators are expected to dedicate to literacy and numeracy activities.

## Procedure

Data collection was done as part of a larger study, which included other measures apart from those utilized in the present study. Each task was administered individually to the child. Total administration time per child for the larger study ranged from 4 to 5 days. In the current study, time-invariant measures (SES, non-verbal intelligence) were collected at entry to K1 and included as covariates in the analyses. We also controlled for age differences in K1 measures. For the remaining measures, children were tested at entry to K1 (the year children turn 5), K2 (the year children turn 6), and P1 (the year children turn 7).

## Materials

### Reading Skills: Wide Range Achievement Test—4th Edition

The *Word Reading* subtest was used to measure children's early literacy skills (Wilkinson and Robertson, 2006). It consisted of Letter Reading (15 items) and Word Reading (55 items). Only the Green form was administered for letter reading, whereas both the Green and Blue forms (parallel versions that can be used interchangeably with comparable results) were administered for word reading; the Green form was always administered first. Test items were scored as "1" if children read the letter/word correctly. Only the word reading task had a discontinue rule, whereby test administration was terminated after 10 consecutive incorrect responses. A reading score was derived by summing the average of the child's word reading score on the Green and Blue forms with the letter reading score (i.e., mean [Green and Blue word reading] + letter reading). A high score indicates better reading skills. Test-retest reliability values using K1 and K2 data were good (ICC and 95% CI)[1] = 0.91 (0.90, 0.93).

### Math Skills: Test of Early Mathematics Ability—3rd Edition

This task measures children's informal and formal mathematics knowledge (Ginsburg and Baroody, 2003). Informal knowledge (acquired outside the context of schooling) is measured through four categories of items: numbering (e.g., verbal counting by ones), number comparisons (e.g., choosing the larger number), calculation (e.g., addition of concrete objects), and concepts (e.g., number constancy). Formal knowledge (skills and concepts learned in school) is also assessed *via* four categories: numeral literacy (e.g., reading or writing numerals), number facts (e.g., subtraction facts), calculation (e.g., written addition accuracy), and concepts (e.g., written representation of sets). The dependent measure was the number of items answered correctly. Items in each of the categories increased in difficulty level as children progress further in the task. Following the TEMA-3 manual, test administration began with an entry point suitable for the children's age and was terminated when ceiling (five items incorrect in a row) and basal (five items correct in a row) were established. Then, we scored all items below the basal correct and all items above the ceiling incorrect. A high score reflects better math skills. Test-retest reliability values using K1 and K2 data were good (ICC and 95% CI)[1] = 0.92 (0.91, 0.93).

### Phonological Awareness: Comprehensive Test of Phonological Processing—2nd Edition

Two subtests from the Comprehensive Test of Phonological Processing—2nd Edition were used to measure children's phonological awareness (Wagner et al., 2012). In the *Elision* subtest (34 items), children were required to listen to a word (e.g., *cup*), repeat it, and then say what is left of that word after dropping designated sound segments (e.g., /k/; *up*). Corrective feedback was given on the first 14 items. The *Blending Words* subtest (33 items) required children to listen to a series of audio-recorded words spoken in segments (e.g., /t/ and /oi/) and to reproduce the whole word (e.g., *toy*) by blending the sound segments. Corrective feedback was given on the first 12 items. A phonological awareness score was derived by summing the total scores from both subtests (i.e., Elision + Blending). A low score indicates low phonological awareness. Test-retest reliability values using K1 and K2 data were good (ICC and 95% CI)[1] = 0.88 (0.87, 0.90).

### Fluency in Identifying and Processing Quantities Represented by Numerals and Object Sets: Number Sets Test

This task assessed the speed and accuracy with which children can identify and process quantities represented by Arabic numerals and/or object sets in a paper-and-pencil format (Geary et al., 2007). Children were presented with pairs or trios of objects (e.g., ▲▲▲|▲▲), Arabic numerals (e.g., 2|3), or both (e.g., 4|▲, ●●|2|▲). Each combination pair or trio is considered an item. Children were required to circle items that matched a target number (five or nine) quickly and accurately within a given time limit (60 s for target number "five"; 90 s for target number "nine"). Performance on this

[1]Average-measurement, consistency, and two-way mixed-effects model.

task depends on children's ability to subitize and map Arabic numerals into representations of small quantities and to perform simple addition with small sets and Arabic numerals (Rousselle and Noël, 2007). The following information was collected from children's responses: the number of items correctly identified as matching the target number (hits), the number of correct matches that were not identified (misses), the number of incorrect items that were identified as matching the target (false alarms), and the number of incorrect items that were not identified (correct rejections). We used a sensitivity measure, d-prime (z scores for hits – z scores for false alarms; MacMillan, 2002), as the performance measure. Test-retest reliability values using K1 and K2 data were good (ICC and 95% CI)[1] = 0.84 (0.82, 0.87).

### Non-verbal Intelligence

The Ravens Colored Progressive Matrices were used as a measure of children's non-verbal reasoning ability (Raven, 1947). The dependent measure was the total number of correct responses across all three sets. Higher scores reflect better non-verbal reasoning ability. Internal consistency in the whole sample was good ($\alpha = 0.89$).

### Socioeconomic Status

A composite SES score was derived from a principal component analysis of four variables: mother's education, father's education, family income, and housing type. Housing type is a common indicator of SES in the Singapore context (e.g., Sabanayagam et al., 2007).

## ANALYSES

To investigate the substantive questions in the current study, we formulated a path model with four different longitudinal chains corresponding to math, reading, phonological awareness, and fluency with number sets. In this model, autoregressive paths (i.e., the extent to which scores at time t for a variable X affect scores at time t + 1 for the same variable) were constrained to equality to reflect similar associations between each pair of adjacent measurements because the intervals between time points were similar (about 12 months). Cross-lagged relations between different variables (i.e., the extent to which scores at time t for a variable X affect scores at time t + 1 for a different variable) were freely estimated to reflect different cross-domain associations over time. Residual variances at each time point were correlated. In this model, we also included time-invariant covariates (SES and non-verbal intelligence) that are known to affect both reading and math skills as well as related domain-specific predictors. These covariates (domain-general predictors) were linked to all variables of interest (reading, math, and related domain-specific predictors) and time points in the path model. We also controlled for age differences at entry to kindergarten since the development of the skills that were measured likely starts before the onset of preschool education. For instance, the odds that older children have better language and numerical skills than younger children are higher.

Parameters were estimated with full information maximum likelihood. Model fit was assessed by inspecting the $\chi^2$ test, as well as the Comparative Fit Index (CFI; values above 0.95 indicate adequate fit, Hu and Bentler, 1999), Root Mean Square Error of Approximation (RMSEA; values below 0.06 indicate good model fit, Chen et al., 2008), and SRMR (values <0.08 indicate good fit, Hu and Bentler, 1999). We used a robust maximum likelihood estimator (MLR), with standard errors that are robust in relation to non-normality and non-independence of observations. All analyses were conducted using MPlus version 8.6 (Muthén and Muthén, 2017). Although some variance lies at the classroom level, our model did not take into account classroom level clustering because of student mobility across the grades. Furthermore, at Kindergarten 2, there were a large number of clusters (87) with a small average cluster size (5; range 1–15).

## RESULTS

Descriptive statistics and age-adjusted bivariate correlations are shown in **Table 1** (top and bottom panel, respectively).

The within-variable correlations over time showed a typical autoregressive pattern (i.e., stronger correlations among observations taken in adjacent waves). This pattern was more evident for reading and math than for phonological awareness and number sets. Indeed, reading and math measures were quite stable over time and showed good reliability (above 0.75 for a one-year gap). Overall, cross-domain associations were large according to Cohen's (1988) standards. Associations of domain-general variables with verbal and numerical variables were moderate and did not change substantially across time points.

### Path Model

The model that was specified fitted the data well ($\chi^2$ (28) = 53.53, CFI = 0.994, TLI = 0.979, RMSEA = 0.042 [0.025, 0.059]). Parameter estimates are shown in **Figure 1**. At entry to K1, children from higher SES backgrounds, those who were older, and those with better non-verbal reasoning skills also had better reading and math skills as well as better scores on number sets and phonological awareness (see parameter estimates in **Supplementary Material**; **Supplementary Table S1**). The proportion of explained variance differed across DVs—ranging from 17 to 30%.

At entry to K2, the analysis revealed SES disparities across the four variables, which indicates that the SES gap in cognitive development increased during the first year in kindergarten. Non-verbal intelligence also predicted scores on number sets. Note that the null association between non-verbal reasoning and the remaining K2 variables means that the magnitude of the disparities found at entry to kindergarten persisted in K2. The analysis also revealed cross-domain associations (or reciprocal influence) between reading and math after accounting for previous math and reading skills and the effect of domain-specific predictors. The standardized coefficients of the cross-lagged associations

**TABLE 1 |** Descriptive statistics (top) and age-adjusted bivariate correlation table (bottom).

| | Math1 | Math2 | Math3 | Read1 | Read2 | Read3 | Nset1 | Nset2 | Nset3 | Phaw1 | Phaw2 | Phaw3 | SES | NvIn |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| n | 498 | 508 | 507 | 505 | 509 | 508 | 510 | 511 | 507 | 503 | 508 | 506 | 467 | 487 |
| M | 23.31 | 34.52 | 44.69 | 14.77 | 21.55 | 29.64 | 0.45 | 1.4 | 2.12 | 13.48 | 22.33 | 30.08 | −0.08 | 14.59 |
| SD | 8.96 | 9.24 | 10.12 | 5.29 | 7.24 | 8.02 | 0.56 | 0.72 | 0.68 | 7.66 | 9.52 | 8.99 | 0.99 | 4.66 |
| Skewness | 0.14 | 0.19 | 0.57 | 0.00 | 0.79 | 0.38 | 0.9 | −0.34 | −0.81 | 0.66 | −0.04 | −0.23 | −0.44 | 0.2 |
| Min | 0 | 8 | 16 | 0 | 1 | 15 | −0.72 | −0.39 | −0.15 | 0 | 0 | 0 | −2.81 | 2 |
| Max | 49 | 70 | 72 | 35.5 | 48 | 55 | 2.67 | 3.29 | 3.68 | 41 | 53 | 56 | 1.75 | 30 |
| Math2 | 0.78 | – | | | | | | | | | | | | |
| Math3 | 0.65 | 0.77 | – | | | | | | | | | | | |
| Read1 | 0.61 | 0.54 | 0.48 | – | | | | | | | | | | |
| Read2 | 0.60 | 0.59 | 0.53 | 0.75 | – | | | | | | | | | |
| Read3 | 0.55 | 0.57 | 0.54 | 0.60 | 0.79 | – | | | | | | | | |
| Nset1 | 0.52 | 0.46 | 0.45 | 0.32 | 0.30 | 0.24 | – | | | | | | | |
| Nset2 | 0.66 | 0.74 | 0.69 | 0.41 | 0.44 | 0.43 | 0.50 | – | | | | | | |
| Nset3 | 0.57 | 0.64 | 0.69 | 0.36 | 0.38 | 0.37 | 0.37 | 0.69 | – | | | | | |
| Phaw1 | 0.57 | 0.45 | 0.43 | 0.43 | 0.49 | 0.48 | 0.36 | 0.40 | 0.34 | – | | | | |
| Phaw2 | 0.63 | 0.58 | 0.49 | 0.53 | 0.65 | 0.67 | 0.31 | 0.48 | 0.42 | 0.63 | – | | | |
| Phaw3 | 0.50 | 0.48 | 0.48 | 0.42 | 0.53 | 0.63 | 0.21 | 0.41 | 0.39 | 0.52 | 0.69 | – | | |
| SES | 0.33 | 0.36 | 0.34 | 0.29 | 0.35 | 0.32 | 0.16 | 0.32 | 0.24 | 0.35 | 0.43 | 0.32 | – | |
| NvIn | 0.42 | 0.39 | 0.35 | 0.29 | 0.28 | 0.30 | 0.33 | 0.43 | 0.37 | 0.33 | 0.33 | 0.28 | 0.24 | – |

*All correlations are significant at the level p<0.001. Math=TEMA raw score; Read=Letter and Word Reading raw score; NSet=Number Sets d-prime; SES=socioeconomic status standardized score; NvIn=Ravens Non-verbal Intelligence raw score; 1=K1 assessment; 2=K2 assessment; and 3=Grade 1 assessment.*

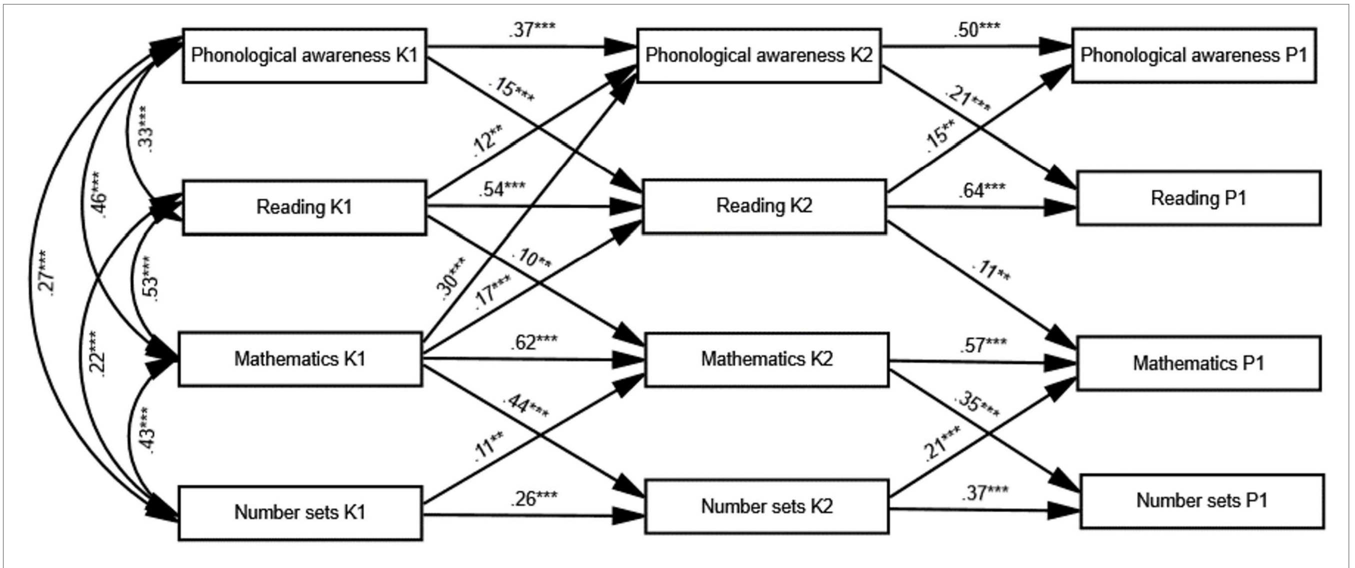


**FIGURE 1 |** Path model with parameter estimates that only significant path is shown in the diagram. For clarity, paths from covariates (SES, age, and non-verbal ability) and residual co-variances are not shown. *p<0.01 and ***p<0.001.

between reading and math suggest that math ability at entry to kindergarten may have a stronger role in the development of reading skills than that of reading skills in the development of math skills during the first year in kindergarten.

Each domain-specific predictor was associated uniquely with its corresponding same-domain variable. The magnitude of these domain-specific associations was similar to that of the cross-domain associations; math and phonological awareness had similar effects on reading skills at the beginning of K2 (0.167 and 149, respectively) and reading and number sets had similar effects on math skills at the beginning of K2 (0.101 and.108, respectively). The magnitude of those associations was small in terms of Cohen's (1988) standards (equivalent to.10–0.17 SD). Note that these associations were statistically significant after accounting for individual differences in the same variable at an earlier time point, so they reflected associations with reading and math growth over the first year in kindergarten. It is worth mentioning that whereas fluency with number sets in K2 was related to math skills in K1 but not reading skills in K1, variability in phonological awareness in K2 was partly explained by math skills in K1. Indeed, this association was stronger than that with reading skills in K1; a 1 SD increase in math at K1 was associated with a 0.30 SD increase in phonological awareness at K2. In comparison, a 1 SD increase in reading at K1 was associated with just a.12 SD increase in phonological awareness of K2.

At entry to P1, only non-verbal reasoning remained associated with scores on the number sets task. This long-term association is noteworthy even if the magnitude of the effect decreases over time; children with better non-verbal reasoning skills at entry K1 showed more sustained gains over the 2 years in kindergarten. It also underscores the non-verbal component of the skills required to solve the number sets task (see "Discussion"). As mentioned above, failing to observe an association with the remaining P1 variables (and the null association between SES and P1 variables) indicates that the magnitude of disparities related to domain-general aspects in K2 persisted when children entered formal education. The analysis also revealed a higher degree of disambiguation between reading and math skills. There were no reciprocal associations between reading and math; only reading skills at K2 were associated with math gains at entry to P1 (math at K2 was not associated with reading gains at entry to P1) and each domain-specific variable was related to its corresponding same-domain variable. The proportion of explained variance was similar across DVs at entry to K2 and P1 (about 50–55% for phonological awareness and fluency with number sets and slightly higher—60–65%—for reading and math skills).

It is worth mentioning that, although the role of the domain-specific predictors increased over time, the dynamics and reciprocal associations between domain-specific predictors and the corresponding academic outcomes (math or reading) were different across domains. Phonological awareness was the leading force in the development of reading skills (this was more evident during the last year in kindergarten). In contrast, the association between math abilities and children's fluency with number sets was one in which math was the leading force over the kindergarten years. Furthermore, although the analysis revealed some cross-domain associations between reading and math over the kindergarten years, we did not observe any reciprocal association between domain-specific predictors.

# DISCUSSION

This study examined the reciprocal associations between early reading and mathematics, and two domain-specific predictors—phonological awareness and fluency with number sets (the skill of operating with different numerical representations). We focused on elucidating the role of these domain-specific skills as well as the within- and cross-domain associations that emerge over the kindergarten years. Results from the study revealed three key findings. First, phonological awareness and number sets are domain-specific predictors of reading and mathematics, respectively (and do not contribute to cross-domain gains). Second, while there are cross-domain associations between reading and math (and between math and phonological awareness), these associations are not stable over time. Third, there are within-domain bi-directional associations between the more general skill (reading or math) and their respective domain-specific skills (phonological awareness and number sets). The pattern of findings suggests that cross-domain associations are more evident when it comes to reading and general math abilities and that the strength of within-domain associations increases over time (as the level of cross-domain associations decreases). We discuss each of these key findings in more detail below.

## Domain-Specific Prediction of Reading and Mathematics

Fluency with number sets and phonological awareness were associated with their respective domains (math and reading, respectively), uniquely contributing to growth in each domain. Although the effect size of those associations was small, it was fairly consistent across domains and increased over time. At entry to K2, the effect size was equivalent to about 0.13 SDs (in reading and math), whereas at entry to P1, that effect size increased to about 0.20 SDs. Note that those effects are calculated after accounting for reading and math disparities at previous stages, which underscores the relevance of phonological awareness and fluency with number sets on reading and math improvements, respectively. In contrast to some previous studies, we did not find that phonological awareness predicted later math achievement (Hecht et al., 2001; Fuchs et al., 2005; De Smedt et al., 2010; Child et al., 2019; Vanbinst et al., 2020). However, our results do align with findings from a recent meta-analysis (Peng et al., 2020) showing that weak relationships of phonological awareness to general math, numerical knowledge, calculations, and word problems were rendered non-significant after controlling for other domains general skills, in this case, working memory and intelligence (see also Amland et al., 2021; Bernabini et al., 2021; Pinto et al., 2016). It is noteworthy that in our model, the role of phonological awareness on later math achievement refers to the contribution to gains in math after accounting for differences in reading skills. Thus, it is feasible that such association reported in other studies simply reflects the role of phonological awareness as a proxy for reading skills or other aspects of phonological processing that may be involved in recognizing symbol numbers (e.g., RAN) or maintaining several chunks of information in memory during multi-step problem solving (short-term memory). These three aspects of phonological processing are highly correlated, and a single phonological processing dimension has been frequently posited (Wagner et al., 1987, 1993; Wagner and Torgesen, 1987).

Far fewer studies have considered whether early developing numerical skills, like those measured by the number sets task, predict reading as well as math. Vanbinst et al. (2020) found that only certain numerical skills (numeral recognition) predicted concurrent reading in 5-year olds (indexed by a letter knowledge task), while numerical magnitude skills (non-symbolic and symbolic comparison) showed no significant cross-domain association (see Child et al., 2019 for similar non-significant prediction of non-symbolic discrimination to reading skills in Grade 2 students). Cirino et al. (2018) in a longitudinal study of children from kindergarten to Grade 1 found that symbolic labeling (ability to name single, two, and three-digit numbers) predicted literacy outcomes (decoding, reading fluency, and reading comprehension). Other numerical measures (rote counting, counting knowledge, and symbolic comparison) did not predict literacy outcomes. In contrast, studies of slightly younger children (3–4 years of age) show that both sensitivity to relative quantities and cardinal knowledge are associated with later reading skills (Chu et al., 2016). Such findings suggest that the prediction of emerging numeracy skills to later reading could be associated with the requirement to recognize abstract symbols, the ability to retrieve associations between visual symbolic and phonological forms, or general processing skills, such as visual attention, that may be common to letter learning and non-symbolic quantity discrimination skills (Anobile et al., 2013). As mentioned above, the same mechanisms that contribute to strengthening associations between sounds of spoken language and symbol numbers may contribute to letter-speech sound correspondence. Further research is needed to confirm the mechanism of this relation between early numeracy skills and later reading skills and the changing nature of this association with age and experience.

## Cross-Domain Associations Between Reading and Mathematics

The second main finding is generally consistent with existing literature supporting a cross-domain association between reading and mathematics (e.g., Duncan et al., 2007; Bailey et al., 2020). Nonetheless, cross-domain associations changed over development. Specifically, mathematics was found to predict growth in reading from wave 1 (Kindergarten 1) to wave 2 (Kindergarten 2) but not from wave 2 to wave 3 (Primary 1). In contrast, reading was a consistent predictor of growth in mathematics ability over the kindergarten years. Although the magnitude of this association was small, it was consistent over development. Erbeli et al. (2020) reported similar findings in elementary children from grades 1 to 4, where annual change in math growth was (partially) accounted for by reading achievement. The reverse coupling, annual change in reading growth predicted by math achievement, was not found. Our findings extend this down to children in the year prior to formal schooling. However, prior to this age, it appears that reciprocal coupling better depicts the development of reading and math skills. Our results also align with findings from Jordan et al. (2003) which indicated that reading performance influenced growth in math, but the reverse direction of influence was not evident. Specifically, elementary school children with math difficulties who were good readers showed greater growth in math compared to children who have both reading and math difficulties. No such advantage was seen for children with reading difficulties who had good math skills—they showed comparable growth in reading as those with comorbid difficulties.

Another observed cross-domain association was that mathematics at K1 predicted change in phonological awareness from K1 to K2. Indeed, the magnitude of this association was similar to that of phonological awareness at an earlier time point (equivalent to 0.30 SD in phonological awareness at entry to K2). A similar cross-domain association was not found for reading at K1 and number sets at K2. A possible explanation for this finding might lie in symbol recognition abilities. Letters of the alphabet and numbers have abstract representations in the form of sounds and quantitative values, respectively. Understanding a system of quantity-related symbols (numbers) may therefore help to facilitate learning a system of sound-related symbols (letters). In this way, symbol recognition may explain how math abilities can contribute to the subsequent development of skills related to phonological awareness. Purpura et al. (2017) also found that earlier math ability predicted growth in phonological awareness. However, this direct relationship was mediated by early math language skills. Others have argued that some math assessments involve both language and code-based skills, and hence may be a proxy for early language abilities, accounting for the prediction of concurrent or later reading abilities (Purpura and Napoli, 2015). In the current study, this may apply to the TEMA which includes skills, such as numeral literacy and counting fluency. In contrast, the number sets task has very little reliance on such language and code-based skills and was not found to predict later reading skills.

Although different hypotheses have been formulated to explain cross-domain associations between reading and math abilities, these hypotheses are complimentary and probably reflect different developmental stages. For instance, it is feasible that underlying shared factors contribute to a larger extent to reading and math at earlier stages. This would explain the association of math with later reading and verbal abilities (as well as that of reading with later math skills) during the first year in kindergarten. Then, content-specific influences may shape to a larger extent the cross-domain associations (for a similar explanation see De Smedt et al., 2010). Exposure to a more diverse set of math abilities during the last year in kindergarten or at the beginning of formal education probably increases the specificity of the mathematical and numerical domain. This aligns with findings from correlational studies that have looked at the role of domain-general aspects. It is thought that domain-general competencies become less relevant as children gain domain-specific expertise (Geary, 2005; Sweller, 2015). In other words, if cross-domain associations between reading and math rely on (domain-general) underlying factors; then, such associations are likely to vanish as the role of domain-general factors decreases.

## Within-Domain Bi-directional Associations

Phonological awareness and number sets do not appear to represent developing precursors to reading and math, respectively. Instead, we see evidence of within-domain bi-directional longitudinal prediction. For example, K1 number sets predict K2 math, but the reciprocal prediction from K1 math to K2 number sets is considerably larger (equivalent to about 0.40 SD in fluency with number sets, which is a moderate effect size in terms of Cohen' standards; Cohen, 1988); a similar pattern of bi-directional associations is also seen from K2 to P1. We see a similar reciprocal relationship between phonological awareness and reading, although earlier phonological awareness to later reading is slightly stronger than from earlier reading to later phonological awareness. Within the mathematical cognition literature, there is ongoing debate regarding the directionality of association between basic number sense skills and formal mathematical ability. Our findings support the idea of a bi-directional relationship (see also LeFevre et al., 2013; Friso-van den Bos et al., 2015; Elliot et al., 2019), whereby basic skills, such as understanding quantity from symbolic and non-symbolic representations, and transcoding between and combining those representations predict more general math achievement. However, they are not precursors to math achievement, because at the same time, we find that general math achievement predicts growth (in this case accuracy and fluency) in using those basic skills. While a number of studies have found performance on the number sets task to predict growth in math achievement (e.g., Fuhs et al., 2016; Geary et al., 2017), these studies did not consider the possibility of a bi-directional relationship. In the field of reading, notably more studies have explored the relationship from earlier phonological awareness to later reading while the possibility of a bi-directional relationship has been considerably less well researched. It remains an unresolved issue if phonological awareness is a precursor skill for reading or if it develops as part of the process of learning to read (Bradley and Bryant, 1985; Castles and Coltheart, 2004; Hulme et al., 2005). Our study provided support for a bi-directional relationship between phonological awareness and reading but with a slightly stronger relationship between early phonological awareness to later reading. The finding is in line with past studies where phonological awareness has been found to be a robust predictor of reading (Lonigan et al., 2000; Ehri et al., 2001), and where reading difficulty (i.e., dyslexia) has been linked to deficits in phonological awareness (Lyon et al., 2003). Similarly, in a study by Hogan et al. (2005), there was a reciprocal relationship found between phonological awareness and word reading.

Overall, and in contrast to Chu et al. (2016), we observed a trend for domain-specific skills to be more strongly related to achievement at the end of kindergarten than at the beginning of kindergarten. While our analytical approach differs substantially from that in Chu et al. (2016), it is also probable that differences relate to the developmental stage that is evaluated. Children in our study were older and (consequently) had a wider range of mathematical abilities. The increasing differentiation of math and reading domains over development, as well as the fact that cross-domain associations seem more likely at earlier stages in development, is also consistent with findings from studies that have tracked the development of math and reading skills separately. For instance, Lee and Bull (2016) found that the role of prior mathematics achievement increased across grades from kindergarten to Grade 9.

## Limitations

Findings from this study should be considered in the context of several limitations. First, the use of the number sets task has its drawbacks, as fluency in identifying and processing quantities represented by numerals and object sets is not exactly a rudimentary skill compared to other early skills associated with mathematics, such as numeral recognition or numerical magnitude discrimination. Thus, there is a possibility that the use of measures of other types of basic skills involved in mathematics may have led to different results. A similar concern can be made regarding the reliance on phonological awareness as the measure of emerging literacy skill. Notably, phonological awareness is only one aspect of phonological process, which includes other components, such as phonological (verbal) working memory, that have also been reliably found to be a precursor for reading (Baddeley et al., 1998; see Baddeley, 2003 for a review). Additionally, other aspects of phonological processing, such as rapid automatized naming, which is pertinent in reading fluency, which have been found to be a longitudinal predictor of reading (Landerl et al., 2019) should also be considered. Future research on the predictors of reading and mathematical ability should seek to consider incorporating a broader variety of these skills. This would be essential for attaining a more holistic understanding of the unique influences that each of these skills may have on reading and mathematics ability and how such skills jointly interact over development.

Second, the relative contribution of domain-specific and cross-domain variables will probably depend on how the learning outcome has been operationalized. We used a measure of general math ability (TEMA) that does not allow us to tease apart specific skills. However, some studies show that the relative contribution varies for skills, such as geometry and measurement, compared to other skills, such as magnitude comparisons (LeFevre et al., 2010). In terms of word reading, while an established measure of reading ability (i.e., WRAT-4) was utilized to assess reading ability using individual word stimuli, it is debatable whether single word reading is representative of skill use in an everyday context. It has been noted that reading in real-life situations often involves several words strung into sentences, which involves the sequential and simultaneous processing of visual and semantic information; these processes are not examined during the reading of solitary words (Zoccolotti et al., 2020).

Third, while the present study has tried to account for other domain-general predictors, such as non-verbal reasoning, that may be involved in the cross-domain association between early reading and mathematics, it is not comprehensive. Future studies should consider the inclusion of other important predictors, such as working memory, where robust relationships have been found. In terms of math, decades of research have shown that working memory skills are closely related to math achievement and precursors of math, such as counting (Bull and Scerif, 2001; Bull et al., 2008; Monette et al., 2011; Van der Ven et al., 2012), as well as early numerical magnitude skills (Geary et al., 2009; Kolkman et al., 2013). Similarly, research indicates that both the phonological loop (verbal working memory) and the central executive are pertinent at different stages of reading. The phonological loop plays a crucial role in the early stages of reading where children start learning the concept of mapping of grapheme-phoneme and gain mastery of decoding, which facilitates both word and non-word reading (Baddeley, 2003). As children's reading development progresses, the central executive is found to play a more important role in facilitating reading comprehension (Cain et al., 2004).

Finally, moderation effects may impact on the relative importance of within- *versus* cross-domain prediction. For instance, children in our sample who are higher achieving will be progressing to problems in the TEMA with increased task difficulty, e.g., word problem solving, which requires storing of verbal information without external support. These tasks may then require children to draw on their language and comprehension skills in solving these problems. This is consistent with previous studies (e.g., Purpura and Logan, 2015) that have found than domain-specific skills, such as processing of non-symbolic quantity, were more likely to predict performance of children at the lower end of the distribution who are completing only simple math questions, while performance of children at the upper end of the distribution (who are completing questions that required more translation between different representations) was more likely to be predicted by math language.

### Conclusion

This study is one of only a few to investigate the cross-domain associations between reading, mathematics, and their domain-specific predictors. Collecting data on all tasks across 3 years have allowed us to examine the changing nature of the relationships within and across domains of learning. Path model analyses highlighted that the reciprocal relationship between reading and mathematics changes over time; specifically, that reading has a stronger influence on mathematics closer to the formal schooling years. The results indicated that math development is supported *via* two routes; firstly, a linguistic route that likely supports skills, such as mastery of numeral recognition and counting. Secondly, a quantitative route that supports children's ability to accurately and fluently process and operate on quantity representations. These align with two of the three pathways to mathematics identified by LeFevre et al. (2010). Importantly, the findings revealed that phonological awareness and number sets fluency do not have a cross-domain effect on the later development of mathematics and reading, respectively. The findings have implications for the timing and nature of interventions focused on improving math and/or reading skills. Specifically, interventions for improving early reading and math abilities may consider tapping on the cross-domain association between these abilities if targeted at very young children. However, these interventions should generally seek to target domain-specific cognitive skill(s) with an established link to reading or math ability. Lastly, our findings also underscore the close link between reading and math during the first years and the progressive differentiation of each domain upon entry to formal school. This suggests that the pattern of reading and math disabilities may vary over development in the sense that the prevalence of comorbidity of reading and math disabilities would be higher in younger children—even if these children do not have a multifaceted deficit. In the same vein, our findings suggest examining how math and reading abilities jointly unfold to differentiate children with specific reading or math disabilities from those with more entrenched deficits.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, and further inquiries can be directed to the corresponding author.

## ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the National Institute of Education (NIE), Nanyang Technological University, Singapore. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

## AUTHOR CONTRIBUTIONS

FK: conceptualization, methodology, formal analysis, data curation, writing-original draft, writing-review and editing, visualization, and project administration. RB: conceptualization, formal analysis, writing-original draft, supervision, project administration, and funding acquisition. DM: conceptualization, methodology, formal analysis, writing-original draft, writing-review and editing, and visualization. All authors contributed to the article and approved the submitted version.

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## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2021.710470/full#supplementary-material

## REFERENCES

Alloway, T. P., Gathercole, S. E., Adams, A. M., Willis, C., Eaglen, R., and Lamont, E. (2005). Working memory and phonological awareness as predictors of progress towards early learning goals at school entry. *Br. J. Dev. Psychol.* 23, 417–426. doi: 10.1348/026151005X26804

Amland, T., Lervåg, A., and Melby-Lervåg, M. (2021). Comorbidity between math and reading problems: is phonological processing a mutual factor? *Front. Hum. Neurosci.* 14:577304. doi: 10.3389/fnhum.2020.577304

Andin, J., Fransson, P., Rönnberg, J., and Rudner, M. (2015). Phonology and arithmetic in the language-calculation network. *Brain Lang.* 143, 97–105. doi: 10.1016/j.bandl.2015.02.004

Anobile, G., Stievano, P., and Burr, D. C. (2013). Visual sustained attention and numerosity sensitivity correlate with math achievement in children. *J. Exp. Child Psychol.* 116, 380–391. doi: 10.1016/j.jecp.2013.06.006

Baddeley, A. (2003). Working memory: looking back and looking forward. *Nat. Rev. Neurosci.* 4, 829–839. doi: 10.1038/nrn1201

Baddeley, A., Gathercole, S., and Papagno, C. (1998). The phonological loop as a language learning device. *Psychol. Rev.* 105:158. doi: 10.1037/0033-295X.105.1.158

Bailey, D. H., Oh, Y., Farkas, G., Morgan, P., and Hillemeier, M. (2020). Reciprocal effects of reading and mathematics? Beyond the cross-lagged panel model. *Dev. Psychol.* 56, 912–921. doi: 10.1037/dev0000902

Bernabini, L., Bonifacci, P., and de Jong, P. F. (2021). The relationship of reading abilities with the underlying cognitive skills of math: A dimensional approach. *Front. Psychol.* 12:577488. doi: 10.3389/fpsyg.2021.577488

Bradley, L., and Bryant, P. (1985). *Rhyme and Reason in Reading and Spelling.* Ann Arbor: University of Michigan Press.

Braeuning, D., Ribner, A., Moeller, K., and Blair, C. (2020). The multifactorial nature of early numeracy and its stability. *Front. Psychol.* 11:2965. doi: 10.1016/j.envpol.2020.113953

Bull, R., and Bautista, A. (2018). "A careful balancing act: evolving and harmonizing a hybrid system of ECEC in Singapore," in *The Early Advantage: Early Childhood Systems that Lead by Example*. ed. S. L. Kagan (New York: Teachers College Press), 155–181.

Bull, R., Espy, K. A., and Wiebe, S. A. (2008). Short-term memory, working memory, and executive functioning in preschoolers: longitudinal predictors of mathematical achievement at age 7 years. *Dev. Neuropsychol.* 33, 205–228. doi: 10.1080/87565640801982312

Bull, R., and Scerif, G. (2001). Executive functioning as a predictor of children's mathematics ability: inhibition, switching, and working memory. *Dev. Neuropsychol.* 19, 273–293. doi: 10.1207/S15326942DN1903_3

Cain, K., Oakhill, J., and Bryant, P. (2004). Children's reading comprehension ability: concurrent prediction by working memory, verbal ability, and component skills. *J. Educ. Psychol.* 96:31. doi: 10.1037/0022-0663.96.1.31

Cameron, C. E., Kim, H., Duncan, R. J., Becker, D. R., and McClelland, M. M. (2019). Bidirectional and co-developing associations of cognitive, mathematics, and literacy skills during kindergarten. *J. Appl. Dev. Psychol.* 62, 135–144. doi: 10.1016/j.appdev.2019.02.004

Cantlon, J. F., Pinel, P., Dehaene, S., and Pelphrey, K. A. (2011). Cortical representations of symbols, objects, and faces are pruned back during early childhood. *Cereb. Cortex* 21, 191–199. doi: 10.1093/cercor/bhq078

Castles, A., and Coltheart, M. (2004). Is there a causal link from phonological awareness to success in learning to read? *Cognition* 91, 77–111. doi: 10.1016/S0010-0277(03)00164-1

Cattell, R. B. (1987). *Intelligence: Its Structure, Growth and Action.* North-Holland: Elsevier.

Chen, F., Curran, P. J., Bollen, K. A., Kirby, J., and Paxton, P. (2008). An empirical evaluation of the use of fixed cutoff points in RMSEA test statistic in structural equation models. *Sociol. Methods Res.* 36, 462–494. doi: 10.1177/0049124108314720

Child, A. E., Cirino, P. T., Fletcher, J. M., Willcutt, E. G., and Fuchs, L. S. (2019). A cognitive dimensional approach to understanding shared and unique contributions to reading, math, and attention skills. *J. Learn. Disabil.* 52, 15–30. doi: 10.1177/0022219418775115

Chu, F. W., vanMarle, K., and Geary, D. C. (2016). Predicting children's reading and mathematics achievement from early quantitative knowledge and domain-general cognitive abilities. *Front. Psychol.* 7:775. doi: 10.3389/fpsyg.2016.00775

Cirino, P. T., Child, A. E., and Macdonald, K. T. (2018). Longitudinal predictors of the overlap between reading and math skills. *Contemp. Educ. Psychol.* 54, 99–111. doi: 10.1016/j.cedpsych.2018.06.002

Cohen, J. (1988). *Statistical Power Analysis for the Behavioral Sciences.* Hillsdale, NJ: Lawrence Erlbaum Associates, Routledge Academic.

Davis, O. S., Band, G., Pirinen, M., Haworth, C. M., Meaburn, E. L., Kovas, Y., et al. (2014). The correlation between reading and mathematics ability at age twelve has a substantial genetic component. *Nat. Commun.* 5, 1–6. doi: 10.1038/ncomms5204

De Smedt, B., Taylor, J., Archibald, L., and Ansari, D. (2010). How is phonological processing related to individual differences in children's arithmetic skills? *Dev. Sci.* 13, 508–520. doi: 10.1111/j.1467-7687.2009.00897.x

Dehaene, S. (1992). Varieties of numerical abilities. *Cognition* 44, 1–42. doi: 10.1016/0010-0277(92)90049-N

Dehaene, S., Piazza, M., Pinel, P., and Cohen, L. (2003). Three parietal circuits for number processing. *Cogn. Neuropsychol.* 20, 487–506. doi: 10.1080/02643290244000239

Duncan, G. J., Dowsett, C. J., Claessens, A., Magnuson, K., Huston, A. C., Klebanov, P., et al. (2007). School readiness and later achievement. *Dev. Psychol.* 43, 1428–1446. doi: 10.1037/0012-1649.43.6.1428

Ehri, L. C., Nunes, S. R., Willows, D. M., Schuster, B. V., Yaghoub-Zadeh, Z., and Shanahan, T. (2001). Phonemic awareness instruction helps children learn to read: evidence from the National Reading Panel's meta-analysis. *Read. Res. Q.* 36, 250–287. doi: 10.1598/RRQ.36.3.2

Elliot, L., Feigenson, L., Halberda, J., and Libertus, M. E. (2019). Bidirectional, longitudinal associations between math ability and approximate number system precision in childhood. *J. Cogn. Dev.* 20, 56–74. doi: 10.1080/15248372.2018.1551218

Erbeli, F., Shi, Q., Campbell, A. R., Hart, S. A., and Woltering, S. (2020). Developmental dynamics between reading and math in elementary school. *Dev. Sci.* 24:e13004. doi: 10.1111/desc.13004

Ferrer, E., and McArdle, J. J. (2004). An experimental analysis of dynamic hypotheses about cognitive abilities and achievement from childhood to early adulthood. *Dev. Psychol.* 40, 935–952. doi: 10.1037/0012-1649.40.6.935

Friso-van den Bos, I., Kroesbergen, E. H., Van Luit, J. E., Xenidou-Dervou, I., Jonkman, L. M., Van der Schoot, M., et al. (2015). Longitudinal development of number-line estimation and mathematics performance in primary school children. *J. Exp. Child Psychol.* 134, 12–29. doi: 10.1016/j.jecp.2015.02.002

Fuchs, L. S., Compton, D. L., Fuchs, D., Paulsen, K., Bryant, J. D., and Hamlett, C. L. (2005). The prevention, identification, and cognitive determinants of math difficulty. *J. Educ. Psychol.* 97, 493–513. doi: 10.1037/0022-0663.97.3.493

Fuchs, L. S., Fuchs, D., Compton, D. L., Powell, S. R., Seethaler, P. M., Capizzi, A. M., et al. (2006). The cognitive correlates of third-grade skill in arithmetic, algorithmic computation, and arithmetic word problems. *J. Educ. Psychol.* 98, 29–43. doi: 10.1037/0022-0663.98.1.29

Fuchs, L. S., Geary, D. C., Compton, D. L., Fuchs, D., Hamlett, C. L., and Bryant, J. D. (2010a). The contributions of numerosity and domain-general abilities to school readiness. *Child Dev.* 81, 1520–1533. doi: 10.1111/j.1467-8624.2010.01489.x

Fuchs, L. S., Geary, D. C., Compton, D. L., Fuchs, D., Hamlett, C. L., Seethaler, P. M., et al. (2010b). Do different types of school mathematics development depend on different constellations of numerical versus general cognitive abilities? *Dev. Psychol.* 46, 1731–1746. doi: 10.1037/a0020662

Fuchs, L. S., Schumacher, R. F., Long, J., Namkung, J., Hamlett, C. L., Cirino, P. T., et al. (2013). Improving at-risk learners' understanding of fractions. *J. Educ. Psychol.* 105, 683–700. doi: 10.1037/a0032446

Fuhs, M. W., Hornburg, C. B., and McNeil, N. M. (2016). Specific early number skills mediate the association between executive functioning skills and mathematics achievement. *Dev. Psychol.* 52, 1217–1235. doi: 10.1037/dev0000145

Geary, D. C. (2005). *The origin of mind: Evolution of brain, cognition, and general intelligence*. Washington, DC: American Psychological Association.

Geary, D. C. (2011). Cognitive predictors of achievement growth in mathematics: a 5-year longitudinal study. *Dev. Psychol.* 47, 1539–1552. doi: 10.1037/a0025510

Geary, D. C., Bailey, D. H., and Hoard, M. K. (2009). Predicting mathematical achievement and mathematical learning disability with a simple screening tool: The number sets task. *J. Psychoeduc. Assess.* 27, 265–279. doi: 10.1177/0734282908330592

Geary, D. C., Hoard, M. K., Byrd-Craven, J., Nugent, L., and Numtee, C. (2007). Cognitive mechanisms underlying achievement deficits in children with mathematical learning disability. *Child Dev.* 78, 1343–1359. doi: 10.1111/j.1467-8624.2007.01069.x

Geary, D. C., Nicholas, A., Li, Y., and Sun, J. (2017). Developmental change in the influence of domain-general abilities and domain-specific knowledge on mathematics achievement: an eight-year longitudinal study. *J. Educ. Psychol.* 109, 680–693. doi: 10.1037/edu0000159

Ginsburg, H., and Baroody, A. (2003). *TEMA-3 Examiners Manual.* Austin, TX: Pro-Ed.

Hecht, S. A., Torgesen, J. K., Wagner, R. K., and Rashotte, C. A. (2001). The relations between phonological processing abilities and emerging individual differences in mathematical computation skills: A longitudinal study from second to fifth grades. *J. Exp. Child Psychol.* 79, 192–227. doi: 10.1006/jecp.2000.2586

Hogan, T. P., Catts, H. W., and Little, T. D. (2005). The relationship between phonological awareness and reading: implication for the assessment of phonological awareness. *Lang. Speech Hear. Serv. Sch.* 36, 285–293. doi: 10.1044/0161-1461(2005/029)

Hu, L., and Bentler, P. M. (1999). Cutoff criteria for fit indexes in covariance structure analysis: conventional criteria versus new alternatives. *Struct. Equ. Model. Multidiscip. J.* 6, 1–55. doi: 10.1080/10705519909540118

Hulme, C., Snowling, M., Caravolas, M., and Carroll, J. (2005). Phonological skills are (probably) one cause of success in learning to read: A comment on Castles and Coltheart. *Sci. Stud. Read.* 9, 351–365. doi: 10.1207/s1532799xssr0904_2

Jordan, N. C., Hanich, L. B., and Kaplan, D. (2003). A longitudinal study of mathematical competencies in children with specific mathematics difficulties versus children with comorbid mathematics and reading difficulties. *Child Dev.* 74, 834–850. doi: 10.1111/1467-8624.00571

Joyner, R. E., and Wagner, R. K. (2020). Co-occurrence of reading disabilities and math disabilities: a meta-analysis. *Sci. Stud. Read.* 24, 14–22. doi: 10.1080/10888438.2019.1593420

Kolkman, M. E., Hoijtink, H. J., Kroesbergen, E. H., and Leseman, P. P. (2013). The role of executive functions in numerical magnitude skills. *Learn. Individ. Differ.* 24, 145–151. doi: 10.1016/j.lindif.2013.01.004

Koponen, T., Aro, M., Poikkeus, A.-M., Niemi, P., Lerkkanen, M.-K., Ahonen, T., et al. (2018). Comorbid fluency difficulties in reading and math: longitudinal stability across early grades. *Except. Child.* 84, 298–311. doi: 10.1177/0014402918756269

Koponen, T., Salmi, P., Eklund, K., and Aro, T. (2013). Counting and RAN: predictors of arithmetic calculation and reading fluency. *J. Educ. Psychol.* 105, 162–175. doi: 10.1037/a0029285

Korpipää, H., Koponen, T., Aro, M., Tolvanen, A., Aunola, K., Poikkeus, A.-M., et al. (2017). Covariation between reading and arithmetic skills from grade 1 to grade 7. *Contemp. Educ. Psychol.* 51, 131–140. doi: 10.1016/j.cedpsych.2017.06.005

Krajewski, K., and Schneider, W. (2009). Exploring the impact of phonological awareness, visual–spatial working memory, and preschool quantity–number competencies on mathematics achievement in elementary school: findings from a 3-year longitudinal study. *J. Exp. Child Psychol.* 103, 516–531. doi: 10.1016/j.jecp.2009.03.009

Landerl, K., and Moll, K. (2010). Comorbidity of learning disorders: prevalence and familial transmission. *J. Child Psychol. Psychiatry* 51, 287–294. doi: 10.1111/j.1469-7610.2009.02164.x

Landerl, K., Freudenthaler, H. H., Heene, M., De Jong, P. F., Desrochers, A., Manolitsis, G., et al. (2019). Phonological awareness and rapid automatized naming as longitudinal predictors of reading in five alphabetic orthographies with varying degrees of consistency. *Scientific Stud. Reading* 23, 220–234. doi: 10.1080/10888438.2018.1510936

Lee, K., and Bull, R. (2016). Developmental changes in working memory, updating, and math achievement. *J. Educ. Psychol.* 108, 869–882. doi: 10.1037/edu0000090

LeFevre, J. A., Fast, L., Skwarchuk, S. L., Smith-Chant, B. L., Bisanz, J., Kamawar, D., et al. (2010). Pathways to mathematics: longitudinal predictors of performance. *Child Dev.* 81, 1753–1767. doi: 10.1111/j.1467-8624.2010.01508.x

LeFevre, J. A., Jimenez Lira, C., Sowinski, C., Cankaya, O., Kamawar, D., and Skwarchuk, S. L. (2013). Charting the role of the number-line in mathematical development. *Front. Psychol.* 4:641. doi: 10.3389/fpsyg.2013.00641

Li, M., Tan, Y., Cui, J., Chen, C., Dong, Q., and Zhou, X. (2019). The semantic network supports approximate computation. *Neuropsychology* 33, 842–854. doi: 10.1037/neu0000548

Lonigan, C. J., Burgess, S. R., and Anthony, J. L. (2000). Development of emergent literacy and early reading skills in preschool children: evidence from a latent-variable longitudinal study. *Dev. Psychol.* 36:596. doi: 10.1037/0012-1649.36.5.596

Lubinski, D., Benbow, C. P., and Kell, H. J. (2014). Life paths and accomplishments of mathematically precocious males and females four decades later. *Psychol. Sci.* 25, 2217–2232. doi: 10.1177/0956797614551371

Lyon, G. R., Shaywitz, S. E., and Shaywitz, B. A. (2003). A definition of dyslexia. *Annals dyslexia* 53, 1–14. doi: 10.1007/s11881-003-0001-9

Macmillan, N. A. (2002). "Signal detection theory" in *Stevens' Handbook of Experimental Psychology. Vol. 4*. eds. H. Pashler and J. Wixted (New York: John Wiley & Sons), 43–90.

Mann Koepke, K., and Miller, B. (2013). At the intersection of math and reading disabilities: introduction to the special issue. *J. Learn. Disabil.* 46, 483–489. doi: 10.1177/0022219413498200

McClelland, M. M., Cameron, C. E., Connor, C. M., Farris, C. L., Jewkes, A. M., and Morrison, F. J. (2007). Links between behavioral regulation and preschoolers' literacy, vocabulary, and math skills. *Dev. Psychol.* 43:947. doi: 10.1037/0012-1649.43.4.947

Melby-Lervåg, M., Lyster, S. A. H., and Hulme, C. (2012). Phonological skills and their role in learning to read: a meta-analytic review. *Psychol. Bull.* 138, 322–352. doi: 10.1037/a0026744

Ministry of Education (2013). Nurturing Early Learners: A Curriculum for Kindergartens in Singapore. Language and Literacy. https://www.nel.moe.edu.sg/qql/slot/u143/Resources/Downloadable/pdf/nel-guide/nel-edu-guide-language-literacy.pdf (Accessed June 17, 2021).

Moll, K., Göbel, S. M., and Snowling, M. J. (2015). Basic number processing in children with specific learning disorders: comorbidity of reading and mathematics disorders. *Child Neuropsychol.* 21, 399–417. doi: 10.1080/09297049.2014.899570

Moll, K., Landerl, K., Snowling, M. J., and Schulte-Körne, G. (2019). Understanding comorbidity of learning disorders: task-dependent estimates of prevalence. *J. Child Psychol. Psychiatry* 60, 286–294. doi: 10.1111/jcpp.12965

Monette, S., Bigras, M., and Guay, M. C. (2011). The role of the executive functions in school achievement at the end of grade 1. *J. Exp. Child Psychol.* 109, 158–173. doi: 10.1016/j.jecp.2011.01.008

Muthén, L.K., and Muthén, B.O. (2017). *Mplus User's Guide. 8th Edn.* Los Angeles, CA: Muthén and Muthén

Napoli, A. R., and Purpura, D. J. (2018). The home literacy and numeracy environment in preschool: cross-domain relations of parent–child practices and child outcomes. *J. Exp. Child Psychol.* 166, 581–603. doi: 10.1016/j.jecp.2017.10.002

Ng, E. L., and O'Brien, B. (2020). Singapore Kindergarten Impact Project [Project Closure Report].

Peng, P., and Kievit, R. A. (2020). The development of academic achievement and cognitive abilities: A bidirectional perspective. *Child Dev. Perspect.* 14, 15–20. doi: 10.1111/cdep.12352

Peng, P., Lin, X., Ünal, Z. E., Lee, K., Namkung, J., Chow, J., et al. (2020). Examining the mutual relations between language and mathematics: A meta-analysis. *Psychol. Bull.* 146:595. doi: 10.1037/bul0000231

Peters, L., Bulthé, J., Daniels, N., de Beeck, H. O., and De Smedt, B. (2018). Dyscalculia and dyslexia: different behavioral, yet similar brain activity profiles during arithmetic. *NeuroImage: Clin.* 18, 663–674. doi: 10.1016/j.nicl.2018.03.003

Pinto, G., Bigozzi, L., Tarchi, C., Vezzani, C., and Accorti Gamannossi, B. (2016). Predicting reading, spelling, and mathematical skills: A longitudinal study from kindergarten through first grade. *Psychol. Rep.* 118, 413–440. doi: 10.1177/0033294116633357

Poulsen, M., Juul, H., and Elbro, C. (2015). Multiple mediation analysis of the relationship between rapid naming and reading. *J. Res. Read.* 38, 124–140. doi: 10.1111/j.1467-9817.2012.01547.x

Pugh, K. R., Mencl, W. E., Jenner, A. R., Katz, L., Frost, S. J., Lee, J. R., et al. (2001). Neurobiological studies of reading and reading disability. *J. Commun. Disord.* 34, 479–492. doi: 10.1016/S0021-9924(01)00060-0

Purpura, D. J., Litkowski, E. C., and Knopik, V. (2019). Mathematics and reading develop together in young children: practical and policy considerations. *Policy Insights Behav. Brain Sci.* 6, 12–20. doi: 10.1177/2372732218815923

Purpura, D. J., and Lonigan, C. J. (2013). Informal numeracy skills: The structure and relations among numbering, relations, and arithmetic operations in preschool. *Am. Edu. Res. J.* 50, 178–209. doi: 10.3102/0002831212465332

Purpura, D. J., and Logan, J. A. (2015). The nonlinear relations of the approximate number system and mathematical language to early mathematics development. *Dev. Psychol.* 51, 1717–1724. doi: 10.1037/dev0000055

Purpura, D. J., and Napoli, A. R. (2015). Early numeracy and literacy: Untangling the relation between specific components. *Math. Think. Learn.* 17, 197–218. doi: 10.1080/10986065.2015.1016817

Purpura, D. J., Logan, J. A., Hassinger-Das, B., and Napoli, A. R. (2017). Why do early mathematics skills predict later reading? The role of mathematical language. *Dev. Psychol.* 53, 1633–1642. doi: 10.1037/dev0000375

Raven, J. C. (1947). *Progressive Matrices. Set A, Ab, B, Book Form*. London: H.K. Lewis

Ritchie, S. J., and Bates, T. C. (2013). Enduring links from childhood mathematics and reading achievement to adult socioeconomic status. *Psychol. Sci.* 24, 1301–1308. doi: 10.1177/0956797612466268

Rousselle, L., and Noël, M. P. (2007). Basic numerical skills in children with mathematics learning disabilities: A comparison of symbolic vs non-symbolic number magnitude processing. *Cognition* 102, 361–395. doi: 10.1016/j.cognition.2006.01.005

Sabanayagam, C., Shankar, A., Wong, T. Y., Saw, S. M., and Foster, P. J. (2007). Socioeconomic status and overweight/obesity in an adult Chinese population in Singapore. *J. Epidemiol.* 17, 161–168. doi: 10.2188/jea.17.161

Sarama, J., Lange, A. A., Clements, D. H., and Wolfe, C. B. (2012). The impacts of an early mathematics curriculum on oral language and literacy. *Early Child Res. Q.* 27, 489–502. doi: 10.1016/j.ecresq.2011.12.002

Schatschneider, C., Carlson, C. D., Francis, D. J., Foorman, B. R., and Fletcher, J. M. (2002). Relationship of rapid automatized naming and phonological awareness in early Reading development: implications for the double-deficit hypothesis. *J. Learn. Disabil.* 35, 245–256. doi: 10.1177/002221940203500306

Schlaggar, B. L., and McCandliss, B. D. (2007). Development of neural systems for reading. *Annu. Rev. Neurosci.* 30, 475–503. doi: 10.1146/annurev.neuro.28.061604.135645

Shin, T., Davison, M. L., Long, J. D., Chan, C. K., and Heistad, D. (2013). Exploring gains in reading and mathematics achievement among regular and exceptional students using growth curve modeling. *Learn. Individ. Differ.* 23, 92–100. doi: 10.1016/j.lindif.2012.10.002

Snowling, M. J. (2001). From language to reading and dyslexia 1. *Dyslexia* 7, 37–46. doi: 10.1002/dys.185

Sweller, J. (2015). In academe, what is learned, and how is it learned? *Curr. Directions Psychol. Sci.* 24, 190–194. doi: 10.1177/0963721415569570

Van der Ven, S. H., Kroesbergen, E. H., Boom, J., and Leseman, P. P. (2012). The development of executive functions and early mathematics: A dynamic relationship. *Br. J. Educ. Psychol.* 82, 100–119. doi: 10.1111/j.2044-8279.2011.02035.x

Vanbinst, K., van Bergen, E., Ghesquière, P., and De Smedt, B. (2020). Cross-domain associations of key cognitive correlates of early reading and early arithmetic in 5-year-olds. *Early Child Res. Q.* 51, 144–152. doi: 10.1016/j.ecresq.2019.10.009

Vander Stappen, C., and Reybroeck, M. V. (2018). Phonological awareness and rapid automatized naming are independent phonological competencies with specific impacts on word reading and spelling: an intervention study. *Front. Psychol.* 9:320. doi: 10.3389/fpsyg.2018.00320

Vukovic, R. K., and Siegel, L. S. (2006). The double-deficit hypothesis a comprehensive analysis of the evidence. *J. Learn. Disabil.* 39, 25–47. doi: 10.1177/00222194060390010401

Wagner, R., Balthazor, M., Hurley, S., Morgan, S., Rashotte, C., Shaner, R., et al. (1987). The nature of prereaders' phonological processing abilities. *Cogn. Dev.* 2, 355–373. doi: 10.1016/S0885-2014(87)80013-8

Wagner, R. K., and Torgesen, J. K. (1987). The nature of phonological processing and its causal role in the acquisition of reading skills. *Psychol. Bull.* 101, 192–212. doi: 10.1037/0033-2909.101.2.192

Wagner, R. K., Torgesen, J. K., Laughon, P., Simmons, K., and Rashotte, C. A. (1993). Development of young readers' phonological processing abilities. *J. Educ. Psychol.* 85, 83–103. doi: 10.1037/0022-0663.85.1.83

Wagner, R., Torgesen, J., Rashotte, C., and Pearson, N. (2012). *Comprehensive Test of Phonological Processing 2nd Edn.* Austin, TX: Pro-Ed.

Wilkinson, G. S., and Robertson, G. J. (2006). *Wide Range Achievement Test 4*. Lutz, FL: Psychological Assessment Resources

Wilson, A. J., Andrewes, S. G., Struthers, H., Rowe, V. M., Bogdanovic, R., and Waldie, K. E. (2015). Dyscalculia and dyslexia in adults: cognitive bases of comorbidity. *Learn. Individ. Differ.* 37, 118–132. doi: 10.1016/j.lindif.2014.11.017

Zaboski, B. A. II, Kranzler, J. H., and Gage, N. A. (2018). Meta-analysis of the relationship between academic achievement and broad abilities of the Cattell-horn-Carroll theory. *J. Sch. Psychol.* 71, 42–56. doi: 10.1016/j.jsp.2018.10.001

Zemlock, D., Vinci-Booher, S., and James, K. H. (2018). Visual–motor symbol production facilitates letter recognition in young children. *Read. Writ.* 31, 1255–1271. doi: 10.1007/s11145-018-9831-z

Zhang, X., and Lin, D. (2018). Cognitive precursors of word reading versus arithmetic competencies in young Chinese children. *Early Child Res. Q.* 42, 55–65. doi: 10.1016/j.ecresq.2017.08.006

Zoccolotti, P., De Luca, M., Marinelli, C. V., and Spinelli, D. (2020). Testing the specificity of predictors of reading, spelling and maths: A new model of the association among learning skills based on competence, performance and acquisition. *Front. Human Neurosci.* 14:573998. doi: 10.3389/fnhum.2020.573998

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# The Demands of Simple and Complex Arithmetic Word Problems on Language and Cognitive Resources

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Solving arithmetic word problems requires constructing a situation model based on the problem text and translating that into a mathematical model. As such, word problem solving makes demands on students' language comprehension and their domain-general cognitive resources. These demands may decrease when students get more experienced and use strategies that do not require fully understanding the situation presented in the problem. The current study aims to address this hypothesis. Students ($N$=444) from third to sixth grade solved a paper-and-pencil task with 48 mathematics problems, comprising symbolic arithmetic problems and standard word problems, as well as more complex word problems that involve two arithmetic steps or include irrelevant numerical information. Their performance was analyzed with multilevel logistic regression analyses. Results showed that within each grade, performance on the different problem types did not differ, suggesting that already in third-grade students seem helped nor hindered by presenting arithmetic problems in a story, even if that story contains irrelevant numerical information. Non-verbal reasoning was more important in standard word problems than in arithmetic problems in symbolic format in one-step arithmetic, and reading comprehension was more important in solving two-step arithmetic word problems than in one-step arithmetic word problems.

**Keywords: word problems, reading comprehension, arithmetic, mathematics, cognitive abilities, non-verbal reasoning, working memory**

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## INTRODUCTION

In contemporary mathematics education, arithmetic word problems (also called verbal or story problems) are omnipresent in instruction and assessment. Solving word problems is a complex, multi-phase process involving an interplay of various cognitive processes (Verschaffel et al., 2000, 2020). Central phases are the construction of a mental representation of the problem situation and the transformation of this situation model to a mathematical model, often a specific arithmetic expression (Kintsch and Greeno, 1985; Cummins et al., 1988; Verschaffel et al., 2000). These processes make demands on language abilities as well as domain-general cognitive resources (Fuchs et al., 2015, 2020; Wang et al., 2016). However, results in more experienced word problem solvers suggest that the steps of constructing a situation and mathematical model become less important, possibly because students use a more superficial strategy, relying heavily on their schemata for solving typical, one-step word problems that does not require fully understanding the situation (Hickendorff, 2013a). The current study aims to address this hypothesis by extending previous studies in three ways: by including students from a wider age range (third to sixth grade), by including more complex word problems (two-step arithmetic problems and problems including irrelevant numerical information), and by including a set of individual differences measures that taps into language comprehension and domain-general cognitive resources.

## Word Problems

Word problems in mathematics education are typically defined as verbal descriptions of a problem situation in which one or more questions are raised that can be answered by the application of mathematical operations that have been learnt at school on the numerical data that are available in the problem situation (Verschaffel et al., 2000, 2020). An example is "there are 136 persons at the party. To play a game they are distributed in groups of four persons. How many groups are formed?" Word problems play an important role in mathematics education for several reasons: They offer practice in applied problem solving and mathematical modeling in real-life situations, they can motivate students for mathematics, they train students to think creatively and develop their problem-solving abilities, and they can aid in the development of new mathematical concepts and skills (Verschaffel et al., 2000, 2020). However, word problems are also among the most difficult problems that students encounter. It is therefore not surprising that a large body of research has been devoted to word problems (for a recent review, see Verschaffel et al., 2020).

One of the branches of research focuses on the complex interplay of cognitive processes that play a role. Word problem solving models typically assume that the most critical steps in solving word problems are the construction of a mental representation of the problem situation (the situation model) and the translation of that situation model into a mathematical model (Kintsch and Greeno, 1985; Verschaffel et al., 2000). Leiss et al. (2019) provided empirical support for this claim by showing that constructing a situation model is crucial for the correct solution of word problems and takes a considerable amount of solution time, depending on the linguistic complexity of the tasks.

However, Hickendorff (2013a) found that students at the end of primary school did not show additional difficulties in solving word problems compared to solving their symbolically presented counterparts, nor did they use different strategies to solve the problems, nor did the problems have differential relations with reading comprehension. This suggests that students at the end of primary school did not perceive real differences between word problems and their symbolic counterparts. Hickendorff (2013a) attempted to reconcile the discrepancy between these patterns and the findings in younger students by the tentative explanation that the interplay between the students' level of experience in solving word problems and the type of word problems used is crucial. More experienced word problem solvers have more developed cognitive schemata to solve these problems (Kintsch and Greeno, 1985). Sixth graders may be seen as experts, with a specialized knowledge base and strategies to form a representation of the problem and solve the problems top-down using their semantic schemata, whereas inexperienced word problem solvers rely more on bottom-up processing of information (De Corte et al., 1985). Typical school mathematics word problems are one-step arithmetical problems without redundant information or misleading key words. Experienced word problem solvers have developed cognitive schemata that fit such problems well, regarding structure, role, and intent of word problems (Verschaffel et al., 2000). In other words, sixth graders have probably become very skillful in selecting the appropriate cognitive scheme based on cues in the text (e.g., the word "distributed" signals the operation "division") and insert the appropriate information from the problem statement into the empty slots (e.g., inserting 136 and 4 in the empty slots of the division operation).

Evidence for this scheme-based approach comes from studies using inconsistent word problems where the relational key words are not consistent with the required arithmetic operation (van der Schoot et al., 2009; Boonen et al., 2013). Other evidence comes from studies using "non-routine" word problems, such as "Brian and Sylvia go to the same school. Brian lives 17 km away from school and Sylvia 8 km. How many km apart do Brian and Sylvia live?." These studies show that experienced students tend to answer these problems in a superficial way by selecting the most likely operation and inserting the numbers in the slots (17–8 = 9 in the example), without making realistic considerations such as that Brian and Sylvia could also live on different sides of the school (Verschaffel et al., 1994, 2020). In the words of Verschaffel et al. (2000, p. 13), students used "the rules of the game of word problem solving."

To overcome this superficial problem-solving approach of "undressing" the word problem to find and execute the arithmetic operation "hidden" in the problem text, the word problems could be made less simple and straightforward. One way to make word problems more complex is by using two-step arithmetic problems that cannot be solved with one single mathematical operation, requiring students to set up and monitor a plan of solution steps (Verschaffel et al., 2020). Another way is to include irrelevant numerical information that must be ignored (Jiménez and Verschaffel, 2014; Wang et al., 2016; Leiss et al., 2019). In both ways, students cannot "skip" the mental modeling step that easily but must devote attention to analyzing the text to construct an appropriate situation model and mathematical model.

Therefore, in the current study, both one-step and two-step arithmetic word problems are included, with and without irrelevant numerical information. By including these more complex types of word problems, we aim to make the steps of constructing a situation model and transforming that into a mathematical model more salient. This should enable capturing the different problem-solving processes involved and investigate the relative influence of individual differences that have been found to impact word problem solving: reading comprehension, non-verbal reasoning, and working memory (Fuchs et al., 2015).

## Reading Comprehension

Since a key factor in constructing an adequate situation model is comprehension of the problem text, it is not surprising that reading comprehension ability and word problem solving are related (Pape, 2004; Fuchs et al., 2006, 2015; Vilenius-Tuohimaa et al., 2008; Hickendorff, 2013a,b; Leiss et al., 2019). In a detailed qualitative analysis of students' solution processes of solving reality-based mathematics tasks, Leiss et al. (2019) found that students' reading comprehension ability was positively related to the construction of a suitable situation model and that tasks with higher reading and situational demands impede construction of the situation model. Boonen et al. (2013) showed that the relation between reading comprehension and word problem solving was partly mediated by the skill of relational processing: the derivation of the correct relations between the solution-relevant elements from the text base of the word problem. Fuchs et al. (2015) found that word problem solving requires general language comprehension processes and word problem-specific language comprehension.

Several studies investigated whether reading comprehension is more strongly related to word problem solving than to solving symbolically presented arithmetic. In younger students (first to third graders; Fuchs et al., 2006; Hickendorff, 2013b), this stronger association was indeed found, supporting the role comprehension processes play in word problem solving. However, in sixth graders (Hickendorff, 2013a), there was no differential relation of reading comprehension with performance on the two problem types. A potential explanation is, again, the superficial, scheme-based problem-solving strategies that more experienced students use to solve these standard "dressed-up" word problems, in which they do not really strive for understanding of the problem text. In the current study, we aim to bridge the age range gap between these existing studies by using a sample of third to sixth graders, expecting to find a decrease in the extent to which reading comprehension is more strongly related to word problem solving that to symbolic arithmetic.

## Cognitive Resources

Word problems not only place demands on language abilities but also require domain-general cognitive resources. Studies with first- to third-grade students have identified several cognitive correlates of word problem solving, among which non-verbal reasoning and working memory seem the most relevant ones (Wang et al., 2016; Fuchs et al., 2020).

Non-verbal reasoning involves the ability to infer and implement rules and to identify patterns and relations (Wang et al., 2016). In word problem solving, it is relevant in targeting and organizing essential information, inferring information that is not immediately evident, and excluding irrelevant information. Wang et al. (2016) found that non-verbal reasoning is particularly important in solving word problems with irrelevant information, because the process of schema identification and application of a viable solution strategy makes strong demands on reasoning ability.

Working memory involves the ability to simultaneously store and process information (Baddeley, 1992). Recent meta-analyses showed that working memory is related to mathematics performance and that the relation with word problem solving is one of the strongest ones (Friso-Van Den Bos et al., 2013; Peng et al., 2016). In word problem solving, it plays a role in storing and manipulating multiple pieces of information in the process of constructing the situation model and transforming that into a mathematical model (Fuchs et al., 2015, 2020; Verschaffel et al., 2020).

## Current Study

Solving word problems involves multiple steps and relies on several cognitive processes. Research suggests that when students progress through primary school and thus get more experienced in solving word problems, the difference between solving standard word problems and their symbolic counterparts disappears. A potential explanation is that experienced students solve word problems in a more superficial way, relying heavily on their cognitive schemata for the semantic structures of typical school word problems. The current study aims to put this explanation to the test by seeking empirical support. To that end, we investigated the performance of students with different levels of experience (third to sixth graders) in word problems that differ in complexity (one-step vs. two-step problems; problems with and without irrelevant numerical information). By investigating the differential role that language (reading comprehension) and domain-general cognitive resources (working memory and non-verbal reasoning) play in problems in different formats and in different grades, we aim to find additional support for the differential importance of the processes.

Research question 1 addresses one-step arithmetic and focuses on the difference between problems presented symbolically or as standard word problem. We expect a performance advantage for symbolic problems over word problems in lower grades but no difference in higher grades (hypothesis 1a). Relatedly, we expect linguistic and cognitive abilities to be more strongly correlated with performance on word problems than with performance on symbolic problems in lower grades, but no differential relations in higher grades (hypothesis 1b).

Research question 2 addresses standard word problems and focuses on the difference between one-step and two-step arithmetic. We expect two-step word problems to be more difficult than one-step word problems, particularly in lower grades where students have less developed cognitive schemata available for two-step problems (hypothesis 2a). Relatedly, we expect the linguistic and cognitive individual differences to be more strongly correlated with performance on two-step problems than with performance on one-step word problems, particularly in lower grades (hypothesis 2b).

Research question 3 focuses on the difference between standard and non-standard word problems which include irrelevant numerical information. Adding irrelevant information requires cognitive resources to inhibit the irrelevant information, it requires more attention for the steps of constructing a situation model and the mathematical model, and it could lead to additional errors by erroneously using the irrelevant numerical information. Therefore, we expect non-standard word problems to be more difficult than one-step word problems, particularly in less experienced students (hypothesis 3a). Relatedly, we expect linguistic and cognitive individual differences (Wang et al., 2016) to be more strongly correlated with performance on non-standard word problems than with performance on standard word problems, particularly in lower grades (hypothesis 3b).

# MATERIALS AND METHODS

## Participants

The sample consisted of 444 students (201 boys, 211 girls, 32 missing data) from seven different schools in the West of the Netherlands (30–98 students per school). There were 121 third graders, 116 fourth graders, 95 fifth graders, and 112 sixth graders. The research protocol was approved by the Institute's IRB (number ECPW-2015 115), and only children with written parental consent participated.

As an indicator of general achievement level in mathematics and in reading comprehension, we collected the students' most recent scores on the mathematics and reading comprehension subtests of CITO's student monitoring system (Feenstra et al., 2010; Janssen et al., 2010; Weekers et al., 2011). This is a widely used assessment system which provides for two tests per grade (halfway and at the end of the school year). It enables schools and teachers to measure students' achievement level and their progression. Based on nationally representative norms, students' performance can be categorized into five quantiles: 1 (lowest 20%) through 5 (highest 20%). In the current sample, there were valid scores on the mathematics achievement subtest for 365 students, with 17.0% in category 1, 20.0% in category 2, 22.7% in category 3, 18.4% in category 4, and 21.9% in category 5. There were valid scores on the reading comprehension subtest for 362 students, with 20.7% in category 1, 19.6% in category 2, 17.7% in category 3, 20.2% in category 4, and 21.8% in category 5. These distributions did not differ by grade for either mathematics ($\chi^2$ (df = 12) = 15.522, $p = 0.214$) or reading comprehension ($\chi^2$ (df = 12) = 15.025, $p = 0.240$). In all, the sample is quite representative for the national population in terms of achievement level in both mathematics and reading comprehension, overall as well as per grade.

## Materials

### Arithmetic Task

The arithmetic task consisted of 48 arithmetic problems, distributed across two booklets of 24 problems each. The problems were constructed according to two dimensions. The first dimension was *presentation format* with three types: symbolic (no text/story), standard word problems, and non-standard word problems including an irrelevant number. The second dimension was the *number of operations*: one-step problems requiring only one arithmetic operation (addition, subtraction, multiplication, or division) or two-step problems requiring two arithmetic operations (addition or subtraction combined with multiplication or division). Full crossing of these dimensions would result in six different problem types. However, two-step problems in symbolic format were not included since that would have necessitated working with brackets (e.g., $(21-4)\times 7$) which is not covered in the primary school mathematics curriculum. **Table 1** presents an overview of the five problem types included in the arithmetic task.

For the one-step problems, there were two problems per operation, and for each problem, there were two numerically parallel versions (e.g., version *a* 283 + 368; version *b* 386 + 238). Thus, in total, there were $4\times 2\times 2=16$ problems. All 16 problems were presented in symbolic format and as word problem: either as standard word problem or as non-standard word problem. That means that students solved numerically identical problems twice, in different formats. To prevent students recalling the problems and solutions, the problems were distributed across the two different booklets, that were administered on different days. Numerically identical problems were never in the same booklet. For instance, in booklet A problem version *a* was presented in symbolic format and version *b* as standard word problem, and in booklet B, problem version *b* was presented in symbolic format and version *a* as non-standard word problem. The stories presented in the two word problems were slightly different to prevent students recognizing the story. For instance, in the one-step problem in **Table 1**, the cycling race was replaced by a running race. The possible combinations of word problem format (standard or non-standard), story used, and problem version *(a* or *b*) were counterbalanced across task versions.

The two-step problems involved a combination of addition or subtraction on the one hand and multiplication or addition on the other. The resulting four different combinations of operations were crossed with the two different orders (addition/subtraction first or multiplication/division first), yielding a total of eight different problems. Each problem was presented twice: as standard word problem in one booklet and as non-standard word problem in the other booklet, again with slightly different stories, for example, the DVDs were replaced by computer games in the example from **Table 1** and a different name was used.

There were 16 different task versions, resulting from crossing the different counterbalancing options for the one-step problems, booklet order (booklet A first or B first), and problem order within each booklet (two pre-specified orders, one being the reverse of the other). The answers to each problem were scored as correct or incorrect. All performance scales had good reliability (Cronbach's alpha > 0.80), see **Table 1**.

### Reading Comprehension

We used two different measures of reading comprehension, one based on the product of reading and the other on the process. The first measure was the earlier mentioned reading comprehension subtest of CITO's national student monitoring system (Feenstra et al., 2010; Weekers et al., 2011). The test included various types of texts, such as informative texts and fictional texts, as well as various text genres, such as reports, letters, or poems. Students answer multiple-choice items that involve questions

**TABLE 1** | Overview of the arithmetic task.

| | One-step arithmetic | | | Two-step arithmetic | | |
|---|---|---|---|---|---|---|
| | **Example** | ***k*** | **Alpha** | **Example** | ***k*** | **Alpha** |
| Symbolic | 684–248 = ___ | 16 | 0.889 | n.a. | n.a. | n.a. |
| Standard word problem | In total 684 contestants from different countries participated in a cycling race. During the race 248 contestants dropped out. How many contestants reached the finish? | 8 | 0.822 | Linda worked 4 days for 37 euros a day. She buys a box with DVDs for 24 euros. How much does she have left? | 8 | 0.829 |
| Non-standard word problem | In total 684 contestants from 10 different countries participated in a cycling race. During the race 248 contestants dropped out. How many contestants reached the finish? | 8 | 0.812 | Linda worked 4 days for 37 euros a day. She buys a box with 3 DVDs for 24 euros. How much does she have left? | 8 | 0.805 |

about the text, items where different sentences must be ordered to create a story, and fill-the-gap items where students have to select the sentence that fits best. Most questions concerned the content and meaning of the text, interleaved with questions concerning text structure. Furthermore, questions are designed to draw on three processes: comprehension, interpretation, and reflection. Reflection questions are not included before grade 4. Validity and reliability have been reported as satisfactory.

The second reading comprehension measure involved a shortened version of the Multiple-choice Online Cloze Comprehension Assessment (MOCCA; Carlson et al., 2014). This instrument is based on theories that suggest that successful reading comprehension involves the extent to which a reader can develop a coherent mental representation of a text through developing a situation model and that causal inferences are crucial (e.g., Graesser et al., 1994; van den Broek et al., 2005). The MOCCA was developed to measure comprehension processes that readers use *during* reading, thereby widening the scope of most traditional school-based reading comprehension assessments such as CITO's test, that focus on the product rather than the process of reading comprehension. It is a paper-and-pencil multiple-choice test that consists of several short narrative texts of seven sentences. In each text, the sixth sentence is deleted, and the readers must select one of four options to complete the text. The best option requires the reader to make a causal inference that results in a coherent representation of the text. The three alternative options represent specific reading comprehension processes (i.e., paraphrases, local bridging inferences, and lateral connections).

The original MOCCA comprising 40 texts was administered to third to fifth graders (Carlson et al., 2014). Cronbach's alpha values of selecting the correct (causal inference) option were in the 0.90 s. In the current study, we used a shortened version of the MOCCA of 20 texts. Cronbach's alpha was 0.86 in the current sample. Split by grade Cronbach's alpha was 0.81, 0.81, 0.79, and 0.73 for grades 3 to 6, respectively.

### Cognitive Abilities

The Raven Standard Progressive Matrices (Raven SPM, Raven et al., 1992) was used as a measure of non-verbal reasoning. The Raven SPM consists of five series of 12 diagrams or designs in which one part is missing. Students are required to select the correct part that logically completes the diagram, from six or eight options. The difficulty of the items increases when the test proceeds. Answers are scored correct (1) or incorrect (0). Internal consistency and validity have been extensively studied and found to be adequate.

The Monkey Game (Van de Weijer-Bergsma et al., 2016) was used as a measure of working memory. This is a self-reliant online computerized backward word span task. Students hear several spoken words, which they must remember and recall backward by clicking on the words presented visually in a 3 × 3 matrix. There are five levels of increasing difficulty determined by the number of words that must be recalled backward: two (level 1) to six (level 5). For each item, it was scored how many words were recalled in the correct backward serial position. This was transformed into a proportion correct score per item. For instance, if the item involved three words and the student recalled two words on the correct backward serial position, the proportion correct score on this item was 0.667. The reliability of the proportion correct scores in the Monkey Game was evaluated in a sample of first to sixth graders, which yielded satisfactory Cronbach's alpha values between 0.78 and 0.85 (Van de Weijer-Bergsma et al., 2016).

## Procedure

The participating classrooms were visited by one of seven research assistants who handed out the materials and gave the instructions to the students. Per classroom there were two sessions, approximately one week apart. In session 1, the first booklet of the arithmetic task was administered as well as one or two other measures: Raven SPM, MOCCA, and/or the Monkey Game. In session 2, the second booklet of the arithmetic task was administered as well as the remaining measure(s). The arithmetic tasks, Raven SPM, and MOCCA, were administered in a classroom situation, where students worked through the tasks independently, with 35 min planned for each 24-problem arithmetic task booklet, 20 min for the Raven SPM, and 20 min for the MOCCA. The Monkey Game was administered individually in 10 min on a school laptop or computer in the classroom or in a quiet room outside the classroom.

## Analyses

To answer all research questions, multilevel logistic regression models were used with the correctness of the answer to each problem (0/1) as binary dependent variable and with a random intercept across students and across problems to account for the nesting of problems within students (for instance, see Fagginger Auer et al., 2016; Pavias et al., 2016). The analyses were run using the glmer function in the lme4-package for R (Bates et al., 2015). The individual difference measures non-verbal reasoning, working memory, and the two reading comprehension measures were sample standardized before entering the models as predictors. Predictor effects were tested using likelihood ratio tests, which involve statistically testing the improvement in model fit (log-likelihood) associated with the inclusion of a particular effect. The statistic is chi-square distributed with degrees of freedom equal to the number of parameters involved with the added effect.

# RESULTS

Descriptive statistics of the measures are presented in **Table 2**, and the results for the arithmetic tasks are also presented graphically in **Figure 1**. On all measures, there were significant differences between grades ($ps < 0.001$). For CITO's reading comprehension, differences between grades could not be tested because it involved grade-specific norm-referenced scores. **Table 3** presents the correlations between the measures (except CITO's reading comprehension). All measures were significantly correlated ($ps < 0.001$). The two different reading comprehension measures MOCCA and CITO correlated 0.492 in grade 3; 0.507 in grade 4, 0.384 in grade 5; and 0.409 in grade 6 ($ps < 0.001$).

## Standard Word Problems Versus Symbolic Problem

Research question 1 involves the comparison of standard, one-step word problems with their symbolically presented counterparts. **Table 4** shows the model-building steps of the multilevel logistic regression models. To test hypothesis 1a, students' grade (3, 4, 5, or 6) and problem format (word problem vs. symbolic format) were added as predictors to an empty model with only random intercepts across students and across problems. The main effect of grade was significant (all pairwise differences were significant), whereas the main effect of problem format was not. The interaction effect between grade and problem format was significant ($p = 0.043$). *Post hoc* comparisons revealed that there was a non-significant performance advantage of symbolic problems in grade 3 ($\beta = -0.26$, $z = -0.49$) and in grade 4 ($\beta = -0.11$, $z = -0.21$) which turned into a non-significant performance advantage of word problems in grade 5 ($\beta = 0.15$, $z = 0.28$) and in grade 6 ($\beta = 0.14$, $z = 0.28$), see also **Figure 1**. This partly confirms hypothesis 1a.

To address hypothesis 1b, we tested each individual difference measure in a separate run of analyses, starting with adding the main effect of that measure (M5), then testing whether there was a differential effect according to problem format (M6), and finally testing whether this differential effect according to problem format depended on students' grade (M7). Both reading comprehension measures and both cognitive abilities were significantly associated with mathematics performance, but only non-verbal reasoning was differentially related to word problem solving versus symbolic problems. As expected, the association with word problem solving was significantly stronger than the association with solving symbolic problems: $\beta_{WP} = 0.77$, $z = 8.60$ vs. $\beta_{symb} = 0.65$, $z = 9.15$; $z_{difference} = 2.02$. This differential relation did not depend on grade, however. Hypothesis 1b was therefore only partly accepted: Non-verbal reasoning was stronger related to word problem solving than to solving symbolic problems across all grades but reading comprehension and working memory were not related differentially to performance on the two types of problems.

## Two-Step Versus One-Step Arithmetic Word Problems

Research question 2 involves the comparison of one-step and two-step arithmetic word problems. **Table 5** shows the model-building steps of the multilevel logistic regression models. To test hypothesis 2a, students' grade (3, 4, 5, or 6) and number of arithmetic steps (one step vs. two steps) were added as predictors to an empty model with only random intercepts. The main effect of grade was significant, whereas the main effect of arithmetic steps and the interaction effect between grade and arithmetic steps were not. Hypothesis 2a was therefore rejected: Two-step word problems were not more difficult than one-step word problems.

To address hypothesis 2b, we again tested each individual difference measure in a separate run of analyses. Both reading comprehension measures and both cognitive abilities were significantly associated with mathematics performance, but the two reading comprehension measures were differentially related to word problem solving versus symbolic problems. As expected, the association with two-step arithmetic word problems was significantly stronger than the association with one-step arithmetic word problems for the CITO measure ($\beta_{2step} = 0.71$, $z = 8.48$ vs. $\beta_{1step} = 0.52$, $z = 6.35$; $z_{difference} = 2.58$, $p = 0.010$) as well as for the MOCCA measure ($\beta_{2step} = 0.83$ and $\beta_{1step} = 0.57$; $z = 3.45$, $p < 0.001$). This differential relation did not depend on grade, however. Hypothesis 2b was therefore only partly accepted: Reading comprehension was stronger related to solving two-step word problems than to solving one-step word problems across all grades but working memory and non-verbal reasoning were not related differentially to performance on the two types of problems, across all grades.

## Non-standard Versus Standard Word Problems

Research question 3 involves the comparison of standard word problems with non-standard word problems that include irrelevant numerical information. **Table 6** shows the model-building steps of the multilevel logistic regression models. To test hypothesis 3a, students' grade (3, 4, 5, or 6), number of arithmetic steps (one step vs. two steps) and problem type (standard vs. non-standard word problems) were added as predictors to an empty model with only random intercepts. The main effect of grade was significant. In this model, the

**TABLE 2 |** Descriptive statistics of the measures: Means and SD's (between brackets).

| | Grade 3 | Grade 4 | Grade 5 | Grade 6 | Total |
|---|---|---|---|---|---|
| One-step symbolic[a] | 24.0 (19.35) | 39.0 (21.09) | 63.3 (24.33) | 74.3 (18.77) | 49.0 (28.86) |
| One-step standard WP[a] | 21.6 (19.90) | 37.8 (24.36) | 65.1 (25.78) | 75.6 (20.09) | 48.8 (31.23) |
| One-step non-standard WP[a] | 18.5 (20.29) | 35.1 (23.01) | 57.6 (27.85) | 73.1 (20.84) | 45.0 (31.20) |
| Two-step standard WP[a] | 8.8 (12.67) | 24.7 (22.14) | 49.6 (29.14) | 64.1 (27.06) | 35.6 (31.77) |
| Two-step non-standard WP[a] | 8.0 (13.50) | 22.1 (20.68) | 44.6 (29.61) | 58.1 (25.26) | 32.2 (29.95) |
| Working memory[b] | 0.463 (0.1470) | 0.522 (0.1293) | 0.576 (0.1187) | 0.606 (0.1205) | 0.538 (0.1409) |
| Non-verbal reasoning[c] | 34.6 (6.60) | 36.5 (7.23) | 41.4 (5.50) | 42.0 (5.83) | 38.4 (7.10) |
| Reading comprehension (MOCCA)[d] | 7.8 (4.37) | 11.4 (4.30) | 13.4 (3.88) | 15.3 (3.20) | 11.8 (4.87) |
| Reading comprehension (CITO)[e] | 3.20 (1.446) | 2.91 (1.508) | 2.91 (1.379) | 3.10 (1.452) | 3.03 (1.451) |

*[a]Percentage correct on the different problem types in the arithmetic task (0–100).*
*[b]Mean proportion correct on the backward recall items of the Monkey Game (0–1).*
*[c]Number of items correct in the Raven SPM (0–60).*
*[d]Number correct on the MOCCA (0–20).*
*[e]Grade-specific norm score CITO reading comprehension test (1 = lowest quintile; 5 = highest quintile).*

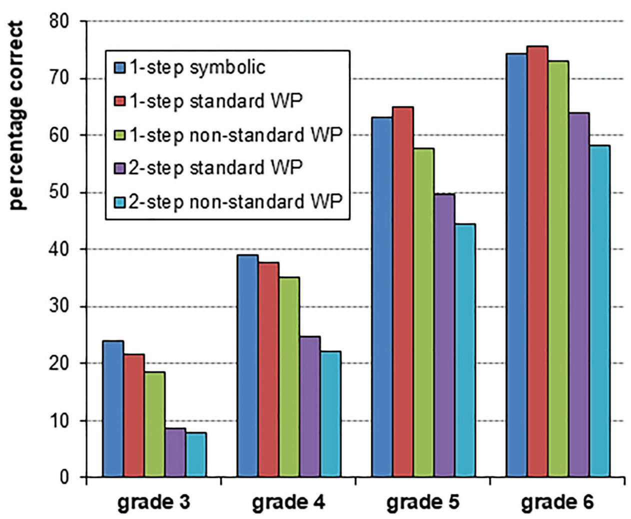


**FIGURE 1 |** Performance means on the five problem types by grade.

main effect of arithmetic steps was significant ($\beta = -0.92$, $z = -2.73$, $p = 0.006$) with lower performance on two-step problems than on one-step problems. The main effect of problem type was not significant nor was the interaction between students' grade and problem type. Hypothesis 3a was therefore rejected: Non-standard word problems with irrelevant numerical information were not more difficult than standard word problems.

To address hypothesis 3b, we again tested each individual difference measure in a separate run of analyses. Both reading comprehension measures and both cognitive abilities were significantly associated with mathematics performance, but not differentially with the two word problem types. Hypothesis 3b was therefore rejected: There were no differential relations with the individual difference measures with performance on standard versus non-standard word problems, across all grades.

## DISCUSSION

Arithmetic word problems require multiple processes, of which constructing a situation model of the problem text and translating that into a mathematical model are the most salient ones. Therefore, word problems are more difficult to solve and make additional linguistic and cognitive demands compared to arithmetic problems in symbolic format, as studies in first to third graders show (Fuchs et al., 2006; Hickendorff, 2013b; Wang et al., 2016). However, research suggests that as students progress through primary school and get more experienced in solving word problems, these extra steps may have less impact on their performance and solution strategies, which could possibly be explained by a heavier reliance on their cognitive schemata for typical one-step arithmetic word problems

**TABLE 3 |** Correlations between the measures.

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| 1. One-step symbolic | | | | | | | |
| 2. One-step standard WP | 0.867 | | | | | | |
| 3. One-step non-standard WP | 0.838 | 0.867 | | | | | |
| 4. Two-step standard WP | 0.822 | 0.811 | 0.822 | | | | |
| 5. Two-step non-standard WP | 0.785 | 0.784 | 0.788 | 0.848 | | | |
| 6. Working memory | 0.460 | 0.452 | 0.455 | 0.470 | 0.456 | | |
| 7. Non-verbal reasoning | 0.549 | 0.543 | 0.528 | 0.526 | 0.509 | 0.467 | |
| 8. Reading comprehension (MOCCA) | 0.573 | 0.557 | 0.570 | 0.609 | 0.555 | 0.393 | 0.447 |

*All ps<0.001.*

**TABLE 4 |** Statistical tests for research question 1: standard word problems versus symbolic problems.

| | Fixed effects | LL | #p | LR | $\chi^2$ | *df* | *p* |
|---|---|---|---|---|---|---|---|
| **Hypothesis 1a** | | | | | | | |
| M0 | - | −5170.9 | 3 | | | | |
| M1 | Grade | −5024.5 | 6 | M1-M0 | 292.824 | 3 | <0.001 |
| M2 | Grade + Pr.Format | −5024.5 | 7 | M2-M1 | 0.004 | 1 | 0.95 |
| M3 | Grade*Pr.Format | −5020.4 | 10 | M3-M2 | 8.146 | 3 | 0.043 |
| **Hypothesis 1b: reading comprehension process (MOCCA)** | | | | | | | |
| M4a | Grade + Pr.Format | −5000.3 | 7 | | | | |
| M5a | Grade + Pr.Format + MOCCA | −4980.2 | 8 | M5a-M4a | 46.144 | 1 | <0.001 |
| M6a | Grade + Pr.Format*MOCCA | −4979.0 | 9 | M6a-M5a | 2.312 | 1 | 0.13 |
| M7a | Grade*Pr.Format*MOCCA | −4978.0 | 15 | M7a-M6a | 2.018 | 6 | 0.92 |
| **Hypothesis 1b: reading comprehension product (CITO)** | | | | | | | |
| M4b | Grade + Pr.Format | −4162.5 | 7 | | | | |
| M5b | Grade + Pr.Format + CITO | −4140.4 | 8 | M5b-M4b | 44.130 | 1 | <0.001 |
| M6b | Grade + Pr.Format*CITO | −4140.4 | 9 | M6b-M5b | 0.818 | 1 | 0.37 |
| M7b | Grade*Pr.Format*CITO | −4138.6 | 15 | M7b-M6b | 2.71 | 6 | 0.82 |
| **Hypothesis 1b: non-verbal reasoning (RAVEN)** | | | | | | | |
| M4c | Grade + Pr.Format | −5024.5 | 7 | | | | |
| M5c | Grade + Pr.Format + RAVEN | −4981.8 | 8 | M5c-M4c | 85.318 | 1 | <0.001 |
| M6c | Grade + Pr.Format*RAVEN | −4979.8 | 9 | M6c-M5c | 3.990 | 1 | 0.046 |
| M7c | Grade*Pr.Format*RAVEN | −4976.1 | 15 | M7c-M6c | 7.424 | 6 | 0.28 |
| **Hypothesis 1b: working memory (WM)** | | | | | | | |
| M4d | Grade + Pr.Format | −4899.9 | 7 | | | | |
| M5d | Grade + Pr.Format + WM | −4875.4 | 8 | M5d-M4d | 48.930 | 1 | <0.001 |
| M6d | Grade + Pr.Format*WM | −4874.4 | 9 | M6d-M5d | 2.154 | 1 | 0.14 |
| M7d | Grade*Pr.Format*WM | −4871.3 | 15 | M7d-M6d | 6.056 | 6 | 0.42 |

*LL, log-likelihood; #p, number of parameters; LR, likelihood ratio test; $\chi^2$, test statistic LR-test; Pr.Format, problem format (word problem or symbolic problem).*

(Hickendorff, 2013a). The current study addressed this hypothesis by extending the age range, making word problems more complex, and including a more varied set of individual differences, tapping into reading comprehension and domain-general cognitive resources.

The first research question involved the comparison of standard, one-step arithmetic word problems with their counterparts in symbolic format. Findings showed that although performance increased across grades, within each grade these two problem formats were just as difficult. However, the non-significant performance advantage of symbolic problems in grades 3–4 flipped into a non-significant performance advantage of standard word problems in grades 5–6. This significant decrease in the performance advantage of symbolic problems is consistent with our expectations that the steps of constructing a situation model and translating that into a mathematical model, which are expected to make word problems relatively difficult, are less prominent when students get more experienced in word problem solving. From the four individual difference measures, only non-verbal reasoning showed a stronger

**TABLE 5** | Statistical tests for research question 2: two-step versus one-step word problems.

| | Fixed effects | LL | #p | LR | $\chi^2$ | *df* | *p* |
|---|---|---|---|---|---|---|---|
| **Hypothesis 2a** | | | | | | | |
| M0 | - | −3465.9 | 3 | | | | |
| M1 | Grade | −3309.0 | 6 | M1-M0 | 313.778 | 3 | <0.001 |
| M2 | Grade + Steps | −3307.5 | 7 | M2-M1 | 3.044 | 1 | 0.081 |
| M3 | Grade*Steps | −3305.5 | 10 | M3-M2 | 4.014 | 3 | 0.26 |
| **Hypothesis 2b: reading comprehension process (MOCCA)** | | | | | | | |
| M4a | Grade + Steps | −3295.1 | 7 | | | | |
| M5a | Grade + Steps + MOCCA | −3261.6 | 8 | M5a-M4a | 63.328 | 1 | <0.001 |
| M6a | Grade + Steps*MOCCA | −3255.8 | 9 | M6a-M5a | 6.480 | 1 | 0.011 |
| M7a | Grade*Steps*MOCCA | −3254.8 | 15 | M7a-M6a | 0.892 | 6 | 0.99 |
| **Hypothesis 2b: reading comprehension product (CITO)** | | | | | | | |
| M4b | Grade + Steps | −2746.9 | 7 | | | | |
| M5b | Grade + Steps + CITO | −2715.2 | 8 | M5b-M4b | 88.702 | 1 | <0.001 |
| M6b | Grade + Steps*CITO | −2712.0 | 9 | M6b-M5b | 0.156 | 1 | 0.69 |
| M7b | Grade*Steps*CITO | −2711.5 | 15 | M7b-M6b | 6.686 | 6 | 0.35 |
| **Hypothesis 2b: non-verbal reasoning (RAVEN)** | | | | | | | |
| M4c | Grade + Steps | −3307.5 | 7 | | | | |
| M5c | Grade + Steps + RAVEN | −3263.1 | 8 | M5c-M4c | 58.582 | 1 | <0.001 |
| M6c | Grade + Steps*RAVEN | −3263.0 | 9 | M6c-M5c | 1.856 | 1 | 0.17 |
| M7c | Grade*Steps*RAVEN | −3259.7 | 15 | M7c-M6c | 2.810 | 6 | 0.83 |
| **Hypothesis 2b: working memory (WM)** | | | | | | | |
| M4d | Grade + Steps | −3227.5 | 7 | | | | |
| M5d | Grade + Steps + WM | −3198.2 | 8 | M5d-M4d | 66.958 | 1 | <0.001 |
| M6d | Grade + Steps*WM | −3197.3 | 9 | M6d-M5d | 11.604 | 1 | 0.001 |
| M7d | Grade*Steps*WM | −3195.9 | 15 | M7d-M6d | 2.032 | 6 | 0.92 |

*LL, log-likelihood; #p, number of parameters; LR, likelihood ratio test; $\chi^2$, test statistic LR-test; Steps, number of arithmetic steps (one or two).*

association with word problem solving than with solving problems in symbolic format, which is consistent with the expectations. The expectation that this depended on grade was not supported. Furthermore, working memory and the two reading comprehension measures were not differentially related to performance on the two problem formats, although we did expect a stronger relation with word problem solving. All in all, there seem to be very little differences between standard word problems and their counterparts in symbolic format in performance as well as in their demands on cognitive and language resources, across all grades. This implies that already in third-grade students seem helped nor hampered by the realistic stories presented in the word problems when it concerns standard one-step arithmetic word problems, replicating the findings of Hickendorff (2013a) and extending that to younger students.

Another manipulation was to make the word problems more complex to diminish the possibilities that they can be solved with superficial strategy of “undressing” the word problem to find the “hidden” arithmetic problem without striving for understanding of the problem situation in the text (Leiss et al., 2019; Verschaffel et al., 2020). Problems were made more complex in two ways: by requiring two-step arithmetic (research question 2) and by including irrelevant numerical information (research question 3). Contrary to our expectations, neither of the two manipulations made the problems more difficult. However, two-step word problems were more strongly related to the two reading comprehension measures than one-step word problems, whereas there were no differential relations with working memory and non-verbal reasoning. This suggests that comprehension processes are more relevant than domain-general cognitive processes in setting up and monitoring a plan of solution steps in solving two-step word problems. Since this held across grades, there was no support for the hypothesis that the language demands lessen when students get more experienced.

The non-standard word problems with irrelevant numerical information did not make additional demands on language or domain-general resources, contrary to our expectations but for language and working memory consistent with findings in second graders (Wang et al., 2016). This implies that students were not hindered by the extra numerical information that they had to ignore. In the Netherlands, students probably encounter a wide variety of realistic situations, because Realistic Mathematics Education (RME) is the dominant instructional approach. In RME, realistic situations play a large role throughout the instructional trajectory, and mathematizating reality is an important goal (Gravemeijer and Doorman, 1999; Van den Heuvel et al., 2014). Consequently, Dutch students may have encountered a wider variety of word problems than students from countries with other instructional approaches. Further studies could investigate how Dutch students solve other types of non-standard word problems such as the non-routine problems

**TABLE 6 |** Statistical tests for research question 3: non-standard versus standard word problems.

| | Fixed effects | LL | #p | LR | $\chi^2$ | *df* | *p* |
|---|---|---|---|---|---|---|---|
| **Hypothesis 3a** | | | | | | | |
| M0 | - | −6617.3 | 3 | | | | |
| M1 | Grade | −6460.0 | 6 | M1-M0 | 314.624 | 3 | <0.001 |
| M2 | Steps + Grade | −6456.7 | 7 | M2-M1 | 6.606 | 1 | 0.010 |
| M3 | Steps + Grade + Pr.Type | −6456.4 | 8 | M3-M2 | 0.640 | 1 | 0.42 |
| M5 | Steps + Grade*Pr.Type | −6453.7 | 11 | M4-M3 | 5.372 | 3 | 0.15 |
| **Hypothesis 3b: reading comprehension process (MOCCA)** | | | | | | | |
| M5a | Steps + Grade + Pr.Type | −6431.2 | 8 | | | | |
| M6a | Steps + Grade + Pr.Type + MOCCA | −6396.8 | 9 | M6a-M5a | 68.718 | 1 | < 0.001 |
| M7a | Steps + Grade + Pr.Type*MOCCA | −6395.7 | 10 | M7a-M6a | 2.282 | 1 | 0.13 |
| M8a | Steps + Grade*Pr.Type*MOCCA | −6394.7 | 16 | M8a-M7a | 2.026 | 6 | 0.92 |
| **Hypothesis 3b: reading comprehension product (CITO)** | | | | | | | |
| M5a | Steps + Grade + Pr.Type | −5364.8 | 8 | | | | |
| M6a | Steps + Grade + Pr.Type + CITO | −5330.0 | 9 | M6b-M5b | 69.726 | 1 | < 0.001 |
| M7a | Steps + Grade + Pr.Type*CITO | −5329.9 | 10 | M7b-M6b | 0.056 | 1 | 0.81 |
| M8a | Steps + Grade*Pr.Type*CITO | −5327.1 | 16 | M8b-M7b | 5.720 | 6 | 0.46 |
| **Hypothesis 3b: non-verbal reasoning (RAVEN)** | | | | | | | |
| M5a | Steps + Grade + Pr.Type | −6456.4 | 8 | | | | |
| M6a | Steps + Grade + Pr.Type + RAVEN | −6407.7 | 9 | M6cb-M5c | 97.412 | 1 | <0.001 |
| M7a | Steps + Grade + Pr.Type*RAVEN | −6406.8 | 10 | M7c-M6c | 1.720 | 1 | 0.19 |
| M8a | Steps + Grade*Pr.Type*RAVEN | −6403.9 | 16 | M8c-M7c | 5.858 | 6 | 0.44 |
| **Hypothesis 3b: working memory (WM)** | | | | | | | |
| M4d | Steps + Grade + Pr.Type | −6303.3 | 8 | | | | |
| M5d | Steps + Grade + Pr.Type + WM | −6270.2 | 9 | M6d-M5d | 66.314 | 1 | <0.001 |
| M6d | Steps + Grade + Pr.Type*WM | −6269.9 | 10 | M7d-M6d | 0.486 | 1 | 0.49 |
| M7d | Steps + Grade*Pr.Type*WM | −6266.8 | 16 | M8d-M7d | 6.202 | 6 | 0.40 |

*LL, log-likelihood; #p, number of parameters; LR, likelihood ratio test; $\chi^2$, test statistic LR-test; Steps, number of arithmetic steps (one or two); Pr.Type, problem type (standard or non-standard word problem).*

from Verschaffel et al. (1994) or problems with more than one piece of irrelevant information.

## Educational Implications

The current findings have several implications for theory and instruction. For theoretical models of word problem solving, it is important to take the level of experience of the problem solver into account. The current study suggests that the steps of constructing a situation model and translating that into a mathematical model are less salient for older students with more experience in word problem solving than studies with younger students indicate. A related implication is that an instructional approach in which students are taught to map a novel problem to one of their problem schemata may run the risk of students looking for the "hidden" problem without striving for true understanding of the problem situation. An important question is then to what extent one can then truly speak of mathematizing reality, which is one of the cornerstones of mathematics education reform such as RME.

Another implication involves the role of comprehension processes, which seem to be more important in two-step arithmetic word problems than in one-step arithmetic word problems but had no differential impact on non-standard versus standard word problems. If researchers or teachers want to impact comprehension processes in word problem solving, we recommend using multiple-step arithmetic problems to make the standard, one-step word problems more challenging. A final point of discussion is that word problems and assessments including many word problems are sometimes criticized for making heavy demands on students' language abilities, thereby disadvantaging students with lower language skills. However, the current study suggests that this does not hold for one-step arithmetic word problems, probably because the linguistic demands of such word problems are not that challenging for upper grade primary students.

## Limitations

Although there are several strong points of the study's methodology, including the large sample size and the careful matching of characteristics of the different problem types, there are of course also limitations. A first set of limitations related to the problems. Since it was not possible to include two-step arithmetic word problems in symbolic format because students did not encounter such problems in their mathematics instruction, we could not compare the processes involved in two-step word problems with those of two-step arithmetic in symbolic format. This study could be replicated in students at the beginning of secondary education where they did learn how to solve such problems, addressing the question whether two-step word problems are more difficult than two-step arithmetic problems in symbolic format. A further limitation was that the linguistic complexity of the problems was not monitored whereas this has effects on the linguistic demands of the problems (Abedi and Lord, 2001).

A second set of limitations concerns the measures. Other studies have chosen different tests for the same constructs (Fuchs et al., 2015; Wang et al., 2016) which could lead to slightly different results. Furthermore, there are also other cognitive correlates of word problem solving that were not included in the current study, such as processing speed (Wang et al., 2016) and inhibitory control, which is increasingly considered to be important in mathematics learning in general and in word problem solving in particular (Van Dooren and Inglis, 2015), and for which it would be particularly interesting to assess its impact influence on problems with irrelevant information that has to be ignored.

A final limitation is that there is no information on the solution strategies students used, since only the answer was scored and analyzed. Consequently, there is no direct test of the suggested mechanism that the steps of constructing a situation model and translating that into a mathematical model are less salient in upper grade students than previous studies reported in younger students. It is therefore not possible to rule out other explanations, such as increased conceptual knowledge in older students aiding constructing the mathematical model. Future research could implement a smaller-scale qualitative study in which students solve the different problem types by thinking aloud. Such process data could give more insights into the steps taken in constructing a situational and a mathematical model and could also yield implications for the improvement of instruction.

### Conclusion

Limitations aside, the current study's findings are consistent with the hypothesis that the steps of constructing a situation model and translating that into a mathematical model, and the demands on language comprehension and domain-general cognitive resources involved with those steps, are less salient in upper grade students than previous studies reported in younger students. Third- to sixth-grade students seem helped nor hindered by situating the arithmetic problem in a story, even if that story includes irrelevant numerical information. Comprehension processes seem particularly relevant in two-step arithmetic word problems.

## DATA AVAILABILITY STATEMENT

The data supporting the conclusions of this paper are uploaded in the DataVerseNL repository: https://doi.org/10.34894/7KI4M9. Requests for further information should be addressed to Marian Hickendorff, hickendorff@fsw.leidenuniv.nl.

## ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Leiden University Institute of Education and Child Studies Commissie Ethiek. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

## AUTHOR CONTRIBUTIONS

MH: conceptualization, methodology, formal analysis, writing – original draft, and writing – review and editing.

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## REFERENCES

Abedi, J., and Lord, C. (2001). The language factor in mathematics tests. *Appl. Meas. Educ.* 14, 219–234. doi: 10.1207/S15324818AME1403_2

Baddeley, A. (1992). Working memory. *Science* 255, 556–559. doi: 10.1126/science.1736359

Bates, D., Maechler, M., Bolker, B., and Walker, S. (2015). Package lme4. *J. Stat. Softw.* 67, 1–91. doi: 10.18637/jss.v067.i01

Boonen, A. J. H., van der Schoot, M., van Wesel, F., de Vries, M. H., and Jolles, J. (2013). What underlies successful word problem solving? A path analysis in sixth grade students. *Contemp. Educ. Psychol.* 38, 271–279. doi: 10.1016/j.cedpsych.2013.05.001

Carlson, S. E., Seipel, B., and McMaster, K. (2014). Development of a new reading comprehension assessment: identifying comprehension differences among readers. *Learn. Individ. Differ.* 32, 40–53. doi: 10.1016/j.lindif.2014.03.003

Cummins, D. D., Kintsch, W., Reusser, K., and Weimer, R. (1988). The role of understanding in solving word problems. *Cogn. Psychol.* 20, 405–438. doi: 10.1016/0010-0285(88)90011-4

De Corte, E., Verschaffel, L., and De Win, L. (1985). Influence of rewording verbal problems on Children's problem representations and solutions. *J. Educ. Psychol.* 77, 460–470. doi: 10.1037/0022-0663.77.4.460

Fagginger Auer, M. F., Hickendorff, M., and van Putten, C. M. (2016). Solution strategies and adaptivity in multidigit division in a choice/no-choice experiment: student and instructional factors. *Learn. Instr.* 41, 52–59. doi: 10.1016/j.learninstruc.2015.09.008

Feenstra, H., Kamphuis, F., Kleintjes, F., and Krom, R. (2010). Wetenschappelijke verantwoording Begrijpend lezen voor groep 3 tot en met 6 [Reading comprehension test for grades 1 through 4]. CITO, National Institute for Educational Measurement. Arnhem, The Netherlands: CITO

Friso-Van Den Bos, I., Van Der Ven, S. H. G., Kroesbergen, E. H., and Van Luit, J. E. H. (2013). Working memory and mathematics in primary school children: a meta-analysis. *Educ. Res. Rev.* 10, 29–44. doi: 10.1016/j.edurev.2013.05.003

Fuchs, L. S., Fuchs, D., Compton, D. L., Hamlett, C. L., and Wang, A. Y. (2015). Is word-problem solving a form of text comprehension? *Sci. Stud. Read.* 19, 204–223. doi: 10.1080/10888438.2015.1005745

Fuchs, L. S., Fuchs, D., Compton, D. L., Powell, S. R., Seethaler, P. M., Capizzi, A. M., et al. (2006). The cognitive correlates of third-grade skill in arithmetic, algorithmic computation, and arithmetic word problems. *J. Educ. Psychol.* 98, 29–43. doi: 10.1037/0022-0663.98.1.29

Fuchs, L. S., Fuchs, D., Seethaler, P. M., and Barnes, M. A. (2020). Addressing the role of working memory in mathematical word-problem solving when designing intervention for struggling learners. *ZDM* 52, 87–96. doi: 10.1007/s11858-019-01070-8

Graesser, A. C., Singer, M., and Tom, T. (1994). Inference generation. *Psychol. Rev.* 10, 371–395.

Gravemeijer, K., and Doorman, M. (1999). Context problems in realistic mathematics education: a calculus course as an example. *Educ. Stud. Math.* 39, 111–129. doi: 10.1023/A:1003749919816

Hickendorff, M. (2013a). The effects of presenting multidigit mathematics problems in a realistic context on sixth graders' problem solving. *Cogn. Instr.* 31, 314–344. doi: 10.1080/07370008.2013.799167

Hickendorff, M. (2013b). The language factor in elementary mathematics assessments: computational skills and applied problem solving in a multidimensional IRT framework. *Appl. Meas. Educ.* 26, 253–278. doi: 10.1080/08957347.2013.824451

Janssen, J., Verhelst, N., Engelen, R., and Scheltens, F. (2010). Wetenschappelijke verantwoording van de toetsen LOVS Rekenen-Wiskunde voor groep 3 tot en met 8. CITO, National Institute for Educational Measurement. Arnhem, The Netherlands: CITO.

Jiménez, L., and Verschaffel, L. (2014). Development of children's solutions of non-standard arithmetic word problem solving. *Revista de Psicodidactica* 19, 93–123. doi: 10.1387/RevPsicodidact.7865

Kintsch, W., and Greeno, J. G. (1985). Understanding and solving word arithmetic problems. *Psychol. Rev.* 92, 109–129. doi: 10.1037/0033-295X.92.1.109

Leiss, D., Plath, J., and Schwippert, K. (2019). Language and mathematics – key factors influencing the comprehension process in reality-based tasks. *Math. Think. Learn.* 21, 131–153. doi: 10.1080/10986065.2019.1570835

Pape, S. J. (2004). Middle school children's problem-solving behavior: A cognitive analysis from a reading comprehension perspective. *J. Res. Math. Educ.* 35, 187–219. doi: 10.2307/30034912

Pavias, M., van den Broek, P., Hickendorff, M., Beker, K., and van Leijenhorst, L. (2016). Effects of social-cognitive processing demands and structural importance on narrative recall: differences between children, adolescents, and adults. *Discourse Process.* 53, 488–512. doi: 10.1080/0163853X.2016.1171070

Peng, P., Namkung, J., Barnes, M., and Sun, C. (2016). A meta-analysis of mathematics and working memory: moderating effects of working memory domain, type of mathematics skill, and sample characteristics. *J. Educ. Psychol.* 108, 455–473. doi: 10.1037/edu0000079

Raven, J. C., Court, J. H., and Raven, J. (1992). *Standard Progressive Matrices*. Oxford, UK: Psychologists Press.

Van de Weijer-Bergsma, E., Kroesbergen, E. H., Jolani, S., and Van Luit, J. E. H. (2016). The monkey game: a computerized verbal working memory task for self-reliant administration in primary school children. *Behav. Res. Methods* 48, 756–771. doi: 10.3758/s13428-015-0607-y

van den Broek, P., Rapp, D. N., and Kendeou, P. (2005). Integrating memory-based and constructionist processes in accounts of reading comprehension. *Discourse Process.* 39, 299–316. doi: 10.1080/0163853x.2005.9651685

Van den Heuvel-Panhuizen, M., and Drijvers, P. (2014). "Realistic Mathematics Education", in *Encyclopedia of Mathematics Education*. ed. S. Lerman.

van der Schoot, M., Bakker Arkema, A. H., Horsley, T. M., and van Lieshout, E. C. D. M. (2009). The consistency effect depends on markedness in less successful but not successful problem solvers: an eye movement study in primary school children. *Contemp. Educ. Psychol.* 34, 58–66. doi: 10.1016/j.cedpsych.2008.07.002

Van Dooren, W., and Inglis, M. (2015). Inhibitory control in mathematical thinking, learning and problem solving: a survey. *ZDM* 47, 713–721. doi: 10.1007/s11858-015-0715-2

Verschaffel, L., De Corte, E., and Lasure, S. (1994). Realistic considerations in mathematical modeling of school arithmetic word problems. *Learn. Instr.* 4, 273–294. doi: 10.1016/0959-4752(94)90002-7

Verschaffel, L., Greer, B., and De Corte, E. (2000). *Making Sense of Word Problems*. Lisse, Netherlands: Swets & Zeitlinger.

Verschaffel, L., Schukajlow, S., Star, J., and Van Dooren, W. (2020). Word problems in mathematics education: a survey. *ZDM* 52, 1–16. doi: 10.1007/s11858-020-01130-4

Vilenius-Tuohimaa, P. M., Aunola, K., and Nurmi, J. (2008). The association between mathematical word problems and reading comprehension. *Educ. Psychol.* 28, 409–426. doi: 10.1080/01443410701708228

Wang, A. Y., Fuchs, L. S., and Fuchs, D. (2016). Cognitive and linguistic predictors of mathematical word problems with and without irrelevant information. *Learn. Individ. Differ.* 52, 79–87. doi: 10.1016/j.lindif.2016.10.015

Weekers, A., Groenen, I., Kleintjes, F., and Feenstra, H. (2011). Wetenschappelijke verantwoording papieren toetsen Begrijpend lezen voor groep 7 en 8. CITO, National Institute for Educational Measurement. Arnhem, The Netherlands: CITO.

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# Ability to Consolidate Instances as a Proxy for the Association Among Reading, Spelling, and Math Learning Skill

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Learning skills (as well as disorders) tend to be associated; however, cognitive models typically focus either on reading, spelling or maths providing no clear basis for interpreting this phenomenon. A recent new model of learning cognitive skills proposes that the association among learning skills (and potentially the comorbidity of learning disorders) depends in part from the individual ability to consolidate instances (taken as a measure of rate of learning). We examined the performance of typically developing fifth graders over the acquisition of a novel paper-and-pencil task that could be solved based on an algorithm or, with practice, with reference to specific instances. Our aim was to establish a measure of individual rate of learning using parameters envisaged by the instance theory of automatization by Logan and correlate it to tasks requiring knowledge of individual items (e.g., spelling words with an ambiguous transcription) or tasks requiring the application of a rule or an algorithm (e.g., spelling non-words). The paper-and-pencil procedure yielded acquisition curves consistent with the predictions of the instance theory of automatization (i.e., they followed a power function fit) both at a group and an individual level. Performance in tasks requiring knowledge of individual items (such as doing tables or the retrieval of lexical representations) but not in tasks requiring the application of rules or algorithms (such as judging numerosity or spelling through sublexical mapping) was significantly predicted by the learning parameters of the individual power fits. The results support the hypothesis that an individual dimension of "ability to consolidate instances" contributes to learning skills such as reading, spelling, and maths, providing an interesting heuristic for understanding the comorbidity across learning disorders.

**Keywords: reading, spelling, Maths, automatization, learning**

## INTRODUCTION

Learning disorders (such as dyslexia, dysgraphia, and dyscalculia) tend to co-occur. This phenomenon is difficult to interpret within the traditional cognitive literature as models of reading, spelling, and maths are typically distinct and offer little basis for understanding the reasons of the possible overlap between these deficits. In his seminal paper, Pennington (2006) emphasized the need to view learning disabilities as well as other developmental disorders (such as ADHD or language impairment) within a multi-factorial interpretation. Thus, different cognitive factors may contribute to the emergence of a given deficit (e.g., dyslexia) and these factors partly overlap with factors accounting for other deficits (e.g., dyscalculia). In recent years, this perspective has driven an increasing amount of research. Thus, several studies examined the co-morbidity between reading and math disorders searching for cognitive factors accounting for their comorbidity even though these studies have not yet converged on a single interpretation (Wilson et al., 2015; Slot et al., 2016; Cheng et al., 2018).

In the present study, we capitalize on previous ongoing work from our research group in which we carried out an initial study on reading, spelling, and maths learning skills in a sample of typically developing children (Zoccolotti et al., 2020a,b). As predicted within the comorbidity perspective (Pennington, 2006), we observed considerable overlap between these learning skills. Indeed, cross-analyses indicated that predictors of reading accounted for performance in calculation much better than did general cognitive predictors; furthermore, maths tests predicted quite well reading and so on (Zoccolotti et al., 2020b). Analyzing individual predictors, we observed that some predictors were specific for a single behavior (e.g., phonological tests predicted only spelling skills), others predicted different behaviors but only for a specific parameter, such as fluency but not accuracy (as in the case of RAN), and finally some variables predicted reading, spelling, and maths skills in quite similar ways.

To interpret this complex pattern of results, we proposed a multi-level model of learning cognitive skills (Zoccolotti et al., 2020b; see **Figure 1**). To this aim, we refer to the distinction between "competence" and "performance," originally put forward by Chomsky (1966) in the discussion of language. In this context, "competence" is the general capacity to process in a given domain, while "performance" refers to the fact that a measure with a given task in a given individual is not a direct measure of competence in that domain but the result of an interaction between competence and the specific characteristics of the task. Thus, the critical difference between competence and performance is that the former is task independent, while the latter is task specific. In this perspective, all measures of a given behavior depend upon both the competence in a specific domain and the performance on the specific task. Consequently, one may assume that deficits in a specific competence (e.g., reading) will show up pervasively across different types of tasks in the domain (such as reading meaningful texts, list of words, pseudo-words.). Conversely, other deficits may be task specific to the extent in which they appear contingently to the requirements of the actual task (e.g., a child may have problems in maths under time pressure while being accurate if enough time is given), pointing to the role of "performance" components. Furthermore, a third level of explanation was posited to relate to the process of "learning" or "acquisition," and particularly to its automatization phase. Acquisition occurs through the effect of practice: learning disorders do not refer to the inability of the child to learn to read or to do computations as much as to *the inability to do so smoothly and efficiently* (Zoccolotti et al., 2020b). Thus, children with dyslexia characteristically read in an effortful, not automatic fashion; in order to read, the child has to place all his/her cognitive resources on decoding the text with little residual ability left for comprehension.

It should be observed that practice affects behavior in different ways influencing all levels of learning skills (not just the acquisition level). Thus, practice is necessary to bring out a "competence" in reading as well as in spelling or maths. Furthermore, practice is necessary to optimize behavior in specific task conditions ("performance"), such as learning to read in a left to right manner or to write using the appropriate hand movements. However, extended practice can also influence behavior by producing automatized responses to specific target items (acquisition level). This would contribute to the ability to read (or spell) words (or make multiplications) not based on grapheme to phoneme conversion (or counting digits) but on direct obligatory memory retrieval of specific target items. Thus, through extended practice the child learns specific items (e.g., regular frequent words, but also irregular words such as "pint," or the output of simple mathematical operations such as $3 \times 8 = 24$ or $5 + 3 = 8$).

A theoretical formalization of the automatization process has been put forward by Logan (1988, 1992). His "*instance theory of automatization*" states that automatization is acquired through repetitive presentation of a stimulus: in this way, the "instance representation" of an individual object or event is stored in memory ("obligatory encoding") and, the more repetitions, the more information becomes directly available ("obligatory retrieval"). The course of learning is initially fast and becomes progressively slower over target repetitions; this pace of learning is well described by a power function (as originally proposed by Newell and Rosenbloom, 1981).

Overall, the multi-level model of learning skills (Zoccolotti et al., 2020b) aims to predict both dissociations of deficits (as did previous traditional models) but also associations of deficits (i.e., comorbidity). In particular, it is assumed that independent competences are present for reading, spelling, and doing maths and that this may account for the observed dissociations among learning disorders. On the other hand, associations are expected whenever behaviors call upon the same performance factors (such as when tasks call for a speeded response or require processing contextual information; see **Figure 1**). Critical for the present study, it is proposed that associations among learning disorders may also be due to an acquisition factor and particularly to the "*ability to consolidate instances*" which is responsible for automatized behavior (see **Figure 1**). Accordingly, some children may have a low ability to consolidate instances (automatize) and this may influence their performance in reading (by limiting their ability to form lexical entries) as well as in spelling (again, limiting lexical acquisition) and doing maths (dampening the ability to acquire arithmetic facts). In this view, the ability to automatize is a factor that contributes to efficient performance across different domains. Thus, poor ability in forming instances does not make the behavior impossible but rather dampens fast and fluid reading, efficient

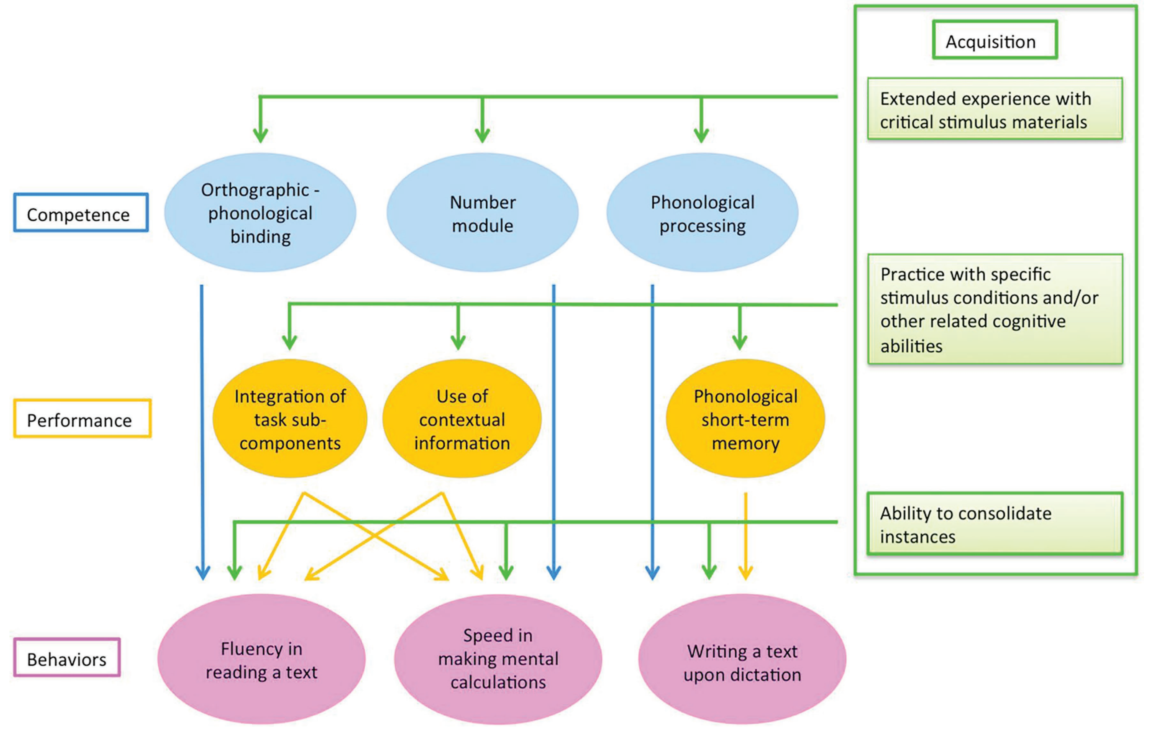


**FIGURE 1** | A multi-level model of learning cognitive skills. Target behaviors are expressed in terms of task-specific exemplars (Zoccolotti et al., 2020b).

spelling, and fast and efficient calculation (Zoccolotti et al., 2021). Indeed, children with dyslexia are not unable to read, but their reading is cumbersome, inefficient, and ultimately tiring, characteristics which indicate a controlled, voluntary mode of processing; by contrast, typically developing peers are characterized by smooth and efficient decoding which marks their pre-attentive, automatic processing (Schneider and Chein, 2003).

Within the multi-level model of learning cognitive skills (Zoccolotti et al., 2020b), a number of predictions follow from this hypothesis on automatization. First, one would expect lack of automaticity to be associated across reading, spelling, and maths. Consistently, it has been reported that adults with dyslexia were defective in their ability to retrieve arithmetic facts, although their numerical representations were spared (De Smedt and Boets, 2010). Second, one would predict that failures in activating lexical entries should be item specific. Angelelli et al. (2010a) examined the consistency of a lexical deficit between a reading (orthographic decision) and a spelling task. Fifth grade children with dyslexia failed to judge the orthographic correctness of the very same words with irregular transcription which they failed to spell. Thus, their lexical deficit was item specific but consistent across reading and writing. Third, one would expect that deficits due to a defective ability to consolidate instances should emerge more clearly late in the course of development, when the typically developing children have consolidated their knowledge of many items allowing fast and smooth reading (spelling or doing maths). Findings along this line have been reported in terms of spelling skills by Angelelli et al. (2010b). Thus, while in third grade, the spelling deficit was generalized encompassing all stimulus categories, in fifth grade errors for spelling words with unpredictable transcription were on the foreground, indicating a prevalent lexical impairment. A prevalent lexical impairment and a deficit in the expansion of the orthographic lexicon in children with developmental dyslexia were also supported by the longitudinal study of Marinelli et al. (2017). Finally, the model predicts that the ability to retrieve individual instances would be independent of the core competence in a given learning skill (i.e., either reading, spelling or maths). Consistently, it has being recently reported that, in spite of their item-based lexical deficit in both reading and spelling, children with dyslexia showed appropriate sensitivity to the distributional information of sound-spelling mappings at sub-lexical level (Marinelli et al., 2017, 2021; Angelelli et al., 2018). Overall, there are experimental data supporting the idea that at least part of the deficits in reading, spelling or maths may be ascribed to a general, cross-domain defect in consolidating individual instances.

Still, it is difficult to use the evidence available in the literature to fully evaluate this hypothesis. On the one hand, data on lexical orthographic knowledge or knowledge of arithmetic facts tell us something about the outcome of the process, but they are not informative about the developmental trajectory of how children have reached a given level of performance. On the other hand, a number of studies have compared children with learning disorders and controls during the course of acquisition. In particular, various studies have examined how children with dyslexia learn pseudo-words over a number of repetitions (Martens and de Jong, 2008; Pontillo et al., 2014; Suárez-Coalla et al., 2014; Kwok and Ellis, 2015). Most of these studies have reported that children with dyslexia learn less rapidly than controls and that, by the end of the training period, they typically maintain a strong sensitivity to the influence of stimulus length (Martens and de Jong, 2008; Pontillo et al., 2014; Suárez-Coalla et al., 2014; Kwok and Ellis, 2015). Thus, these studies are consistent with the idea that children with dyslexia are less efficient in learning and forming new representations of individual items (or lexical entries). However, most of these studies are focused on a single behavior (i.e., reading) and as such are not informative as to the breath of the influence of this differential learning across behaviors. Nicolson and Fawcett (2000) examined long-term acquisition of children with dyslexia in a more general perspective. In two studies, they examined the performance of a group of dyslexic adolescents and a matched group of typically developing controls on long-term training of two different tasks (a simulated pacman game and a choice reaction time task). In the pacman game, the dyslexic adolescents showed lower initial performance and, while they improved over time, the general performance differences were maintained by the end of the training. Similar results were present in the choice reaction time task. Nicolson and Fawcett (2000) interpret this pattern of findings as consistent with the hypothesis that dyslexia would be linked to a deficit in automatization possibly associated with cerebellar dysfunctioning.

As stated above, the multi-level model of learning skills (Zoccolotti et al., 2020b) proposes that a low ability to consolidate instances represents a domain-independent factor which may account for a sizeable part of the association among different learning skills (and potentially for the comorbidity among different developmental disorders). To provide for a sensitive test of this hypothesis in the present study, we examined the ability of an unselected group of children to learn a novel task allowing to examine the typical shift with practice from an algorithm-based to an instance-based performance. The experiment was modeled after the instance theory of automatization put forward by Logan (1988, 1992). Accordingly, one expects that, with practice, performance (in terms of time) changes following a power function, i.e., improvements in performance are greatest in the first trials and become progressively smaller with continuing practice. While most studies based on this model use reaction time measures, in order to simplify the paradigm for the use with children we devised a new paper-and-pencil test. This allowed us to test a sufficiently large sample of participants. We reasoned that, if the curves of learning follow the predicted power law of practice (Logan, 1992), this would allow establishing individual performance in terms of a number of critical parameters: the scaling parameter a (i.e., the asymptote, reflecting an irreducible limit on performance); the scaling parameter b (i.e., the difference between initial and asymptotic performance); and the exponent c (which determines the shape of the function).

We hypothesized that the individual ability to consolidate instances with learning opportunities of a child would be correlated with his/her ability in tasks that call for the specific knowledge of individual items, such as spelling or making an orthographic decision on a word with ambiguous transcription or retrieving arithmetic facts. Critically for the model presented in **Figure 1**, this association should hold irrespective of behavior, i.e., in reading, spelling as well as maths. Conversely, we did not expect that the individual ability to consolidate instances would be associated with tasks that call into action the application of algorithms (such as spelling non-words) or the abstract ability to represent number quantities. It must also be acknowledged that, in several tasks, performance may be aided by knowledge of individual items though it is ideally possible to carry out the task also without such reference (i.e., solely based on the application of rules or algorithms). For example, this is the case of reading or spelling of regular words or carrying out mental or written calculations. Thus, a child may read (or spell) a regular word either with reference to the grapheme to phoneme conversion rules or by referring to the lexicon. In calculation, the child may use algorithm-based procedures but may also speed up his/her performance by using knowledge about specific arithmetic facts.

Operationally, we examined the performance of a sample of fifth grade typically developing children over the acquisition of a novel task that could be solved with reference to an algorithm or, with practice, with reference to specific instances. Our aim was to establish measures of their individual rate of learning (i.e., their ability to consolidate instances) using the parameters envisaged by the instance theory of automatization (Logan, 1988, 1992). Then, we examined if such learning ability would predict performance in tasks that require knowledge of individual items (such as spelling words with an ambiguous transcription) as well as to measures that do not call for the knowledge of individual items (such as spelling non-words). We expected that individual rate of learning should be associated with the former but not to the latter. For exploratory reasons, we also included tasks for which no explicit predictions could be advanced, i.e., tasks that can be solved either by knowledge of individual items or by the application of algorithm-based rules (such as spelling regular words or making written calculations). Finally, as a further control we also included tasks mapping domain-general skills (i.e., non-verbal intelligence and short-term memory) for which we expected no specific relationship with the rate of learning dimension.

# MATERIALS AND METHODS

## Sample

A total of 140 children accepted to participate in the experiment. Three children with an impaired performance on the Raven's Coloured Progressive Matrices (CPM; i.e., 2 standard deviation below the according to Italian normative values, Pruneti et al., 1996) were excluded from the sample. Then, participants were 137 Italian children (82 M, 55F, mean age = 10.36, SD = 0.60) attending fifth grade schools in areas of Lecce and Roma characterized by a middle-class socio-educational conditions. As described in detail below, we focused our analyses only on the children whose performance on our experimental task proved reliable, a procedure which led to exclude additional 12 children (ca 8.8% of the original sample). Thus, the subsample analyzed in the present study eventually included 125 Italian children (78 M, 47F, mean age = 10.34, SD = 0.61). The mean z score in the CPM test was about zero for the whole sample of 137 children (Mean = 0.20, SD = 0.89) as well as for the subsample of 125 children (Mean = 0.20, SD = 0.91).

Parents were informed about the screening activities and authorized their child's participation by signing the appropriate informed consent paperwork. The study was carried out in accordance with the principles of the Declaration of Helsinki and was approved by the school authorities.

Children were tested with several tests evaluating mathematical, reading, and spelling skills, as well as domain-general skills and the instances acquisition ability. A description of these various tests used follows.

# Tests

## Reading Assessment

### *MT Reading Test*

The participant must read aloud a passage within a 4-min time limit (Cornoldi and Colpo, 1998). Speed (seconds per number of syllables read) and accuracy (number of errors, adjusted for the amount of text read) were scored.

### *One Minute Reading Test*

The test evaluates together speed and accuracy in reading aloud words (Turner, 1987). We used the Italian version of the test (Marinelli et al., in preparation). It consists of a matrix of 158 short (5-letter) bi-syllabic low-frequency words (mean = 15.54, SD = 6.44; range 6–30, according to the children's word frequency database, Marconi et al., 1993). Words are presented simultaneously on a grid format as in a RAN matrix. Children have to read aloud as many words as possible processing from left to right within the time limit of 1 min. The score was the number of words correctly read in one minute.

### *Orthographic Decision Test*

In this test, children have to judge the orthographic correctness of 72 words with inconsistent spellings due to the presence of a phonemic segment with two homophonic transcriptions (only one of which is orthographically correct) and, for control, of 36 regular words (i.e., not containing any inconsistently spelled phonemic segment) (Marinelli et al., 2017). Half of each experimental set was made of high-frequency words (mean = 242.6, SD = 385) and half of low-frequency words (mean = 5.6, SD = 5) according to Marconi et al.'s (1993) database.

A pseudo-word (composed of legal letter sequences) was created for each stimulus. Pseudo-words derived from inconsistently spelled words were pseudo-homophones (i.e., they resulted in a string that could be read as homophonous to the target; e.g., *SQUOLA derived from SCUOLA, school). Thus, they can be detected only by relying on the lexical procedure. Pseudo-words derived from regular words resulted in strings that were non-homophonic because of the substitution or permutation of graphemes (e.g., DENORO derived from DENARO, money). They can be detected through either the lexical or the sub-lexical procedure. The accuracy is scored (for more details see Marinelli et al., 2017).

## Spelling Assessment

### *Single Word and Pseudo-Word Dictation Test (DDO-2 Short Version)*

The test is composed of four sections: Section A ($N = 24$): Words with full one-sound-to-one-letter correspondence: Section B ($N = 6$): Words requiring the application of context-sensitive sound-to-spelling rules; Section C ($N = 15$): Words with unpredictable phonology-to-orthography mapping (i.e., ambiguous words; e.g., /kwo/in/kwota/, share): QUOTA and not *CUOTA) and therefore writable correctly only using the lexical way; and Section D ($N = 15$): Pseudo-words with one-sound-to-one-letter correspondence (Angelelli et al., 2016).

Words and non-words are presented in separate lists and in randomized order. The examiner reads each item aloud without emphasizing the presence of difficulties; the children are asked to repeat it (to make sure they have understood it) and afterward to spell the stimulus. The number of spelled correctly items in each section is computed.

### *"Nonna Concetta" Passage Dictation Test*

The task is a spelling to dictation test, consisting in a meaningful passage that includes words with regular and unpredictable spelling, tapping the efficiency of both lexical and non-lexical spelling procedures (Marinelli et al., 2016). The experimenter reads the meaningful passage, following the pauses established by the test. The child has to spell the text on a white paper. The scoring is made by calculating the total number of elements correctly spelled.

## Mathematical Skills

### *Written Arithmetic Calculations Test (From the AC-MT Battery)*

This test assesses child's ability to perform 8 written computational operations (two calculations for each of the four basic number operations: addition, subtraction, multiplication, and division; Cornoldi et al., 2002). The number length varies from 3 to 5 digits and sometimes includes decimals. One point score is given for every correct calculation.

### *Number Ordering Test (From the AC-MT Battery)*

This task assesses semantics of numbers (Cornoldi et al., 2002). Ten series of four numbers are presented, and the child must be able to place them in the correct order (5 series from the largest to the smallest; 5 series from the smallest to the largest). Accuracy is recorded.

### *Dictation of Numbers Test (From the AC-MT Battery)*

This task assesses students' ability to activate lexical retrieval as well to elaborate the syntactic structure of number. Students listen 8 numbers over a thousand, and they have to spell them (Cornoldi et al., 2002). Accuracy is scored.

#### *Judgment of Number Magnitude Test (From the AC-MT Battery)*
This task assesses students' ability to understand semantics and syntactic proprieties of numbers, asking them to indicate the bigger one of a couple of numbers (Cornoldi et al., 2002). Accuracy is scored for a total of 6 items.

#### *Backward Counting Test (From the AC-MT 6–11 Battery)*
The test assesses knowledge of the number line (Cornoldi et al., 2002). The child has to count backwards from 100 to 50 as rapidly and accurately as possible. Every interruption of the sequence is evaluated as error. The sum of correct numbers reported are scored.

#### *Arabic Number Reading Test (From the Developmental Dyscalculia Battery, DDB)*
The child has to read a list of 16 numbers (from 3 to 6 digits) aloud (Biancardi et al., 2004), without time constraints. The digit "0" is often present (e.g., "20,056" or "4,080"), in order to evaluate also children's ability to process implicit numbers. The time to complete the task and the number of correct responses is scored. However, only accuracy was entered into the analyses.

#### *Transformation of Numbers Into Digits Test (From the AC-MT Battery)*
The test investigates syntactic knowledge about the positional value of the digits: 6 numbers are presented with mixed units, tens, hundreds, thousands, tenths and hundredths and the child is asked to rewrite the corresponding number (for example: 6 tens 8 hundredths 2 units 0 tenths, and 5 hundreds correspond to the number 562,08; Cornoldi et al., 2002). Accuracy is scored.

#### *Arithmetical Facts Test (From the AC-MT Battery)*
This task investigates if children have stored arithmetical facts and are able to automatically retrieve the results of basic and simple operations from the memory (Cornoldi et al., 2002). Children are asked to recall 12 arithmetic facts, each within a maximum of 5 s. Accuracy is scored. Responses given beyond 5 s are considered errors, because are not retrieved automatically from memory as arithmetic facts.

#### *Additions and Subtractions Within "10" Test (From DDB)*
The child must say within the time limit of 2 s the results of 8 additions and 8 subtractions within "10," and thus quickly solvable with the retrieval of the arithmetic facts from memory (e.g., 4 + 2 = ?, 3–1 = ?; Biancardi et al., 2004). Hesitations (silent pauses longer than 2 s) or responses beyond the time limits are considered invalid responses. The number of correct responses (within the 2 s time limit) is scored.

#### *Multiplications Test (From DDB)*
The child must say the result of sixteen multiplications (for example 3 times 8, 9 times 5, etc.) as rapidly as possible (Biancardi et al., 2004). Hesitations (silent pauses longer than 2 s), responses beyond the time limit or based on the use of a times table are considered invalid responses. The number of correct responses is scored.

#### *Times Table in Series Test (From DDB)*
The child must report the times tables of 4 and 7 (i.e., 4, 8, 12…; 7, 14, 21…) as rapidly as possible (Biancardi et al., 2004). Hesitations (silent pauses longer than 2 s) are considered as invalid responses. The number of correct responses is scored, with a maximum of 20.

#### *Computation Strategies Test (From the AC-MT 11–14 Battery)*
Written calculations are printed on a sheet of paper, and the result of each calculation is shown along with the calculation (Cornoldi and Cazzola, 2003). Besides each complete calculation, there is a similar calculation to be computed; this latter calculation may differ from the adjacent one by inversion of the terms, increase in one of the terms by addition of a unit (or multiplication by tens), substitution of one of the terms with the result, and so on. Thus, the child can determine the result of these operations without actually calculating them but reasoning on the base of the similar complete calculations shown beside. The child is requested to perform rapidly (with an overall time constraint of 2 min) as well as accurately over a total of 16 trials. The number of computations performed correctly within the time limit was scored.

### General Cognitive Skills
#### *Raven's Coloured Progressive Matrices*
This test evaluates non-verbal intelligence. The number of correct responses is scored (Raven, 1965).

#### *Forward and Backward Span Of Numbers (From The Bvn Battery)*
The forward task requires the immediate serial recall of a sequence of digits (Bisiacchi et al., 2005; verbal short-term memory). The span corresponds to the last length for which at least two sequences were correctly recalled. In the backward task, the child has to recall each sequence in backward order. The forward and backward spans are measured.

### Experimental Test
The experimental test consists of a paper-and-pencil test, administered individually, which evaluates the learning of an invented rule (presumably never applied before by children). The stimulus features a matrix of 36 letters (with six target letters presented six times each), and the child is asked to write for each letter another letter applying the rule: letter +2 positions ahead in the alphabet = ?. Thus, the task consists in advancing by two positions with respect to the starting letter written on the sheet, writing the corresponding letter next to it. An example of such a matrix is presented in **Figure 2**. Letters were arranged in 4 × 9 matrices. As shown in the figure,

an example of the rule to be applied is shown at the top of the matrix (B + 2 = D) and is therefore always available to the child. A total of 22 matrices were devised. In the first 20 matrices (A1 to A20), the target stimuli inserted within each matrix were always the same letters (A, M, T, N, F, and I) but displayed in a different order across matrices. Two additional matrices (B1 and B2) contained different stimuli (U, C, R, E, Q, and L) and were used to examine the degree of generalization of learning to stimuli not subjected to exercise.

After explaining the instructions for the task to the children, they were given a practice matrix containing 8 letters (not used in the actual test) which was used to make sure that the child understood the instructions well. Then, the participants were presented with the series of 22 matrices, whose administration was organized in two consecutive days. In the first day, the child was given matrices from A1 to A10 and, on the second day, matrices from A11 to A20 as well as matrices B1 and B2. The test was administered individually. Children were instructed to go as fast as possible but trying to be correct. They were also informed that it was not possible to go back and correct. For each matrix, overall time (in sec.) and number of errors were measured.

## Procedure

Children were tested individually in a quiet room in their school in two consecutive days.

## Data Analysis

The Logan's model (1988, 1992) hypothesizes that time to perform a visuo-motor task, such as the one included in our study, follows a power function as a function of practice:

$$T = a + bN^{-c} \quad (1)$$

In equation 1, T indicates time, a is a scaling parameter indicating the asymptote, which reflects an irreducible limit on performance, b is a scaling parameter indicating the difference between initial and asymptotic performance, c indicates the exponent with higher values indicating steeper rates of learning and N is the amount of practice.

We initially used equation 1 to model the individual data with least squares method to test whether performance improved as a function of practice following a power function in compliance with Logan's model. The asymptote a was constrained not to be lower than the minimum time spent by each observer in completing the matrices independently from the session number.

**B + 2 = D**

| | | | |
|---|---|---|---|
| A = | M = | T = | N = |
| F = | T = | I = | F = |
| N = | A = | M = | A = |
| T = | I = | F = | A = |
| I = | T = | M = | I= |
| N = | A = | F = | M = |
| F = | I = | A = | N = |
| M = | A = | T = | F = |
| T = | I = | F = | N = |

Time: _____

**FIGURE 2** | Example of a matrix of the experimental task. The rule is presented on top of the matrix.

In order to evaluate the specific hypotheses of the study, we estimated the individual three main parameters: the scaling parameters a and b and the exponent. We considered for each fit the $R^2$, i.e., the variance explained; higher values indicate better fits. As presented in detail in the Results section, the power fit for the total sample was quite good confirming the efficacy of the paradigm. Individual power fits were generally good, but a number of children showed somewhat irregular learning curves and accordingly had low individual $R^2$ values. To use individual data, we adopted an arbitrary cut-off of $R^2 > 0.30$. In this way, the data of 125 children out of the 137 tested (91.2%) could be used for further analyses.

To test our hypotheses, we used the learning parameters (a, b, and c) of each child with a curve with $R^2 > 0.30$ as predictors of the performance in the various reading, spelling, calculation, and control tests. To this aim, we calculated separate multiple regression analyses (Enter method) using the performance in each test as dependent measure and the parameters of the power fit as the predictors. Our hypotheses concern the relationships between parameters of the individual power functions and the performance in tasks that require reference to individual instances but not to tasks that call for the application of an algorithm.

The effectiveness of the learning and the subsequent fall in the test in which the stimuli are modified was also evaluated with ANOVAs for repeated measurements (described more analytically in the results).

# RESULTS

## Learning Effects in the Experimental Task

**Figure 3** (left) shows the learning curves obtained by the sample of 137 children. The results indicate that all children reduced their time to solve the 20 matrices (i.e., from A1 to A20), with their improvement closely following a power function. In some cases, the goodness of the fit was low ($R^2 < 0.3$); thus, the data of twelve children have been excluded from further analyses. The remaining sample of 125 children showed a time reduction according to a power function with a median $R^2 = 0.68$ (range 0.3–0.93).

**Figure 3** (right) shows the fit applied to the median of the data of the subgroup of children. Execution time reduced with practice according to the power law ($R^2 = 0.95$) with the following global parameters:

$$T = 45 + 95.6^{-0.86}$$

The figure also shows that mean performance markedly slowed down when a matrix with new items (B1, light grey bar) was presented, highlighting the specificity of instance learning. Note, however, that performance again appreciably improved at the second presentation of this new matrix (B2, dark grey bar).

The effects of learning across experimental trials were also investigated with ANOVAs for repeated measurements separately for response times and accuracy. As far as response times, an ANOVA with repetition indicated a significant learning effect across the 20 repetitions ($F_{(19,\ 2,356)} = 361.21$; $p < 0.0001$). In a different analysis, we compared the first presentation (A1) with the last one (A20) and the first presentation with new stimuli (B1; see **Figure 4**). The condition effect was highly significant ($F_{(2,\ 248)} = 484.74$; $p < 0.0001$), indicating a significant decrease in times with practice (of about 94 s., $p < 0.0001$, Tukey's test) and a significant increase in times in the condition with new stimuli (B1) with respect to the A20 presentation (of about 75 s., $p < 0.0001$, Tukey's test); performance in the B1 presentation (122 s, SD = 32 s) was much slower than the performance at the A20 matrix (47 s, SD = 12 s), although slightly faster than in the A1 (141 s, SD = 40 s) presentation (of about 19 s., $p < 0.0001$, Tukey's test).

As for accuracy, the results showed a significant effect of learning across the 20 presentations ($F_{(19,\ 2,356)} = 3.78$; $p < 0.0001$). A significant effect also emerged in the analysis that compared the A1, A20, and B1 presentations ($F_{(2,\ 248)} = 6.16$; $p < 0.01$): errors decreased from 2.52% in A1 to 1.61% in A20 ($p = 0.09$) for increasing again to 3.14% in the B1 matrix (with respect to the A20 matrix, $p < 0.001$); accuracy in performing the B1 matrix was not significantly different from the A1 matrix.

## Relationship Between the Performance in the Experimental Task and Other Reading, Spelling, Calculation, and Control Tests

The multiple regression results are presented in **Table 1**. For the sake of clarity, we present the different multiple regression analyses according to the different learning domains (reading, spelling, maths, and control tests). Furthermore, we separately group the tasks for which a relationship with performance in the experimental tasks is expected, those for which no relationship is expected, those for which the prediction is uncertain and finally the control tasks.

Inspection of the table indicates that all regression analyses for which we expected a significant relationship were significant (with overall $R^2$ ranging from 0.071 to 0.131). As for the contribution of different parameters in the power fits in the experimental task, the scaling parameters a (asymptotic performance) and b (difference between initial and asymptotic performance), but not the exponent c, significantly predicted the reading performance in the Orthographic Decision test ($p < 0.01$) and the spelling performance on words with unpredictable transcription ($p < 0.01$). The pattern of findings was similar for the maths tasks (Arithmetic Facts, Times table in series, Multiplications, Additions, and Subtractions within "10"). The scaling parameter b significantly entered in all analyses, while the scaling parameter a entered in the analyses on Arithmetic facts and Multiplications but not the other two; the exponent c did not enter significantly in any of these regression analyses.

In the case of tasks for which a relationship was not predicted, none of the multiple regression analyses were significant, as expected (the overall $R^2$ ranging from 0.006 to 0.064). In one case (Judgment of Numbers), the scaling parameter b was significant but in the context of an overall insignificant prediction.

As anticipated, results were more scattered in the case of tasks for which the prediction was uncertain. In the case of reading tasks, the regression analyses were significant in the case of reading speed (MT test) and for the One-Minute test;

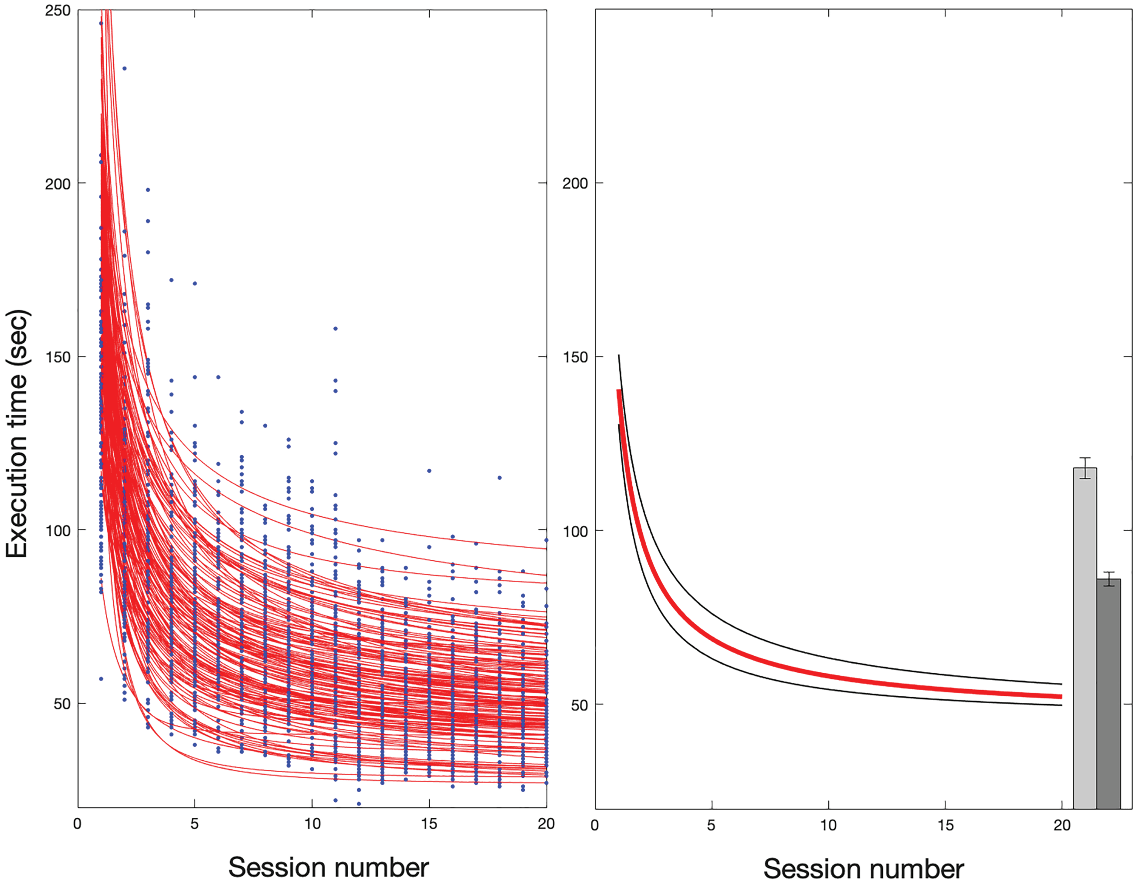


**FIGURE 3 |** Learning trend in the experimental task. The panel on the **left** shows the individual fits obtained by the entire sample of 137 children. Twelve fits showed an $R^2 < 0.3$, and the data were excluded from further analyses. The panel on the **right** shows the fit applied to the median of the data of the remaining sample of 125 children (red solid line) with an $R^2 = 0.95$ and the 95% confidence intervals (black lines). The bars on the far right show the medians and standard deviations of the two retest conditions (B1 = 118, SD = 32; B2 = 89, SD = 24).

for spelling, an overall significant prediction was present for the "Nonna Concetta" dictation task and for the total accuracy of the DDO-2 test; finally, for maths tests, the regression was significant in the case of the total correct score for Arabic Number Reading. In all these cases, the scaling parameter a significantly contributed to the multiple regression; the scaling parameter b contributed to all analyses expect the One-Minute test and the Arabic Number Reading; the exponent c did not enter significantly in any of these regression analyses. In one case (DDO-2 test: regular words), the scaling parameter b was significant but in the context of an overall insignificant prediction.

Finally, none of the models with the control tests (Raven Matrices and Digit span) proved significant (with overall $R^2$ ranging from 0.005 to 0.092). Furthermore, none of the individual parameters showed a significant contribution.

## DISCUSSION

The results indicate that the paper-and-pencil procedure yielded clear acquisition curves quite consistent with the predictions of the instance theory of automatization by Logan (1988, 1992). Children improved their speed in performing the experimental task across the twenty repetitions given, and their rate of improvement closely followed a power function fit, as anticipated by the theory. When matrices of new stimuli were presented, performance slowed substantially although not quite as to the original level. This pattern is predicted by the instance theory by Logan (1988, 1992) and indicates that the automatization of response is closely associated with learning of individual items (or instances).

Most children showed acquisition curves with good individual fits, and it was possible to submit to regression analyses individual values from 125 out of the total 137 children examined (91%). Therefore, it appears that the paradigm used was sufficiently sensitive and reliable to allow examining the curve parameters also at an individual level.

Results from the multiple regression analyses gave some support to the hypotheses we put forward. Children with higher performance improvement with practice (i.e., with higher b scaling values) and lower asymptotic performance (i.e., lower scaling value a) tended to have better performance in tasks

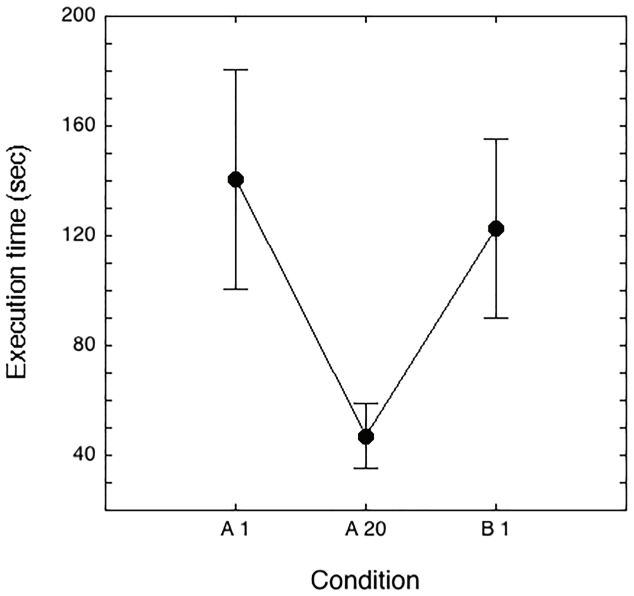


**FIGURE 4** | Mean time spent (seconds) and SDs in the experimental test in the A1 and A20 matrices, containing the same stimuli, and in the B1 matrix, containing new stimuli.

in which the knowledge of individual items is specifically required during acquisition. This was the case of recalling arithmetic facts or making multiplications, additions, and subtractions without the aid of algorithms. The scaling parameters of the power fits were also associated with the performance in spelling words with an ambiguous transcription in spelling words that require to use the lexical route in spelling. Finally, they were associated with the performance in making orthographic judgments on words with ambiguous transcription. Therefore, consistent with the hypotheses, the scaling parameters of the power fits significantly contributed to models across domains, i.e., for maths, reading, and spelling tasks. Note that the exponent c did not enter as a significant predictor in any of the multiple regression analyses. Thus, it is not the shape of the curve to be critical as much as the actual change of performance (as assessed by scaling parameter b) and, in some cases, the asymptotic value reached by the child (as assessed by scaling parameter a).

In the model presented in **Figure 1**, the individual ability to consolidate instances is considered as an across-domain skill which favors performance whenever reference to individually learnt items (or instances) have to be recalled to efficiently perform a task. Conversely, a low ability in consolidating instances is expected to contribute to learning disorders in a way that is not domain specific, i.e., it may help accounting for the presence of co-morbidities across learning disorders. By and large, the present results were in line with these predictions.

We also predicted that individual learning rate would not be associated with tasks in which application of rules or algorithms is required and no reference to previous knowledge of individual instances can be used. For all the tasks considered in this category, no overall significant model was found as predicted. Consistently with the hypotheses, no effect was also present for control tasks, mapping non-verbal intelligence, and short-term memory.

For exploratory purposes, we also correlated individual learning rate with performance on standard clinical tests, such as reading a text passage or performing written calculations. In this case, it is difficult to anticipate predictions as performance in these tests typically calls for both the ability to activate instances (such as strategically using arithmetic facts to solve a complex calculation) and that of applying rules or algorithms. Thus, only *a posteriori* comments can be advanced on the observed pattern of results and results should be viewed with caution. At any rate, one may conjecture that the significance of the model would mark the contribution of item-based processing in a given task while its absence might indicate the preponderance of algorithm-based processing. In particular, individual learning parameters predicted speed in reading a text passage and the ability to read correctly and rapidly single words at the One-minute reading test. In this vein, the item-based processing allows ensuring an automatized reading and then a good reading speed, at least in a consistent orthography such as Italian (in which lexical processing is not necessary for ensuring accuracy, but it is indispensable for fluent reading). Furthermore, learning parameters also significantly predicted the accuracy in spelling a meaningful text passage and the total performance in the DDO-2 spelling test (in this case, this value includes the section of words with ambiguous transcription). By contrary, models failed to reach significance for the spelling of words without a 1:1 mapping (as well as for pseudowords) and approached significance in the case of regular words. Children with greater capacity to acquire instances showed better performance in spelling meaningful stimuli: this finding may suggest that regular words were generally spelled through the lexical procedure also in a consistent orthography such as Italian. Finally, learning parameters significantly predicted accuracy in reading numbers: the lexical retrieval of the number name is related to the ability to acquire instances. On the contrary, no relationship was found in the case of making written mathematical operations, probably due to an analytic application of computation procedures (at least at the age examined in the present study) instead of an automatic retrieval of the result.

We have noted in the introduction that very few studies have examined rate of acquisition in children with learning disorders, and most of these studies were focused on a single behavior (i.e., reading). The study by Nicolson and Fawcett (2000) is a notable exception as they examined the effect of learning new tasks as a function of an extended training. However, a direct comparison with this study is difficult. In particular, here we focused on a task that with practice could be solved by relying on instance learning; by contrast, the tasks used in the Nicolson and Fawcett's (2000) study did not clearly call for learning of specific instances. Thus, apart from the use of different types of populations, the two studies appear to tackle different types of learning problems. A direct comparison is also difficult with studies investigating implicit

**TABLE 1 |** Each line of the table reports the results of a separate multiple regression analysis.

| | Full model | | a (scaling parameter) | | b (scaling parameter) | | c (exponent) | |
|---|---|---|---|---|---|---|---|---|
| | $R^2$ | *F* | beta | *t* | beta | *t* | beta | *t* |
| **Cases in which a correlation is predicted** | | | | | | | | |
| **Reading** | | | | | | | | |
| Orthographic Decision | **0.107** | **4.84**** | **0.17** | **2.00*** | **0.25** | **2.73**** | **0.13** | **1.42** |
| **Spelling** | | | | | | | | |
| DDO-2: Words with unpredictable mapping | **0.093** | **4.13**** | **–0.22** | **–2.44*** | **–0.18** | **–1.94*** | **0.04** | **0.39** |
| **Maths** | | | | | | | | |
| Arithmetic Facts | **0.107** | **4.85**** | **0.21** | **2.44*** | **0.21** | **2.35*** | **–0.03** | **–0.31** |
| Times Table in Series | **0.086** | **3.80*** | **–0.14** | **–1.63** | **–0.23** | **–2.47**** | **0.03** | **0.37** |
| Multiplications | **0.131** | **6.08***** | **–0.25** | **–2.9**** | **–0.23** | **–2.58**** | **–0.04** | **–0.41** |
| Additions and Subtractions within "10" | **0.071** | **3.08*** | **–0.10** | **–1.11** | **–0.24** | **–2.57**** | **–0.09** | **–0.94** |
| **Cases in which a correlation is NOT predicted** | | | | | | | | |
| **Spelling** | | | | | | | | |
| DDO-2: Pseudo-words | 0.032 | 1.31 | –0.12 | –1.37 | –0.11 | –1.17 | –0.01 | –0.08 |
| | | | | *Maths* | | | | |
| Judgment of Number | 0.036 | 1.52 | 0.08 | 0.92 | –0.19 | –1.99* | –0.09 | –1.02 |
| Transformation into Digits | 0.042 | 1.77 | 0.07 | 0.75 | 0.05 | 0.56 | –0.17 | –1.88 |
| Number Order | 0.021 | 0.85 | –0.08 | –0.84 | –0.10 | –1.06 | –0.07 | –0.79 |
| Dictation of Numbers | 0.006 | 0.15 | –0.06 | –0.51 | 0.00 | 0.01 | –0.04 | –0.38 |
| Computation Strategies test | 0.064 | 1.75 | –0.20 | –1.78 | –0.13 | –1.11 | –0.03 | –0.28 |
| **Cases in which prediction is uncertain** | | | | | | | | |
| **Reading** | | | | | | | | |
| MT accuracy | 0.056 | 2.37 | 0.13 | 1.42 | 0.14 | 1.53 | –0.09 | –0.99 |
| MT speed | **0.132** | **6.13***** | **–0.21** | **–2.44*** | **–0.25** | **–2.86**** | **–0.15** | **–1.68** |
| One-Minute test | **0.090** | **3.51*** | **–0.24** | **–2.59**** | **–0.10** | **–1.07** | **0.10** | **1.02** |
| **Spelling** | | | | | | | | |
| "Nonna Concetta" dictation task | **0.125** | **5.74***** | **–0.17** | **–2.02*** | **–0.23** | **–2.63**** | **0.12** | **1.35** |
| DDO-2: Regular words | 0.056 | 2.39 | 0.00 | 0.03 | –0.23 | –2.45* | –0.15 | –1.60 |
| DDO-2: Words with context-sensitive rules | 0.024 | 0.99 | –0.14 | –1.50 | –0.04 | –0.46 | –0.04 | –0.44 |
| DDO-2: Total accuracy | **0.090** | **4.01**** | **–0.19** | **–2.12*** | **–0.21** | **–2.33*** | **–0.03** | **–0.35** |
| **Maths** | | | | | | | | |
| Written Arithmetic Calculations | 0.026 | 1.09 | –0.02 | –0.23 | –0.16 | –1.72 | –0.03 | –0.33 |
| Arabic Number Reading (total correct) | **0.070** | **3.04*** | **–0.19** | **–2.11*** | **–0.10** | **–1.12** | **0.12** | **1.32** |
| Arabic Number Reading (tot. seconds) | 0.018 | 0.74 | 0.13 | 1.41 | –0.03 | –0.34 | 0.03 | 0.28 |
| **Control tests** | | | | | | | | |
| Raven Matrices | 0.015 | 0.62 | –0.01 | –0.06 | –0.12 | –1.23 | 0.02 | 0.21 |
| Digit Span forward | 0.005 | 0.09 | 0.07 | 0.48 | –0.04 | –0.30 | –0.03 | –0.19 |
| Digit Span back | 0.092 | 1.82 | –0.01 | –0.07 | –0.25 | –1.83 | –0.21 | –1.53 |

*(Continued)*

**TABLE 1** | Continued

*In all cases, the dependent measure is the task in the left column and the predictors entered in the analysis were the parameters of the individuals power fits. For each model, the overall value for R2 (and the related F value), the betas connected to the scaling parameter a (asymptotic performance), b (the difference between initial and asymptotic performance), and c (the exponent of the power function) as well as the related Student t values are reported. Significance of F and Student's t values are indicated by asterisks. Results indicating overall significant predictions are presented in bold. For the organization of the table as a function of the hypotheses of the study see main text.*
**p<0.05.; **p<0.01 and ***p<0.001*

learning of linguistic and non-linguistic regularities, both in typically developing children and in children with dyslexia (for a systematic review see Schmalz et al., 2017); for a meta-analysis see van Witteloostuijn et al., 2017). These studies use different experimental paradigms to present rule-governed situations (e.g., letter sequences or shape sequences or visual-motor rule-governed tasks) to participants who, unaware of the embedded rules, are requested to perform some sort of tasks (e.g., memorize or simply observe) in a first exposure phase and then, in a testing phase, are evaluated on their newly acquired knowledge related to the situation. However, to our knowledge these studies do not analyze the curves of acquisition but focus on group differences (e.g., readers with dyslexia vs. typically developing readers; adults vs. children) or paradigms/materials (e.g., linguistic vs. non-linguistic materials). Moreover, the relationship to literacy tasks is often speculated or inferred on the basis of a poor performance on implicit learning tasks in individuals with developmental dyslexia. However, Nigro et al. (2015) investigated the implicit learning ability in Spanish third grade typically developing children and found a significant correlation between the implicit learning task performance and the ability to spell words with unpredictable mapping, i.e., stimuli which require word specific knowledge to resolve the spelling inconsistencies. By contrast, they did not find any relationship with the word and non-word reading abilities and did not evaluate the mathematical domain. According to the authors, the implicit learning mechanism may play a role in the acquisition of lexical knowledge and thus, in writing proficiency. In spite of several methodological differences, the pattern of findings and the interpretation advanced by Nigro et al. (2015) presents a number of similarities to the present proposal.

Here, our main interest was in evaluating the hypothesis that a good learning ability, as assessed by better ability in consolidating instances, would act as a cross-domain predictor of performance. We feel that the present study well illustrates the complexities to pursue such a goal. First, the measure needs to be dynamic, i.e., it aims to capture the change in performance with practice not just the performance at one point in time. Second, in order to have a reliable measure of improvement one needs to refer to a model of learning. Indeed, simple measures of change such as the difference between the initial and final performance after training may not be ideal as this would be inevitably correlated with initial performance (for a discussion on the problems connected with difference scores see Capitani et al., 1999; Zoccolotti and Caracciolo, 2002). Finally, if the goal is to obtain a general measure of the ability to consolidate instances, the task should be as much as possible novel, that is independent from previously consolidated abilities.

These complexities indicate that it may actually be difficult to generate a clinically valid test to measure the ability to consolidate instances although this goal is certainly worth pursuing it. At the same time, it must be noted that failure to account for the role of experience may indeed be critical in fully understanding learning disorders. This point was persuasively made in a recent review of the research on dyslexia by Huettig et al. (2018). For example, these authors noted that most studies on illiterate subjects yielded results quite similar to studies on children with dyslexia. Accordingly, they raised the possibility that reading disorders may actually be a consequence of reduced and suboptimal reading experience. This does not necessarily indicate that learning disorders are merely epiphenomena of reduced practice. Rather, the analysis made by Huettig et al. (2018) underscores the difficulty in interpreting measures of performance taken only at a single point of time, as typical of standard clinical tests of reading (spelling or doing maths). Indeed, these measures express the joint effect of several different factors. First, individual performance may depend upon the individual ability in the behavior object of the test (such as reading, spelling or doing maths). However, second, individual performance at any point in time will also vary as an effect of the amount of practice on that task. Third, the performance will also express the ability of the individual to improve as an effect of practice. In other terms, the effect of practice may depend on its quantity but also on the individual capacity to take advantage from it. Within the instance theory of automatization, this individual dimension would specifically express as the capacity of consolidating instances. The important consequence of these multi-factorial influences is that there is no simple way to separate the effect of these components when examining a child under standard clinical conditions. Much to the contrary, it is likely that these components tend to interact to each other. Thus, it is well known that children who are not proficient in reading (spelling or doing maths) do not like to do these activities with the result that, all other things being equal, they tend to practice less.

Some limitations of the present study should be put forward. Based on the predictions of the multi-level model of learning skills, we originally planned to have measures for which individual learning rate would not be associated in all domains considered, i.e., reading, spelling, and maths. To this aim, in reading, we planned to use a pseudo-word reading task. However, due to problems during data collection, information on this specific task was not obtained in most children. Therefore, the prediction that the individual rate of learning would not predict non-word reading still needs to be tested to be able to fully appreciate the predictions of the model.

The model presented in **Figure 1** aims to predict performance both in the typically developing range as well as in the impaired range (i.e., the well-known comorbidity among learning disorders). In the present study, as well as our previous one (Zoccolotti et al., 2020a, 2020b), we examined unselected populations of children. Therefore, before confirming the specific role of instance-based learning on the comorbidity of learning disorders, it will be crucial to directly test populations of children with different patterns of learning disabilities. This study is currently under way (although severely slowed down by the current pandemic). In particular, we predict that a low ability in consolidating instances will be particularly associated with some areas of processing, such as lexical activation, in the case of reading and spelling, and acquisition and retrieval of arithmetic facts, in the case of maths. In other words, this prediction is selective for some aspects of behavior, not the general ability of reading (spelling or doing maths). Extending data from unselected populations of children to the pathological range partly depends on the way learning disorders are conceptualized. In a line of thought, developmental disorders of reading (spelling and maths) are seen as the low end of a continuous distribution (e.g., Protopapas and Parrila, 2018). Alternatively, a body of literature has described qualitatively different patterns of impairments in reading as well as spelling and maths (for reviews see for example Geary, 2004; McCloskey and Rapp, 2017; Friedmann and Coltheart, 2018). It seems that focused research is needed to clarify this important point. We propose here that referring to an individual dimension of "ability to consolidate instances" may provide an interesting heuristic for studying the comorbidity across learning disorders.

Reviewing a large body of neurophysiological evidence, Keresztes et al. (2018) have proposed that the learning system has to balance the need of "*detecting regularities in the world through generalization* versus *encoding and remembering particular events and their details through mnemonic specificity.*" In our previous work (Zoccolotti et al., 2020a,b), we have proposed that the ability to use information from specific events, conceptualized as a dimension of "*ability to consolidate instances,*" is a general-purpose skill that may foster performance across domains. The present findings provide some support to this hypothesis since the learning rate on a novel task was selectively correlated with performance requiring acquired knowledge of individual items across reading, spelling, and maths tasks. While there is certainly a need for further work in this area, we propose that the procedure developed here may provide useful insights on the contribution of the role of automatization skills in the genesis of learning disorders.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Comitato Etico – Fondazione Santa Lucia, Rome, Italy. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

## AUTHOR CONTRIBUTIONS

CM, PA, MM, MT, and PZ contributed conception and design of the study. MT organized and supervised the database collection. CM and MM performed the statistical analyses. PZ wrote the first draft of the manuscript. All authors wrote sections of the manuscript, contributed to manuscript revision, read and approved the submitted version.

## REFERENCES


Angelelli, P., Marinelli, C.V., Iaia, R., Notarnicola, A., Costabile, D., Judica, A., et al. *DDO-2. Diagnosi dei Disturbi Ortografici in età Evolutiva*. Trento: Centro studi Erickson, (2016).

Angelelli, P., Marinelli, C. V., Putzolu, A., Notarnicola, A., Iaia, M., and Burani, C. (2018). Learning to spell in a language with transparent orthography: distributional properties of orthography and whole-word lexical processing. *Quart. J. Exp. Psychol.* 71, 704–716. doi: 10.1080/17470218.2016.1275715

Angelelli, P., Marinelli, C. V., and Zoccolotti, P. (2010a). Single or dual orthographic representations for reading and spelling? A study on Italian dyslexic and dysgraphic children. *Cogn. Neuropsychol.* 27, 305–333. doi: 10.1080/02643294.2010.543539

Angelelli, P., Notarnicola, A., Costabile, D., Judica, A., Zoccolotti, P., and Luzzatti, C. (2010b). Spelling impairments in Italian dyslexic children: phenomenological changes in primary school. *Cortex* 46, 1299–1311. doi: 10.1016/j.cortex.2010.06.015

Biancardi, A., Mariani, E., and Pieretti, M. (2004). *La discalculia evolutiva. Dai modelli neuropsicologici alla riabilitazione*. Franco Angeli: Milano

Bisiacchi, P.S., Cendron, M., Gugliotta, M., Tressoldi, P.E., and Vio, C. (2005).*BVN 5–11: batteria di valutazione neuropsicologica per l'età evolutiva [BVN 5–11: Battery for the Evaluation of Neuropsychological Evaluation during Development]*. Trento: Centro studi Erickson.

Capitani, E., Laiacona, M., Barbarotto, R., and Cossa, F. M. (1999). How can we evaluate interference in attentional tests? A study based on bi-variate non-parametric tolerance limits. *J. Clin. Exp. Neuropsychol.* 21, 216–228. doi: 10.1076/jcen.21.2.216.934

Cheng, D., Xiao, Q., Chen, Q., Cui, J., and Zhou, X. (2018). Dyslexia and dyscalculia are characterized by common visual perception deficits. *Dev. Neuropsychol.* 43, 497–507. doi: 10.1080/87565641.2018.1481068

Chomsky, N. *Topics in the Theory of Generative Grammar (Janua Linguarum, Series Minor). Vol. 56*. Paris, The Hague: Mouton and Co., (1966).

Cornoldi, C, and Cazzola, C. (2003). *Test AC-MT 11–14—Test di valutazione delle abilità di calcolo e problem solving*. Trento: Erickson,

Cornoldi, C., and Colpo, G. (1998). *Prove di lettura M.T. per la scuola elementare – 2. Manuale*. Organizzazioni Speciali:Firenze

Cornoldi, C., Lucangeli, D., and Bellina, M. (2002). *AC-MT: test di valutazione delle abilità di calcolo-gruppo MT*. Trento: Centro studi Erickson

De Smedt, B., and Boets, B. (2010). Phonological processing and arithmetic fact retrieval: evidence from developmental dyslexia. *Neuropsychologia* 48, 3973–3981. doi: 10.1016/j.neuropsychologia.2010.10.018

Friedmann, N., and Coltheart, M. (2018). "Types of developmental dyslexia," in *Handbook of Communication Disorders*. eds. A. Bar-On and P. Ravid (Berlin: De Gruyter Mouton), 721–55.

Geary, D. C. (2004). Mathematics and learning disabilities. *J. Learn. Disabil.* 37, 4–15. doi: 10.1177/00222194040370010201

Huettig, F., Lachmann, T., Reis, A., and Petersson, K. M. (2018). Distinguishing cause from effect–many deficits associated with developmental dyslexia may be a consequence of reduced and suboptimal reading experience. *Lang. Cogn. Neurosci.* 33, 333–350. doi: 10.1080/23273798.2017.1348528

Keresztes, A., Ngo, C. T., Lindenberger, U., Werkle-Bergner, M., and Newcombe, N. S. (2018). Hippocampal maturation drives memory from generalization to specificity. *Trends Cogn. Sci.* 22, 676–686. doi: 10.1016/j.tics.2018.05.004

Kwok, R. K. W., and Ellis, A. W. (2015). Visual word learning in skilled readers of English. *Q. J. Exp. Psychol.* 68, 326–349. doi: 10.1080/17470218.2014.944549

Logan, G. D. (1988). Toward an instance theory of automatization. *Psychol. Rev.* 95, 492–527. doi: 10.1037/0033-295X.95.4.492

Logan, G. D. (1992). Shapes of reaction-time distributions and shapes of learning curves: A test of the instance theory of automaticity. *J. Exp. Psychol. Learn.* 18, 883–914. doi: 10.1037/0278-7393.18.5.883

Marconi, L., Ott, M., Pesenti, E., Ratti, D., and Tavella, M. (1993). *Lessico elementare. Dati statistici sull'italiano letto e scritto dai bambini delle elementari.* Zanichelli: Bologna.

Marinelli, C. V., Cellini, P., Zoccolotti, P., and Angelelli, P. (2017). Lexical processing and distributional knowledge in sound–spelling mapping in a consistent orthography: A longitudinal study of reading and spelling in dyslexic and typically developing children. *Cogn. Neuropsychol.* 34, 163–186. doi: 10.1080/02643294.2017.1386168

Marinelli, C. V., Iaia, M., Burani, C., and Angelelli, P. (2021). Sensitivity to distributional properties of the orthography in the spelling of Italian children with dyslexia. *Q. J. Exp. Psychol.* 74, 1007–1020. doi: 10.1177/1747021821998925

Marinelli, C. V., Judica, A., Cucciaioni, C., Verni, F., Deidda, C., Notarnicola, A., et al. (2016). Nonna Concetta: Una prova di dettato di brano per la valutazione delle abilità ortografiche nella scuola primaria. *Psicol. Clin. Svilupp.* 20, 425–449. doi: 10.1449/85045

Martens, V. E. G., and de Jong, P. F. (2008). Effects of repeated reading on the length effect in word and pseudoword reading. *J. Res. Read.* 31, 40–54. doi: 10.1111/j.1467-9817.2007.00360.x

McCloskey, M., and Rapp, B. (2017). Developmental dysgraphia: An overview and framework for research. *Cogn. Neuropsychol.* 34, 65–82. doi: 10.1080/02643294.2017.1369016

Newell, A., and Rosenbloom, P. S. (1981). "Mechanisms of skill acquisition and the law of practice," in *Cognitive Skills and their Acquisition*. ed. J. R. Anderson (Hillsdale, New Jersey: Lawrence Earlbaum Associates), 1–55.

Nicolson, R. I., and Fawcett, A. J. (2000). Long-term learning in dyslexic children. *Eur. J. Cogn. Psychol.* 12, 357–393. doi: 10.1080/09541440050114552

Nigro, L., Jiménez-Fernández, G., Simpson, I. C., and Defior, S. (2015). Implicit learning of written regularities and its relation to literacy Acquisition in a Shallow Orthography. *J. Psycholinguist. Res.* 44, 571–585. doi: 10.1007/s10936-014-9303-9

Pennington, B. F. (2006). From single to multiple deficit models of developmental disorders. *Cognition* 101, 385–413. doi: 10.1016/j.cognition.2006.04.008

Pontillo, M., De Luca, M., Ellis, A. W., Marinelli, C. V., Spinelli, D., and Zoccolotti, P. (2014). Failure to learn a new format in developmental dyslexia. *Sci. Rep.* 4:4869. doi: 10.1038/srep04869

Protopapas, A., and Parrila, R. (2018). Is dyslexia a brain disorder? *Brain Sci.* 8:61. doi: 10.3390/brainsci8040061

Pruneti, C., Fenu, A., Freschi, G., Rota, S., Cocci, D., Marchionni, M., et al. (1996). Aggiornamento della standardizzazione italiana del test delle Matrici Progressive Colorate di Raven (CPM). *Boll. di Psicol. Appl.* 217, 51–57.

Raven, J. C., (1965). *Advanced Progressive Matrices*. London: HK Lewis.

Schmalz, X., Altoè, G., and Mulatti, C. (2017). Statistical learning and dyslexia: A systematic review. *Ann. Dysl.* 67, 147–162. doi: 10.1007/s11881-016-0136-0

Schneider, W., and Chein, J. M. (2003). Controlled and automatic processing: behavior, theory, and biological mechanisms. *Cogn. Sci.* 27, 525–559. doi: 10.1207/s15516709cog2703_8

Slot, E. M., van Viersen, S., de Bree, E. H., and Kroesbergen, E. H. (2016). Shared and unique risk factors underlying mathematical disability and reading and spelling disability. *Front. Psychol.* 7:803. doi: 10.3389/fpsyg.2016.00803

Suárez-Coalla, P., Avdyli, R., and Cuetos, F. (2014). Influence of context-sensitive rules on the formation of orthographic representations in Spanish dyslexic children. *Front. Psychol.* 5:1409. doi: 10.3389/fpsyg.2014.01409

Turner, M. *One Minute Reading Test*. South Africa:Transvaal Education Department, (1987).

van Witteloostuijn, M., Boersma, P., Wijnen, F., and Rispens, J. (2017). Visual artificial grammar learning in dyslexia: A meta-analysis. *Res. Dev. Disabil.* 70, 126–137. doi: 10.1016/j.ridd.2017.09.006

Wilson, A. J., Andrewes, S. G., Struthers, H., Rowe, V. M., Bogdanovic, R., and Waldie, K. E. (2015). Dyscalculia and dyslexia in adults: cognitive bases of comorbidity. *Learn. Individ. Differ.* 37, 118–132. doi: 10.1016/j.lindif.2014.11.017

Zoccolotti, P., Angelelli, P., Marinelli, C. V., and Romano, D. L. (2021). A network analysis of the relationship among reading, spelling, and math skills. *Brain Sci.* 11:656. doi: 10.3390/brainsci11050656

Zoccolotti, P., and Caracciolo, B. (2002). "Psychometric characteristics of attention tests in neuropsychological practice," in *Applied Neuropsychology of Attention: Theory, Diagnosis and Rehabilitation*. eds. M. Leclercq and P. Zimmermann (London: Psychology Press), 152–185.

Zoccolotti, P., De Luca, M., Marinelli, C. V., and Spinelli, D. (2020a). Predicting individual differences in reading, spelling and maths in a sample of typically developing children: A study in the perspective of comorbidity. *PlosOne* 15:e0231937. doi: 10.1371/journal.pone.0231937

Zoccolotti, P., De Luca, M., Marinelli, C. V., and Spinelli, D. (2020b). Testing the specificity of predictors of reading, spelling and maths: a new model of the association among learning skills based on competence, performance and acquisition. *Front. Hum. Neurosci.* 14:573998. doi: 10.3389/fnhum.2020.573998

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# Are Different Types of Learning Disorder Associated With Distinct Cognitive Functioning Profiles?

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**Introduction:** DSM-5 presented a revised conceptualization of specific learning disorders (LD). Contrary to former versions, the various types of LD—i.e., mathematics disorder, reading disorder, and writing disorder—are not treated as distinct diagnostic entities but are integrated into one single LD category. In support of this new classification, it has been argued that the various types of LD overlap to a great extent in their cognitive functioning profiles and therefore do not exhibit a distinct set of cognitive causes. In contrast, ICD-11 still adheres to the idea of discrete categories and thus follows the specificity hypothesis of LD. Using latent profile analysis (LPA), we therefore tested the specificity of cognitive strengths and weaknesses in children with different types of LD. Secondly, we aimed at examining the extent to which observed LD characteristics (type and severity of LD as well as IQ-achievement discrepancy) were consistent with the membership of a given latent profile.

**Method:** 302 German third-graders (134 girls; IQ $\geq$ 85; $M_{age}$ = 111.05 months; *SD* = 5.76) with single or comorbid types of LD in the domains of mathematics, reading, and spelling completed a wide range of domain-specific and domain-general cognitive functioning measures.

**Results:** Five qualitative distinct profiles of cognitive strengths and weaknesses were identified. Profile 1 (23% of the sample) showed Comprehensive Cognitive Deficits, performing low in all measures except for naming speed, language, and inhibition. Profile 2 (21%) included children with a Double Deficit in Phonological Awareness and Phonological Short-term Memory. Profile 3 (20%) was characterized by a Double Deficit of Phonological Awareness and Naming Speed. Profile 4 (19%) included children with a Single Deficit in Attention, and profile 5 (17%) consisted of children without any cognitive deficits. Moreover, type and severity of LD as well as IQ-achievement discrepancy discriminated between the profiles, which is in line with the specificity hypothesis of LD.

**Discussion:** Overall, the finding of specific associations between the LD types and the identified cognitive profiles supports the ICD-11 classification of LD. Yet, those inferences may not be valid for an individual child but need to be examined through comprehensive diagnostic.

**Keywords: latent profile analysis (LPA), mathematics disorder, reading disorder, writing disorder, cognitive functioning, comorbidity, IQ-achievement discrepancy**



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## INTRODUCTION

DSM-5 (American Psychiatric Association, 2013) and ICD-11 (World Health Organization, 2021), the two major international classification systems for mental disorders, share some key assumptions concerning specific learning disorders (LD) such as (a) the presence of academic skills below the age-expected level, (b) the onset of symptoms during the first years of schooling, and (c) the persistence of the learning problems. However, they take quite different approaches to the classification of these disorders. Those differences refer to the classification of the various LD types as distinct disorders and to the requirement of an IQ-achievement-discrepancy criterion in diagnosing LD.

Specifically, in ICD-11, as in previous versions, the various types of LD—that is, mathematics disorder (MD), reading disorder (RD), and writing disorder (WD)—are classified as discrete diagnostic entities, each with its own diagnostic criteria. This *specificity hypothesis* assumes that these three LD types are qualitatively different from each other with respect to their symptoms, their (neuro-)biological markers, and their cognitive correlates so that a separate classification is justified. In contrast, in the newest version of DSM-5, the various types of LD are integrated into one single category and are thus considered to reflect different subtypes of the same underlying disorder. As a consequence, children receive the same overarching diagnosis of a *Specific Learning Disorder* irrespective of the academic domain(s) affected by the learning problems. However, different manifestations at the symptom level present at the time of diagnosis can be expressed through the use of specifiers, thus taking into account that children might exhibit severe learning problems in one or two academic domains only. In support of this new classification, the DSM task force (Tannock, 2013) argued that the various types of LD seem to overlap considerably in their cognitive functioning profiles and, therefore, may not exhibit a distinct set of cognitive causes. Rather, differences in underlying cognitive skills between MD, RD, and WD were considered to be merely dimensional in nature, rather than qualitatively different (cf. Tannock, 2013). In her commentary and literature review on the empirical findings considered in the revision of DSM-5, Tannock (2013) yet pointed out that studies directly comparing the cognitive *profiles* of the three LD types were largely missing. This limits our understanding of the *qualitative specificity* of LD and points to the need for empirical studies that profile potential qualitative differences in the cognitive skills associated with the various types of LD. Among the arguments in favor of a common LD classification, the DSM-5 task force also highlighted the high comorbidity between the three LD types at the time of diagnosis, and even more so in their course of development suggesting the presence of joint cognitive risk factors (cf. Tannock, 2013). That is, low cognitive specificity (i.e., high overlap in the underlying cognitive deficits) might be a crucial factor in explaining why single LD often worsen into multiple LD or even change from one domain (e.g., MD-only) to another (e.g., RD-only) throughout the school career. For example, Kohn et al. (2013) examined the longitudinal stability of MD and found that after 2.5 years, 21% of the children did not reach the criteria of an MD anymore, but exhibited an LD in reading and spelling challenging the clinical validity of the various LD types as distinct diagnostic entities.

With respect to IQ-achievement discrepancy, ICD-11 (as its previous versions) requires the child's low academic achievement to be unexpected given his or her intellectual potential. This uncoupling between intelligence and academic achievement has fueled the notion that children who fulfill the IQ-achievement discrepancy criterion are qualitatively distinct from poor learners whose achievement scores are in line with expectations based on their intelligence (e.g., Meyer, 2000). Over the past decades, however, this criterion has been highly debated (cf., Snowling et al., 2020) and DSM-5 has now abolished this criterion in the definition of LD. At first glance, there is cumulating evidence supporting the notion that children with IQ-discrepant achievement problems do not differ from non-discrepant poor learners on underlying cognitive functioning skills (e.g., Stuebing et al., 2002; Snowling et al., 2020) or in the general course of their learning problems (e.g., O'Malley et al., 2002; Gresham and Vellutino, 2010). Yet again (and just like with the various LD types), studies directly contrasting cognitive profiles between IQ-discrepant and non-discrepant LD are scarce. Consequently, to date there is no sound empirical knowledge base that can answer the question of whether the IQ-achievement discrepancy criterion leads to the identification of *qualitatively* different subgroups.

This is because, previous studies on the cognitive correlates of LD and the IQ-achievement discrepancy merely used a variable-centered approach to data modeling such as general linear modeling or confirmatory factor analyses. Those statistical techniques assume that the nature of individual differences is homogenous across different learners and thus the relationship between the measures of interest is the same for all children (cf. Hickendorff et al., 2018). As a consequence, they are most suitable for examining *dimensional* differences in cognitive functioning skills among learners, whereas *heterogeneous* response patterns are modeled as statistical noise. In contrast, person-centered approaches such as latent profile analysis (LPA) specifically aim at capturing the heterogeneity in the population by identifying subgroups of children—namely, the latent profiles—exhibiting as many differences between profiles and similarities within profiles as possible.

Although the number of studies using LPA in learning research is consistently growing, previous studies were mostly conducted with learners of the full ability range. For instance, Archibald et al. (2019) profiled the math, reading, and oral langue skills of 327 primary school children and identified six academic profiles. Of these, four were separated dimensionally by ability level (from well below average to well above average) with otherwise similar patterns across domains. The two remaining profiles, however, comprised children with a relative weakness in reading or math, respectively, which might be taken as evidence for the specificity of LD symptom manifestation. Among the few existing LPA studies specifically focusing on LD, most focused on either RD (e.g., Niileksela and Templin, 2018; Capin et al., 2021) or MD (e.g., Yang et al., 2005; Pieters et al., 2015; Huijsmans et al., 2020), instead of examining LD profiles across learning domains. Furthermore, profiling in these studies has been mainly based on the children's academic abilities rather than on their cognitive functioning skills. We identified only three exceptions in the literature: First of all, Gray et al. (2019) used LPA to examine the memory profiles of 167 typical achievers and 135 children with RD and/or developmental language disorder. Using measures that pertained to visual-spatial short-term memory, phonological short-term memory, updating in working memory, and memory binding, four profiles emerged, reflecting distinct groups of children: (1) performing low in all memory tasks, (2) exhibiting a specific deficit in number updating only, (3) performing at an average level, but exhibiting a relative weakness in memory binding along with a specific strength in number updating, and (4) performing high across all memory measures. Subsequent (descriptive) analyses revealed that children from each diagnostic group were present in each of the profiles, suggesting memory profiles not to be entirely consistent with the diagnostic group. Nevertheless, the diagnostic groups were not *equally* distributed among the profiles either, which in turn supports the idea of higher within-group than between-group similarities in cognitive functioning (cf. Gray et al., 2019). For instance, RD-only and the comorbid disorder were much more prevalent in the low memory profile than were the typical learners, whereas the reverse was true for the high memory profile.

In the domain of mathematics, the second study by de Souza Salvador et al. (2019) used a clustering approach based on measures of magnitude comparison, visual-spatial working memory, and verbal working memory to identify distinct cognitive subgroups among 192 typical achievers and 150 children with MD. In addition to two profiles without any cognitive deficits, two low achieving profiles were identified, consisting of children with low visuospatial abilities and with poor magnitude processing, respectively. Importantly, as opposed to the two normally achieving profiles found, both of these profiles showed a high frequency of children with MD (56.5 and 38.9%, respectively).

Concerning the IQ-achievement discrepancy, the third identified study by O'Brien et al. (2012) applied taxometric classification to capture the cognitive heterogeneity in 671 children with IQ-discrepant and non-discrepant RD on measures of phonological awareness and rapid automatized naming. The authors found two different taxa (i.e., distinct classes): one with and one without phonological awareness deficits. Interestingly, the IQ-discrepant poor readers were less likely to be in the latent class with phonological awareness deficits, whereas the non-discrepant readers were equally distributed among the two classes. For naming speed, differences between the reading groups were even more pronounced: Whereas two distinct taxa (one with and one without deficits in rapid naming) emerged for the non-discrepant poor readers, this was not the case for the IQ-discrepant children, whose naming speed deficits extended along a continuum.

These three studies provide support that (different forms of) LD may be associated with different cognitive functioning profiles. Among the cognitive correlates promising in distinguishing the various types of LD are domain-specific skills such as visual-spatial and phonological processing, as well as domain-general skills like executive functions and visual attention. With respect to the former, meta-analyses (e.g., David, 2012) and literature reviews (e.g., Raghubar et al., 2010) have reported large deficits in the short-term storage for visual and spatial information for children with MD, whereas there seem to be (if at all) only small deficits in visual-spatial short-term memory in children with RD (e.g., Carreti et al., 2009; Kudo et al., 2015). For WD, research on cognitive deficits is still limited and therefore, no meta-analytic results were found. Yet, Schuchardt et al. (2006) reported no poor visual-spatial short-term memory in German third-graders with poor writing skills. In contrast, for phonological short-term memory, medium deficits were found in children with RD (e.g., Swanson et al., 2009; Kudo et al., 2015), and only small to moderate deficits in children with MD (e.g., Swanson and Jerman, 2006; David, 2012; den Bos et al., 2013). Specifically, the magnitude of phonological deficits might depend on stimulus type: In their meta-analysis, Swanson and Jerman (2006) found higher phonological short-term memory for words in children with MD than in those with RD, but comparable deficits across groups with respect to the short-term storage of digits. For children with WD-only, in two single studies, Wimmer and Mayringer (2002) and Wimmer and Schurz (2010) observed reduced non-word repetition skills—a common measure of phonological short-term memory—in German-speaking children with poor spelling skills.

Concerning the meta-linguistic ability of phonological awareness, large deficits have been reported in a recent meta-analysis for RD, suggesting a marked deficit in the discrimination and manipulation of the sound structure of spoken language (Kudo et al., 2015). Yet, there is increasing evidence that performance in phonological awareness is highly moderated by orthographic transparency. Specifically in transparent orthographies, phonological awareness does not seem to be as crucial in learning to read as in less transparent orthographies such as English (e.g., Landerl and Wimmer, 2000). Therefore, phonological awareness has not always been reported as a significant cognitive marker underlying RD in German orthography (e.g., Wimmer and Mayringer, 2002; Moll and Landerl, 2009). German children with poor writing skills, however, appear to exhibit pronounced and comprehensive deficits in phonological awareness (e.g., Wimmer and Schurz, 2010). This might be due to higher transparency for reading than in spelling in German orthography (cf. Wimmer and Schurz, 2010). We did not find any meta-analytic results examining phonological awareness in children with MD. However, a recent one by Peng et al. (2020) focusing on the full ability range revealed only a small to moderate association between phonological awareness and mathematical achievement in general.

With respect to naming speed, the meta-analysis by Kudo et al. (2015) reported large deficits in the rapid naming of familiar stimuli such as letters and colors for children with RD, indicating an inefficient retrieval of verbal codes from long-term memory. The results concerning mathematics are mixed: Whereas some studies point to a specific naming deficit in children with MD only when quantities are used as stimuli (e.g., Landerl et al., 2009), a more recent meta-analysis (Koponen et al., 2017) suggests a significant relationship of medium effect size between naming speed and mathematics, irrespective of stimulus type. For WD, few single studies (e.g., Wimmer and Mayringer, 2002; Moll and Landerl, 2009) show that children with poor spelling skills do not exhibit a deficit in naming speed.

Besides those *phonological* language skills, previous research has also examined the association between LD and *semantic* language skills. For instance, there is profound evidence that children with RD show much lower vocabulary knowledge than their typically achieving peers (e.g., Kudo et al., 2015; Snowling and Melby-Lervåg, 2016). In contrast, the association between math achievement and semantic language skills seems to be lower, yet significant in the medium range for vocabulary and oral comprehension and can be attributed to the fact that language skills are important for mathematical problem-solving and learning (e.g., Peng et al., 2020). Moreover, in a recent longitudinal study, Snowling et al. (2021) demonstrated that children who fulfilled the diagnostic criteria for language disorder at the age of 6 years were not only at increased risk for developing an RD in subsequent years but also more likely to develop an MD by the age of 9, suggesting (early) language problems to be a mutual risk factor underlying both disorders.

Concerning domain-general cognitive skills, executive functions—including updating in working memory and inhibition—have been most often studied in children with LD. In fact, several meta-analyses (e.g., Swanson and Jerman, 2006; Carreti et al., 2009; Swanson et al., 2009; David, 2012; Kudo et al., 2015; Peng and Fuchs, 2016) converge on the finding that both RD and MD are associated with an overall deficit in executive functions of medium to large effect size. Whereas, both groups show a comparable deficit in verbal working memory, MD seems to be associated with marginally but significantly higher deficits in visual-spatial (Swanson and Jerman, 2006) and numerical working memory measures than RD (Peng and Fuchs, 2016) suggesting some differences with respect to task modality. Concerning different components of executive functions, working memory tasks produce greater effect sizes in both groups than tasks of inhibition (Carreti et al., 2009; den Bos et al., 2013). For WD, Schuchardt et al. (2006) reported reduced performance in children with poor spelling skills only in a counting span task, but not in two backward span measures. Likewise, Tiffin-Richards et al. (2007) found lower performance in children with poor spelling in only one of their two working memory tasks. For RD, Bosse et al. (2007) proposed a deficit in the visual attention span as an alternative explanation to the widely accepted phonological deficit. Accordingly, Tafti et al. (2014) found a medium effect size in a meta-analysis of visual attention deficits in RD which included studies with a variety of visual attention measures.

The various types of LD may also co-occur in some children. In fact, Moll et al. (2014) reported that among German 3rd and 4th graders comorbid LD occurs as frequently as single forms of LD. Concerning cognitive functioning skills, there is evidence that children with comorbid LD exhibit a combination of the specific weaknesses associated with each single disorder, suggesting an additive pattern of cognitive deficits (e.g., Moll and Landerl, 2009; Kißler et al., 2020).

Based on these domain-specific and domain-general cognitive skills, the first objective of this study was to thoroughly examine the cognitive strengths and weaknesses associated with LD by using LPA. To this end, we addressed the following research question: *How many and which cognitive functioning profiles emerge in children with various types of LD?* Given the multifactorial causes leading to LD, we expected to find several cognitive profiles that differ from one another mainly in qualitative rather than quantitative ways. Secondly, we were interested in the specificity of the emerging profiles with respect to the LD group and therefore addressed the research question: *Are the cognitive profiles systematically associated with the LD subtypes?* To this end, we examined whether or not the observed LD characteristics (i.e., type and severity of LD as well as IQ-discrepancy) were consistent with the membership of a given latent profile. Based on previous results, that mainly stem from variable-centered approaches, we hypothesized that profiles characterized by poor phonological processing would contain more children with LD in the literacy domain than children with MD. In addition, given the growing body of research suggesting additivity of cognitive deficits in children with comorbid forms of LD, we expected children with multiple LD to be predominantly found in the profiles with the most comprehensive cognitive deficits. Lastly, with respect to IQ-achievement discrepancy, according to O'Brien et al. (2012), we hypothesized that children with discrepant and those with non-discrepant learning problems would not be equally distributed among the emerging profiles.

# MATERIALS AND METHODS

## Participants

The sample included 302 third graders (168 boys/134 girls) with different types of LD. **Table 1** shows the descriptive characteristics of the sample as a function of the group. The children were recruited via a screening of scholastic skills that took place in elementary schools in and around three cities in the northern and central parts of Germany (viz., Frankfurt am Main, Hildesheim, Oldenburg). Children who fulfilled the diagnostic criteria of an LD (see below) were invited to take part in additional assessments of cognitive functioning. These assessments were split over two sessions each lasting up to 90 min and took place individually in schools or in the universities' laboratories. Parental informed written consent was obtained for all children prior to testing.

Classification of children was based on norm-referenced and standardized German school achievement measures and was thus based on standard scores. Classification criteria were as follows: All children showed at least average non-verbal intelligence (IQ $\geq$ 85). Children with a single learning deficit exhibited below-average achievement (i.e., more than 1.0 *SD* below the normed reference group's mean; equals $T < 40$) in one academic domain (i.e., mathematics, reading, or writing), whereas their performance in the other two academic domains was grade-appropriate ($T \geq 40$ and at least 5 T-points above the child's low academic domain). Correspondingly, children with multiple learning deficits showed below-average performance in either

**TABLE 1 |** Means and standard deviations for age and classification measures as a function of group.

| | MD (9 boys/47 girls) (22 non-discrepant/34 discrepant) | | RD (34 boys/22 girls) (21 non-discrepant/35 discrepant) | | WD (48 boys/14 girls) (26 non-discrepant/36 discrepant) | | RD+WD (46 boys/18 girls) (26 non-discrepant/38 discrepant) | | MD+RD+WD (31 boys/33 girls) (27 non-discrepant/37 discrepant) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | ***M*** | ***SD*** | ***M*** | ***SD*** | ***M*** | ***SD*** | ***M*** | ***SD*** | ***M*** | ***SD*** |
| Age (in months) | 104.38 | 6.65 | 101.91 | 4.72 | 104.63 | 5.79 | 104.19 | 6.22 | 104.98 | 5.56 |
| Intelligence[a] | 100.32 | 10.35 | 101.14 | 11.33 | 102.21 | 11.46 | 101.11 | 11.28 | 96.30 | 8.61 |
| Mathematics[b] | 34.68 | 3.33 | 51.66 | 6.12 | 53.96 | 7.29 | 51.86 | 6.48 | 33.83 | 3.40 |
| Reading[b] | 48.93 | 6.08 | 35.43 | 2.80 | 48.74 | 5.06 | 34.98 | 3.25 | 37.82 | 8.62 |
| Writing[b] | 47.84 | 6.51 | 45.23 | 3.80 | 35.60 | 4.28 | 34.33 | 3.30 | 34.58 | 4.45 |

*MD, Mathematical Disorder; RD, Reading Disorder; WD, Writing Disorder.*
*[a] IQ-score (M = 100, SD = 15).*
*[b] T-Score (M = 50, SD = 10).*

two or all three academic domains (T < 40). In the case of an LD in two domains, the third academic domain was grade-appropriate (T ≥ 40 and at least 5 T-points above the child's low academic domains). According to these criteria, 56 children showed an MD-only, 56 an RD-only, 62 a WD-only, 64 comorbid RD+WD, and 64 comorbid MD+RD+WD. In addition, approximately half of the children in each LD group showed an IQ-achievement discrepancy of at least 1.2 *SD* (see **Table 1**, for details).

Since the cut-off criteria used in the literature for the classification of LD are rather heterogeneous, we want to outline the rationale for the criteria used in the present study: In Germany, a norm-referenced cut-off score of T < 40 for the low achievement criterion and of 1.2 SDs for the IQ-discrepancy criterion correspond to the recommended diagnostic guidelines (Strehlow and Haffner, 2002) which are most frequently used in German educational and clinical settings (Hasselhorn et al., 2008; Klicpera et al., 2010). That is, by applying these cut-off scores, our sample best represented the subpopulation of school children in Germany commonly referred to as having a learning disorder. In addition, our low-achievement criterion of T < 40 (percentile < 16) is well within the range reported in the international literature on LD, where cut-off scores of percentile 10, 16, 25 or even 30 are generally used to identify children with LD (Büttner and Hasselhorn, 2011).

# Measures

## Classification Measures

The German version of the *Culture Fair Intelligence Test 1* (CFT 1; Cattell et al., 1997) was used as an indicator of fluid intelligence. To examine mathematical performance, the children completed the *DEMAT 2+* (Krajewski et al., 2004), a German curricular-valid test of basic arithmetic, magnitude, and geometry. The DEMAT 2+ is a speed test consisting of ten subtests, for which the children have 60–90 s each to complete. The *WRT 2+* (Birkel, 2007), a German spelling test for second and third graders, required the children to spell 43 dictated words embedded in short sentences. Children's reading skills were assessed using a German reading test, the *ELFE 1–6* (Lenhard and Schneider, 2006). The three subtests assess decoding speed using a picture-word-matching task, reading comprehension on sentence-level using a sentence gap task, and on text-level using multiple-choice items in response to short narratives. All classification measures yield norm-referenced performance scores and were administered in groups.

## Measures of Cognitive Functioning

### *Rapid Automatized Naming*

Speeded retrieval of phonological codes from long-term memory was measured with two alphanumeric subtests, which assessed naming speed for digits (1, 4, 5, 6, 8) and letters (f, k, r, s, t). The child's task was to name all 50 items as quickly as possible while making as few errors as possible. Naming time (in seconds) was recorded. For ease of interpretation, the scores were computed as the number of items per second, so that, as in the other tasks, higher values reflect better performance. Cronbach's alpha for the two measures was 0.71. Although the internal consistency was lower than suggested for individual diagnostics, for which a Cronbach's alpha of ≥0.80 is generally recommended, values of around 70 are within an acceptable and common range for basic research (cf. Nunnally and Bernstein, 1994).

### *Semantic Language Skills*

Receptive and expressive language skills in the domain of semantics were assessed with two subtests of the *Language Proficiency Test for Children aged 5 to 10 Years* (SET 5-10; Petermann, 2010). Receptive Vocabulary was assessed by 40 object drawings, which the child was asked to name. Morphology was assessed by giving children a word or pseudoword in the singular and then asking for the corresponding plural. The task consisted of 9 words and 9 pseudowords. Cronbach's alpha was 0.91 for the receptive vocabulary subtest and 0.84 for morphology.

### *Phonological Awareness*

Three subtests of the *Test of Basic Competencies for Reading and Spelling* (BAKO 1–4; Stock et al., 2003) were used to assess PA on phoneme level. In the *Phoneme Reversal* subtest (18 items), the child's task was to pronounce a given (pseudo)word in reversed order (e.g., ruf → fur). In the *Vowel Substitution* subtest (12 items), the child's task was to substitute all /a/ vowels in a given word with an /i/ vowel (e.g., Sand → Sind). In the *Vowel Length* subtest (10 items), the child had to identify one out of four pseudowords that did not match the others with respect to vowel lengths (e.g., /re:m/ - /fe:r/ - /nεl/ - /be:f/). Items of the BAKO were presented audibly via computer and subtest presentation was stopped once the child answered three subsequent items incorrectly. Cronbach's alpha of the measures was 0.90, 0.84, and 0.75, respectively.

#### *Phonological Short-Term Memory*

The short-term storage of phonological information was assessed using four subtests of the *Working Memory Test Battery for Children aged Five to Twelve Years* (AGTB 5–12; Hasselhorn et al., 2012). In the *Digit Span* task, the child was asked to repeat increasing sequences of different digits after their auditory presentation. Similarly, the *Word Span* task required the serial repetition of high-frequency words. There were two versions of the task—one with monosyllabic and one with trisyllabic words—resulting in separate span scores for short and long words, respectively. Both the Digit Span task and the two Word Span tasks consisted of 10 trials starting with a three-item sequence. Sequence lengths in the remaining trials were determined by an adaptive algorithm based on the child's performance. In the *Non-word Repetition* task, 24 pseudowords with lengths of three to five syllables had to be repeated immediately after their auditory presentation. Cronbach's alpha of the measures was 0.96 (Digit Span), 0.95 (monosyllabic Word Span), 0.92 (trisyllabic Word Span), and 0.74 (Non-word Repetition).

#### *Visual-Spatial Short-Term Memory*

The short-term storage for visual and spatial information was assessed using two subtests of the AGTB 5–12. In the *Matrix Span* task, a pattern of black squares was presented on a touchscreen within a four-by-four matrix. Immediately after the presentation, the child had to reproduce the pattern in an empty matrix. In the *Corsi Span* task, a sequence of smileys appeared in squares distributed on the touchscreen. At the end of each trial, the child had to reproduce the serial order of the smileys by touching the respective squares. Both tasks consisted of 10 trials starting with a three-item sequence. Sequence lengths in the remaining trials were determined by an adaptive algorithm based on the child's performance. Cronbach's alpha of the measures was 0.99 and 0.96, respectively.

#### *Working Memory*

Updating in working memory was assessed using four subtests of the AGTB 5–12. The *Backward Digit Span* task was identical to the forward condition used to assess phonological short-term memory, except that the child was instructed to recall the sequences in reverse order. In the *Backward Color Span* task, a sequence of colored dots was presented on the touchscreen. Immediately after the presentation, the child was asked to tap the colors on the screen in reverse order. In the *Counting Span* task, a sequence of squares and dots of varying numbers were distributed randomly on the touchscreen and the child's task was to count aloud the dots. At the end of a trial, the child was asked to recall the number of dots in the correct serial order. In the *Object Span* task, an increasing number of objects (e.g., candle, cheese) was presented one by one on the touchscreen and the child had to classify whether the object was edible or not. Subsequently, the child was asked to recall the objects in the correct serial order. All four span tasks consisted of 10 trials starting with a two-item sequence. Sequence lengths in the remaining trials were determined by an adaptive algorithm based on the child's performance. Cronbach's alpha of the measures was 0.90 (Backward Digit Span), 0.84 (Backward Word Span), 0.97 (Counting Span), and 0.96 (Object Span).

#### *Inhibition*

Two subtests of the AGTB 5–12 were used as an indicator for inhibition: In the *Go/Nogo* task, the child was asked to press a button on the touchscreen whenever she or he saw a specified item (go trial) within a picture of children, for example, a yellow balloon. In a Nogo trial, a similar item (e.g., a red balloon) was shown as a distractor, on which the child should not press the button. The number of correct reactions served as dependent variables. In the *Stroop* task, a drawing of a man or woman was shortly presented on the upper half of the touchscreen, whereas the same drawing of the man and the woman were continuously shown on the lower right and left corner of the screen. Simultaneously with the visual presentation, the child was given the verbal cue of the word "man" or "woman." The child was asked to react to the visual stimulus only by tapping onto the respective figure in the lower half of the touchscreen (man – man; woman – woman) while ignoring the verbal cue. The dependent variable was the child's reaction time to incongruent trials. Cronbach's alpha of the measures was 0.67 and 0.76, respectively.

#### *Visual Attention*

To assess visual attention, an attentional response speed task of the *Intelligence and Development Scales* (IDS; Grob et al., 2009) was used. In this task, a sheet with 225 ducks arranged in nine rows à 25 ducks was presented to the child. The child's task was to mark as quickly as possible all ducks that look to the right-hand sight and that contain two orange elements (e.g., two orange feet) while making as few errors as possible. There was a time limit of 15 s per row. The dependent variable was the number of correctly marked ducks. This test required processing speed, visual scanning, and attentional resources. Cronbach's alpha of this measure was 0.87.

### Statistical Analyses

For each cognitive construct, the respective subtests were combined into a mean scale score that was used for the LPA. Mean scores were based on the norm-referenced T-scores ($M = 50$; $SD = 10$). For the rapid automatized naming task, norms were not available. Therefore, we calculated sample-based z-scores ($M = 0$; $SD = 1$) and converted these scores to T-scores by means of linear transformation with the following formula: $T = 50 + 10 * z$, so that this measure was on the same scale as the other cognitive functioning indicators. Means and standard deviations on the scale scores entered in the LPA as well as their bivariate correlations are displayed in **Table 2**.

Prior to the LPA, we checked the distributional characteristic of the scale scores. There were neither any univariate outliers

**TABLE 2 |** Bivariate correlations and norm-referenced means and standard deviations of the sample in the cognitive scales entered in the LPA.

| | 1. | 2. | 3. | 4. | 5. | 6. | 7. | 8. |
|---|---|---|---|---|---|---|---|---|
| 1. RAN | – | | | | | | | |
| 2. LAN | −0.16* | – | | | | | | |
| 3. PA | 0.11 | 0.13* | – | | | | | |
| 4. PSTM | 0.03 | 0.36* | 0.32* | – | | | | |
| 5. VSTM | −0.12* | 0.11 | 0.10 | 0.18* | – | | | |
| 6. WM | 0.14* | 0.12* | 0.37* | 0.48* | 0.41* | – | | |
| 7. INH | 0.18* | −0.02 | 0.12 | 0.02 | 0.22* | 0.26* | – | |
| 8. ATT | −0.05 | 0.05 | 0.03 | 0.12 | 0.33* | 0.11 | 0.21* | – |
| *M* | –[a] | 50.55 | 42.06 | 48.09 | 48.87 | 46.77 | 50.69 | 45.79 |
| *SD* | –[a] | 8.85 | 6.38 | 7.40 | 7.68 | 6.52 | 7.22 | 8.71 |

*RAN, rapid automatized naming; LAN, semantic language skills; PA, phonological awareness; PSTM, phonological short-term memory; VSTM, visual-spatial short-term memory; WM, working memory; INH, inhibition; ATT, visual attention. The reported means and standard deviations are norm-referenced T scores (M = 50; SD = 10).*

[a]*For the RAN task, norms were not available, thus we standardized these scores on our own sample.*

*$^*p < 0.05$.*

(defined as cases deviating more than 3.29 *SD*s from the sample's means) nor any multivariate outliers based on Mahalanobis distance in the dataset. In addition, data showed univariate normality with standardized skewness <3 and standardized kurtosis <4.

The analyses were conducted in Mplus 8.4 (Muthén and Muthén, 1998-2019) using maximum likelihood estimation with robust standard errors (MLR). We started the LPA with a one-profile solution and subsequently added additional profiles in a step-by-step manner. To ensure that the models converge on the global maximum, the default setting was increased to 1,000 random starts as well as 250 final stage optimizations, and we additionally checked whether the best log-likelihood value was replicated multiple times (Wang and Wang, 2012). Furthermore, to warrant a reliable *p*-value for the BLRT, we increased the number of bootstrap draws to 200 and the numbers of the initial stage random starts and the final stage optimizations for the bootstrapped data to 20 and 5 for the (k-1)-profile model, and to 100 and 25 for the k-profile model, respectively (Wang and Wang, 2012). A combination of statistical fit measures, parsimony, interpretability of the profiles, and profile size (Hickendorff et al., 2018) was used to determine the optimal number of profiles. With respect to statistical fit, we used (a) information criterion indices, in which lower values indicate better model fit, such as Akaike's information criterion (AIC), Bayesian information criterion (BIC), and sample-size adjusted Bayesian information criterion (aBIC) as well as (b) log-likelihood ratio tests such as the Lo-Mendel-Rubin test (LMR) and the parametric bootstrapped likelihood ratio test (BLRT), that examine whether the model with k profiles fits the data better than the comparison model with k-1 profiles, as indicated by a significant *p*-value. In case of conflicting statistical information, the BLRT and the BIC are to be preferred over the other indices as demonstrated by simulation studies (Nylund et al., 2007).

The quality of latent profile membership classification was evaluated based on (a) the relative entropy criterion REN(k), and (b) the average latent profile posterior probabilities (aCPP), for both of which values ≥0.70 suggest an acceptable classification (Wang and Wang, 2012).

For each of the identified profiles in the selected LPA model, the average T-scores in the cognitive measures were consulted to create interpretative labels for the profiles: A performance score of T ≤ 43.3, which equals the bottom 25% of the norming sample (percentile ≤ 25), was considered as indicating a weakness in the corresponding cognitive skill. In addition, we used the omnibus Wald test to examine whether the cognitive functioning indicators contributed to differentiating the identified profiles. When significant, we made pairwise comparisons to establish which profiles differed significantly from each other.

With respect to our second objective, that is, examining the specificity of the cognitive profiles, we added the following dichotomous factors as auxiliary variables in the LPA using the DCAT setting (Asparouhov and Muthén, 2020): mathematical problems (no = 0, yes = 1), reading problems (no = 0, yes = 1), spelling problems (no = 0, yes = 1), severity of LD (single LD = 0, multiple LDs = 1), and IQ-achievement discrepancy (non-discrepant = 0, discrepant = 1).

# RESULTS

## Model Selection

We estimated latent profiles up to a 6-profile solution and identified the model with 5 profiles as the best fitting and most informative model for understanding the nature of cognitive strengths and weaknesses in children with LD. **Table 3** shows the model fit statistics and the classification quality for each solution. Although the LMR pointed to the 2-profile solution, the BLRT and all the information criteria suggested that models with more than two profiles fit the data better. Moreover, the two emerging profiles in this model were not informative in understanding the various cognitive patterns associated with LD, as the children were just separated into a big subgroup of individuals with poorer cognitive functioning skills (64% of the sample, with average scores of around T = 45) and a small group of children (36%) with higher performance scores (T-scores around 53).

Both the BLRT and the BIC—the two measures that are to be preferred over the other indices in case of conflicting results (Nylund et al., 2007)—pointed to the 5-profile solution, which was therefore selected as having the best fit. Reversed entropy for this model was 0.70 and the average probabilities for profile membership were between 0.768 and 0.870, both of which indicate an acceptable classification quality and thus suggest that the 5-profile solution produced separable subgroups of children with different patterns of cognitive strengths and weaknesses. With ∼20% of the sample placed in each profile, the distribution of children was nearly balanced in the five profiles and the profiles were well-interpretable.

The 6-profile solution, in contrast, revealed slightly better AIC and aBIC values than the 5-profile model. Yet, this solution comprised two average performing groups, which did not add relevant information compared to the more parsimonious 5-profile solution, which comprised only one group of average performers. In addition, the other four emerging subgroups were

**TABLE 3 |** Model fit statistics and classification quality of the latent profiles.

| #Profiles | LL | AIC | BIC | aBIC | LMR (*p*) | BLRT (*p*) | REN(k) | aCPP | *n* in profiles |
|---|---|---|---|---|---|---|---|---|---|
| 1 | −8,258.03 | 16,548.06 | 16,607.43 | 16,556.69 | – | – | – | – | 302 |
| 2 | −8,163.40 | 16,376.80 | 16,469.56 | 16,390.27 | 0.0004 | <0.0001 | 0.73 | 0.919–0.924 | 199/103 |
| 3 | −8,139.34 | 16,346.68 | 16,472.84 | 16,365.01 | 0.36 | <0.0001 | 0.70 | 0.776–0.900 | 50/171/81 |
| 4 | −8,117.31 | 16,320.63 | 16,480.18 | 16,343.80 | 0.39 | <0.0001 | 0.70 | 0.800–0.860 | 71/119/48/64 |
| **5** | **−8,090.27** | **16,284.55** | **16,477.49** | **16,312.57** | **0.34** | <0.0001 | **0.70** | **0.768–0.870** | **69/64/61/58/50** |
| 6 | −8,076.50 | 16,274.99 | 16,501.33 | 16,307.87 | 0.23 | 0.06 | 0.70 | 0.742–0.869 | 55/65/39/51/54/38 |

*Optimum solution in bold. LL, log likelihood; BIC, Bayesian Information Criterion; AIC, Akaike Information Criterion; aBIC, adjusted Bayesian Information Criterion; LMR, Lo-Mendell-Rubin adjusted likelihood test; BLRT, Bootstrapped likelihood ratio test; REN(k), relative entropy criterion; aCPP, average Class Posterior Probabilities.*

rather comparable across the 5- and the 6-profile solution with respect to their cognitive patterns. The 6-profile model was therefore discarded.

## Profile Description

The five profiles are visualized in **Figure 1** and the respective parameter estimates are presented in **Table 4**. As shown by the omnibus Wald test, each of the eight cognitive functioning indicators contributed to differentiating the profiles. We performed pairwise comparisons between the profiles for all eight cognitive scales to examine which of the profiles differed significantly from each other on a particular cognitive functioning indicator (**Table 5**).

Profile 1 included 69 children (23%) with the most *Comprehensive Cognitive Deficits*, as their T-scores in five out of the eight scales fell in the bottom 25% of the respective norming samples ($T \leq 43.3$). Most severe were the children's deficits in phonological awareness, in which they scored more than 1 *SD* below the normative sample; followed by deficits in working memory, visual-spatial short-term memory as well as phonological short-term memory, and attention. Moreover, the children in this profile showed the lowest scores in these cognitive scales compared to the other four profiles. This pattern was also supported by the pairwise comparisons: Children in this profile performed (a) significantly lower than all the other profiles in WM and (b) significantly lower than nearly all the other profiles in phonological awareness as well as in visual-spatial and phonological short-term memory. Performance in the three remaining measures (naming speed, inhibition, and semantic language skills) was around average, yet fell below the mean performance of $T = 50$.

Profile 2 (64 children, 21%) included children with a *Double Deficit in Phonological Awareness and Phonological Short-term Memory*: These children showed specific impairments in the storing of verbal information as well as in the discrimination and manipulation of phonemes. These two phonological skills were comparably low as in Profile 1, which significantly distinguished this profile from the remaining three profiles. Especially the children's deficit in phonological awareness was profound, as it reached the below-average range with a T-score more than 1 *SD* lower than the normative sample. In addition, the marked performance gap (more than 10 T-scores, i.e., >1 *SD*) between the children's phonological short-term memory ($T = 43$) as opposed to the one for visual-spatial information ($T = 53$) is noteworthy. In fact, in the other identified profiles, performance differences in these two domains of short-term memory were much smaller (<5 T-points). Performance in the other cognitive features was mostly around the normative average and ranged from $T = 45$ (working memory) to $T = 52$ (inhibition).

Profile 3 (61 children, 20%) was—similar to Profile 2—characterized by a double deficit in phonological processing. Yet, instead of deficits in phonological short-term memory, these children exhibited low naming speed—that is, a deficit in the retrieval speed for information stored in verbal long-term memory—along with their impairments in phonological awareness. This profile was, therefore, labeled the group with a *Double Deficit in Phonological Awareness and Rapid Automatized Naming*. Also of interest is the children's marked strength in semantic language skills (T-score of about 59), which significantly distinguished this profile from all the other profiles as indicated by the pairwise comparisons. Besides that, children in this profile showed performance scores that ranged from $T = 45$ (attention) to $T = 54$ (phonological short-term memory).

Profile 4 (58 children, 19%) comprised children with a *Single Deficit in Visual Attention*, as the children in this profile displayed a single but profound deficit in attentional resources. The children also showed a considerable strength in naming speed, with a T-score nearly one *SD* above the sample's average. The children's strength in naming speed was further supported by the pairwise comparisons: Children in this profile were significantly faster in the naming of alphanumeric stimuli than those in nearly all the other profiles. Performance in the other cognitive skills was mostly around the normative average and ranged from $T = 45$ (phonological awareness, visual-spatial short-term memory) to $T = 52$ (inhibition).

Profile 5 (50 children, 17%) included children with *Cognitive Strengths*, because their mean performance scores in seven out of the eight cognitive scales were better than the normative average of $T = 50$. This was especially true for the children's visual-spatial short-term memory ($T = 58$) and their performance in the executive functions ($T = 56$ for inhibition, and $T = 55$ for working memory), which was further supported by the pairwise comparisons: Children in this profile performed (a) significantly higher than all the other profiles in inhibition and (b) significantly better than nearly all the other profiles in visual-spatial short-term memory and working memory. Interestingly,

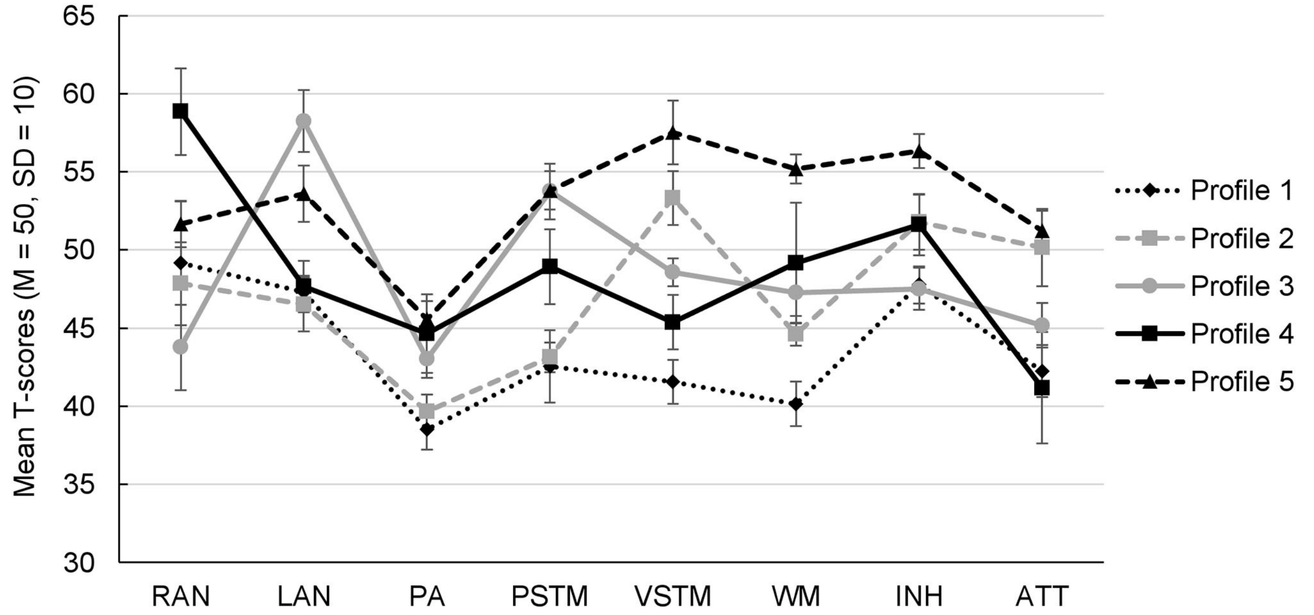



**FIGURE 1 |** Cognitive profile plot of the 5-profile solution. RAN, rapid automatized naming; LAN, semantic language skills; PA, phonological awareness; PSTM, phonological short-term memory; VSSP, visual-spatial short-term memory; WM, working memory; INH, inhibition; ATT, visual attention.

**TABLE 4 |** *T*-scores of the cognitive functioning scales for the five-profile solution.

| | Profile 1 ($n = 69$) | | Profile 2 ($n = 64$) | | Profile 3 ($n = 61$) | | Profile 4 ($n = 58$) | | Profile 5 ($n = 50$) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | *M* | *S.E.* | *M* | *S.E.* | *M* | *S.E.* | *M* | *S.E.* | *M* | *S.E.* | Wald test |
| RAN | 49.16 | 3.99 | 47.84 | 2.66 | 43.76 | 2.74 | 58.85 | 2.79 | 51.64 | 1.48 | 13.73* |
| LAN | 47.31 | 1.04 | 46.52 | 1.72 | 58.25 | 1.98 | 47.65 | 1.64 | 53.61 | 1.80 | 62.25* |
| PA | 38.52 | 1.30 | 39.67 | 1.08 | 43.03 | 1.22 | 44.64 | 2.52 | 45.56 | 1.17 | 50.36* |
| PSTM | 42.55 | 2.33 | 43.13 | 0.94 | 53.74 | 1.80 | 48.92 | 2.39 | 53.81 | 1.22 | 97.70* |
| VSTM | 41.55 | 1.40 | 53.32 | 1.74 | 48.56 | 0.90 | 45.38 | 1.74 | 57.52 | 2.05 | 135.60* |
| WM | 40.15 | 1.43 | 44.60 | 0.72 | 47.25 | 1.49 | 49.17 | 3.84 | 55.20 | 0.93 | 195.37* |
| INH | 47.76 | 1.19 | 51.77 | 1.77 | 47.51 | 1.35 | 51.61 | 1.96 | 56.34 | 1.08 | 48.60* |
| ATT | 42.24 | 1.66 | 50.15 | 2.46 | 45.18 | 1.42 | 41.18 | 3.55 | 51.23 | 1.30 | 43.26* |

*RAN, rapid automatized naming; LAN, semantic language skills; PA, phonological awareness; PSTM, phonological short-term memory; VSTM, visual-spatial short-term memory; WM, working memory; INH, inhibition; ATT, visual attention. The reported values are norm-referenced T scores (M = 50; SD = 10) except for RAN, for which norms were not available so that we standardized these scores on our own sample.*
*$^*p < 0.05$.*

this subgroup of children showed a marked performance gap and, thus, a relative weakness in phonological awareness, with a mean score approximately half a *SD* below the normative average (T = 46).

## Association of the Cognitive Profiles With LD Characteristics

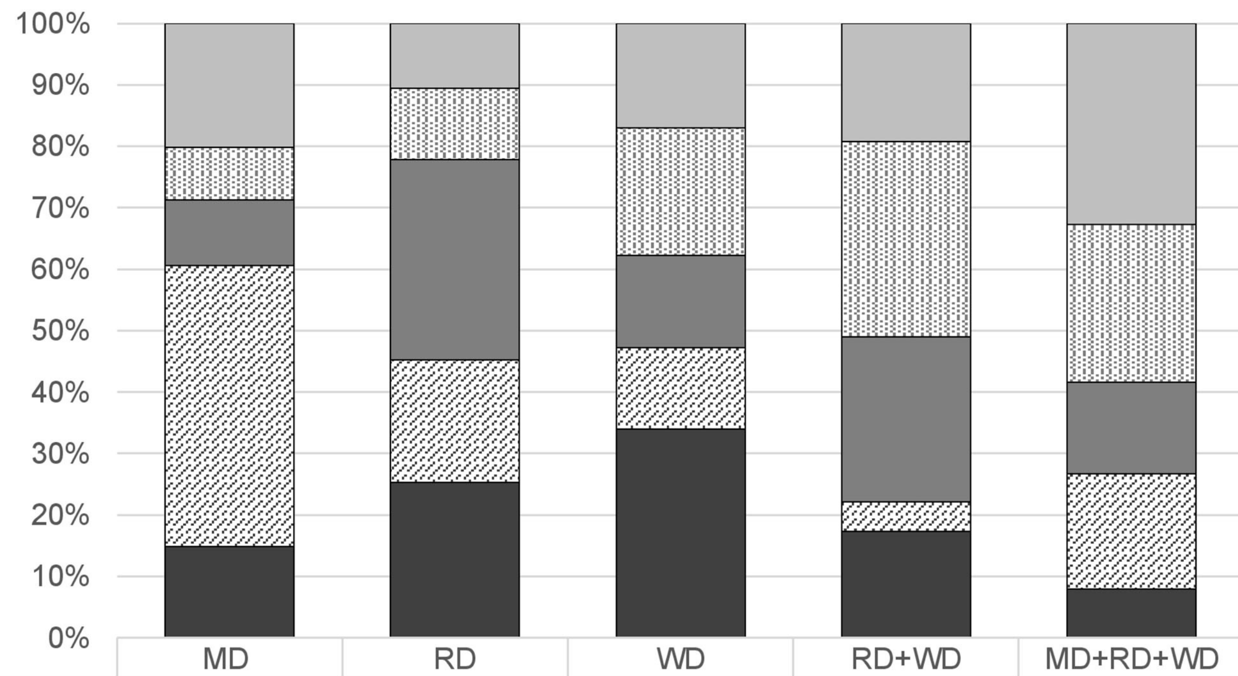
**Figure 2** displays the distribution of profile classification across the five LD groups. It shows that children with MD were most often classified in profile 4 (single attention deficit) and most seldom in one of the profiles that showed a double deficit in phonological processing (i.e., profile 2 and profile 3). Interestingly, the reverse pattern was true for children with comorbid RD+WD, as these children were proportionally most represented in profile 2 (*Double Deficit in Phonological Awareness and Phonological Short-term Memory*) or profile 3 (*Double Deficit in Phonological Awareness and Rapid Automatized Naming*), but rarely present in profile 4. Children with an RD-only were proportionally most likely to be classified in profile 3 (*Double Deficit in Phonological Awareness and Rapid Automatized Naming*), whereas children with a WD-only were most often grouped in profile 5 (*Cognitive Strengths*). Finally, children with an LD in all three academic domains were most likely to be grouped in profile 1 (*Comprehensive Cognitive Deficits*) and were rarely present in profile 5 (*Cognitive Strengths*).

Next, we examined the association between the cognitive profiles and the various LD characteristics by investigating whether profile membership classification *significantly* differed

**TABLE 5 |** Mean differences and standard errors between the latent profiles in the cognitive functioning measures.

| Comparison | RAN | | LAN | | PA | | PSTM | | VSTM | | WM | | INH | | ATT | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *M*Δ | *S.E.* | *M*Δ | *S.E.* | *M*Δ | *S.E.* | *M*Δ | *S.E.* | *M*Δ | *S.E.* | *M*Δ | *S.E.* | *M*Δ | *S.E.* | *M*Δ | *S.E.* |
| Profile 1 to Profile 2 | 1.32 | 3.72 | 0.79 | 2.11 | −1.15 | 1.56 | −0.58 | 2.36 | **−11.77** | 1.42 | **−4.46** | 1.75 | −4.00 | 2.44 | **−7.91** | 3.21 |
| Profile 1 to Profile 3 | 5.40 | 3.16 | **−10.94** | 2.30 | **−4.51** | 1.62 | **−11.19** | 2.66 | **−7.01** | 1.57 | **−7.10** | 1.91 | 0.25 | 1.71 | −2.94 | 1.88 |
| Profile 1 to Profile 4 | −9.69 | 6.11 | −0.34 | 2.11 | **−6.12** | 1.75 | **−6.37** | 1.83 | −3.83 | 2.49 | **−9.02** | 2.87 | −3.85 | 2.20 | 1.06 | 4.76 |
| Profile 1 to Profile 5 | −2.49 | 4.70 | **−6.30** | 2.07 | **−7.04** | 1.87 | **−11.26** | 2.95 | **−15.97** | 2.83 | **−15.05** | 1.42 | **−8.56** | 1.56 | **−8.99** | 1.77 |
| Profile 2 to Profile 3 | 4.08 | 3.18 | **−11.73** | 1.92 | **−3.35** | 1.59 | **−10.62** | 1.80 | **4.77** | 2.01 | −2.64 | 1.77 | 4.25 | 2.58 | 4.97 | 3.13 |
| Profile 2 to Profile 4 | **−11.01** | 4.71 | −1.13 | 2.57 | **−4.97** | 2.51 | **−5.80** | 2.49 | **7.95** | 2.81 | −4.57 | 4.14 | 0.16 | 2.54 | **8.97** | 4.10 |
| Profile 2 to Profile 5 | −3.80 | 3.34 | **−7.09** | 2.87 | **−5.89** | 1.67 | **−10.68** | 1.60 | −4.20 | 3.23 | **−10.59** | 1.26 | **−4.58** | 2.16 | −1.08 | 3.01 |
| Profile 3 to Profile 4 | **−15.09** | 4.96 | **10.60** | 2.63 | −1.62 | 2.74 | 4.82 | 2.89 | 3.18 | 1.73 | −1.92 | 3.83 | −4.10 | 2.32 | 4.00 | 4.27 |
| Profile 3 to Profile 5 | **−7.88** | 3.37 | 4.64 | 3.19 | −2.54 | 1.81 | −0.07 | 2.50 | **−8.97** | 2.01 | **−7.95** | 1.33 | **−8.83** | 1.51 | **−6.05** | 1.66 |
| Profile 4 to Profile 5 | **7.21** | 2.92 | **−5.96** | 2.42 | −0.92 | 2.95 | −4.89 | 2.96 | **−12.15** | 1.86 | −6.02 | 3.56 | **−4.73** | 2.09 | **−10.05** | 4.13 |

*Significant differences in bold p < 0.05. RAN, rapid automatized naming; LAN, semantic language skills; PA, phonological awareness; PSTM, phonological short-term memory; VSTM, visual-spatial short-term memory; WM, working memory; INH, inhibition; ATT, visual attention.*




| | MD | RD | WD | RD+WD | MD+RD+WD |
|---|---|---|---|---|---|
| Profile 1 | 19 | 10 | 18 | 20 | 33 |
| Profile 2 | 8 | 11 | 22 | 33 | 26 |
| Profile 3 | 10 | 31 | 16 | 28 | 15 |
| Profile 4 | 43 | 19 | 14 | 5 | 19 |
| Profile 5 | 14 | 24 | 36 | 18 | 8 |

**FIGURE 2 |** Distribution of the latent cognitive profiles across the LD subtypes. MD, Mathematical Disorder; RD, Reading Disorder; WD, Writing Disorder.

with respect to the different forms of LD. The results of this analysis are presented in **Table 6** and Table A1 of the **Appendix**.

For mathematical problems, the overall comparison was highly significant, $Chi^2(4) = 27.83$, $p < 0.001$, suggesting differences between the profiles concerning the proportion of children with impairments in mathematics and those without. Specifically, the pairwise results showed that children with impairments in mathematics were more likely to belong in profile

**TABLE 6 |** Proportional distribution of LD characteristics within the latent profiles.

| | Profile 1 % | Profile 2 % | Profile 3 % | Profile 4 % | Profile 5 % | $\chi^2$ |
|---|---|---|---|---|---|---|
| **Mathematical problems** | | | | | | |
| No | 43 | 66 | 82 | 27 | 84 | 27.83* |
| Yes | 57 | 34 | 18 | 73 | 16 | |
| **Reading problems** | | | | | | |
| No | 34 | 16 | 25 | 83 | 63 | 28.50* |
| Yes | 66 | 84 | 75 | 17 | 37 | |
| **Spelling problems** | | | | | | |
| No | 21 | 6 | 48 | 70 | 42 | 43.31* |
| Yes | 79 | 94 | 52 | 30 | 58 | |
| **Severity of LD** | | | | | | |
| Single LD | 31 | 20 | 60 | 81 | 85 | 41.31* |
| Multiple LD | 69 | 80 | 40 | 19 | 15 | |
| **IQ-discrepancy** | | | | | | |
| No | 50 | 50 | 24 | 44 | 29 | 9.91* |
| Yes | 50 | 50 | 76 | 56 | 71 | |

*$p < 0.05$.

4 with a *Single Deficit in Attention* than in profile 3 with a *Double Deficit in Phonological Awareness and Rapid Automatized Naming* or than in profile 5 with *Cognitive Strengths.* Likewise, they were more likely to be in profile 2 with a *Double Deficit in Phonological Awareness and Phonological Short-term Memory* than in profile 5 with *Cognitive Strengths*.

For reading problems, the overall comparison was highly significant, Chi²(4) = 28.50, $p < 0.001$, indicating that profile membership classification differed between children with and without impairments in reading. Specifically, the pairwise results revealed that children with impairments in reading were more prevalent in profile 1 (*Comprehensive Cognitive Deficits*) and profile 3 (*Double Deficit in Phonological Awareness and Rapid Automatized Naming*) than in profile 4 (*Single Deficit in Attention*) or profile 5 (*Cognitive Strengths*). In addition, they were also more likely placed in profile 2 (*Double Deficit in Phonologucal Awareness and Phonological Short-term Memory*) than in Profile 4 (*Single Deficit in Attention*).

The overall comparison was also highly significant for spelling problems, Chi²(4) = 43.31, $p < 0.001$. As indicated by the pairwise comparisons, children with impairments in spelling were more likely to be in profile 2 with a *Double Deficit in Phonological Awareness and Phonological Short-term Memory* than in profile 3 with a *Double Deficit in Phonological Awareness and Rapid Automatized Naming* or in profile 4 with a *Single Deficit in Attention*. They were also more prevalent in profile 1 with *Comprehensive Cognitive Deficits* than in profile 3 (*Double Deficit in Phonologiacl Awareness and Rapid Automatized Naming*), profile 4 (*Single Deficit in Attention*), or profile 5 (*Cognitive Strengths*), respectively.

Overall, profile membership also differed with respect to the severity of LD, Chi²(4) = 41.31, $p < 0.001$, suggesting differences between the profiles concerning the proportion of children with learning problems in only one domain and those with problems in multiple domains. As indicated by the pairwise comparisons, children with multiple LDs were more likely to be placed in profile 1 with *Comprehensive Cognitive Deficits* or in profile 2 with a *Double Deficit in Phonological Awareness and Phonological Short-term Memory* than in the other three profiles. In addition, the proportion of children with multiple LDs was also significantly higher in profile 3 with a *Double Deficit in Phonological Awareness and Rapid Automatized Naming* than in profile 4 with a *Single Deficit in Attention* or profile 5 with no cognitive deficits.

Lastly, for IQ-discrepancy the overall comparison was marginally significant, Chi²(4) = 9.91, $p = 0.04$, indicating that profile membership differed for children with discrepant and non-discrepant learning problems. Specifically, the pairwise results revealed that children who met the IQ-achievement discrepancy criterion were more likely to be in profile 5 with *Cognitive Strengths* or profile 3 with a *Double Deficit in Phonological Awareness and Rapid Automatized Naming* than in profile 1 with *Comprehensive Cognitive Deficits* or in profile 2 with a *Double Deficit in Phonological Awareness and Phonological Short-term Memory.*

## DISCUSSION

The first aim of this study was to examine the heterogeneity of domain-specific and domain-general cognitive functioning skills underlying LD. Using LPA, five profiles reflecting different cognitive strengths and weaknesses were identified among 302 third-graders with different types of LD. Specifically, children of profile 1 showed comprehensive cognitive deficits as they scored in the bottom 25% of the respective standardizing samples in five out of the eight cognitive features. Two profiles were characterized by a double deficit in phonological processing consisting of children with an impairment in phonological awareness in combination with deficits in phonological short-term memory (profile 2) or low naming speed (profile 3). Profile 4 included children with a single deficit in visual attention, and children of profile 5 did not perform poorly in any of the cognitive functioning facets assessed. Taken together, as evident from **Figure 1**, the profiles differed from one another in qualitative rather than dimensional ways, since there were no two profiles that differed from each other only in performance level but showed otherwise the exact same pattern of strengths and weaknesses in the cognitive skills (i.e., the same pattern of peaks and dips in **Figure 1**). Moreover, the size of the profiles was nearly balanced with about 20% of the children placed in each profile, suggesting that a dominant "*core profile*" in LD does not exist. This is in line with the notion that the cognitive deficits associated with–and probably causing–LD are multifactorial and are obviously not the same for all children.

Moreover, all eight cognitive functioning skills contributed to differentiating the profiles. There were, yet, some differences between the constructs. As apparent from **Figure 1**, differences in naming speed, working memory, and visual-spatial short-term memory each covered a wide performance range. This means they were good at distinguishing the profiles, as opposed to phonological awareness, which showed much less variance between the profiles. Besides the magnitude of performance differences, the level of performance itself is of interest. In this respect, a striking finding was that all profiles performed relatively low in phonological awareness, with two profiles scoring even below-average level. Phonological awareness, thus, seems to play a crucial role in all children with LD reflecting a common cognitive weakness. From an etiological point of view, this means that phonological awareness (among other factors) might be responsible for the high comorbidity between the various types of LD. It has to be acknowledged, however, that our phonological awareness tasks, which required children to operate on the phoneme level, were rather complex and cognitively demanding, which might have contributed to this result. In fact, according to Yopp's (1988) widely accepted classification, measures of phonological awareness can be separated into two subcategories (viz., simple vs. complex) based on the working memory demands required in their execution. According to this view, the three tasks used in this study pertain to the complex subcategory as they require two mental operations (e.g., in vowel substitution, first operation: isolating the /a/ vowel in a given word, second operation: substituting it by an /i/ vowel) rather than just one and thus place additional demands on working memory. This is important to mention, as previous research on transparent orthographies (e.g., Landerl and Wimmer, 2000; de Jong and van der Leij, 2003) has suggested that initial deficits in phonological awareness might not be persistent in children with LD throughout development. Rather, in later years, they seem to depend on the complexity of the tasks used. Specifically, whereas deficits on the rhyme and syllable level do not seem to be evident after the first years of schooling, complex phonological awareness measures that require several mental operations continue to pose a challenge for children with LD even in later years. These developmental changes are generally explained as resulting from the transparency of the German orthography and the synthetic phonics teaching approach often used in German schools, which enables even struggling learners to acquire basic competencies in phonological awareness (cf. Landerl and Wimmer, 2000).

Another noteworthy finding regarding the performance level is that none of the profiles showed a weakness in inhibition or semantic language skills, as even the lowest-performing profiles performed way above the 25th percentile. This suggests that deficits in semantic language skills and/or inhibition might not represent a main problem in *third-graders* with LD – a finding that should, however, be validated further by future studies. This is especially important since this study did not sufficiently cover the broad construct of language: Whereas vocabulary and morphology are indicators for semantic language skills, phonological awareness is an aspect of the phonology of a language. However, language proficiency clearly also includes aspects of pragmatics or prosody, which were not assessed in this study. And even within the domain of vocabulary and morphology, it has to be acknowledged that the two subtests used in this study only provide a broad screening for language problems. This is because morphological rules are not only relevant for the plural formation of nouns, but, for example, also play a role in the formation of verbs and adjectives. Likewise, there might be differences between a child's receptive and expressive vocabulary skills. Against this backdrop, the language profiles of children with LD should therefore be explored more comprehensively in future studies. Likewise, from a developmental perspective, it cannot be ruled out that deficits in semantic language skills or inhibition exist at children's earlier developmental stages, but are not evident anymore when the LD becomes manifest. For instance, Snowling et al. (2021) recently demonstrated that language deficits at kindergarten age are a long-term predictor and thus an early cognitive marker for LD at the age of 9. Taken together, it is possible that language skills are a good longitudinal predictor of LD (as shown by Snowling et al., 2021), but might not necessarily also be a comparabley good concurrent predictor of LD (as shown in our study). In this respect, deficits in language skills may constitute a marker for LD only at a particular developmental stage. This would suggest a discontinuity in symptoms and cognitive causes of LD throughout child development, just like the discontinuity sometimes found in clinical developmental psychology research between childhood and adult psychopathology (Rutter et al., 2006).

Concerning our second research question, we found some support for the specificity of the cognitive profiles, as profile membership classification significantly differed between LD groups. Children with MD-only were most frequently represented in profile 4 (single attention deficit, 40%) and profile 1 (comprehensive cognitive deficits, 18%). Interestingly, both were the profiles with the lowest performance in visual-spatial short-term memory–although only profile 1 reached the cut-off score of percentile ≤25. This finding suggests that the majority of children with MD-only, namely 58%, show relatively low performance in the storing and processing of visual and spatial information, which highlights the crucial role of the visual-spatial short-term memory as a domain-specific skill in the learning of mathematics. Given the close relationship between visual-spatial and mathematical skills, this is well in line with theoretical models suggesting cognitive deficits in visual-spatial memory and visual-spatial attention processing as one of the causes leading to MD (e.g., Geary, 2010). In their literature review, for instance, Hubbard et al. (2005) present robust neural and behavioral evidence for a deep numerical-spatial connection in the brain, which is responsible for the automatic activation of spatial representations in the parietal lobe whenever numbers are presented and processed—even when spatial information is not primarily relevant to the numerical task. According to this view, the visual-spatial short-term memory serves as a mental blackboard to assist and process number information, relevant for counting and solving arithmetic tasks but also for mathematical problem solving in general (cf. Alloway and Passolunghi, 2011).

Children with RD-only were with almost 30% most often placed in profile 3, which comprised children with a double deficit in phonological awareness and rapid automatized naming. This finding converges nicely with the vast amount of research on variable-centered approaches, in which this particular profile has become prominent under the so-called "*double deficit* *hypothesis of RD*" (Wolf and Bowers, 1999). The importance of phonological awareness and rapid automatized naming for the acquisition and development of reading skills can be explained in several ways: The awareness of phonemes is needed to understand the correspondence and blending rules between graphemes, namely letters or letter strings, and phonemes, that is sounds, especially important in the alphabetical phase of reading acquisition and when reading unknown words (Nagler et al., 2018). Moreover, phonological awareness seems to be relevant for the buildup of stable orthographical representations relevant in reading fluency (cf. Share, 2008). This seems to be especially true for transparent orthographies such as German, for which orthographic representations are organized at the phonemic level (cf. Goswami, 1997). For a similar reason, naming speed is considered to facilitate reading fluency as it may assess how seeing a familiar written word leads to the rapid activation of its lexical entry through the process of phonological recoding (cf. Wagner, 1986). That is, children with a large sight vocabulary who rapidly retrieve entire words are able to read with greater efficiency than children who use an effortful letter-by-letter decoding strategy.

Children with WD-only were with 38% most frequently grouped in profile 5, which consisted of children without any cognitive deficits but a relative weakness in phonological awareness. The children's relatively low performance in phonological awareness is in line with some variable-centered studies (e.g., Wimmer and Schurz, 2010) suggesting problems in the discrimination and manipulation of language sounds as a cause in the development of WD. This seems reasonable, as phonological awareness is crucial in the buildup of phoneme-to-grapheme correspondence rules relevant in spelling (Moll and Landerl, 2009). In addition, phonological awareness is drawn upon when children apply orthographic rules to derive the correct spelling of words. For instance, Landerl (2003) demonstrated that the ability to correctly perceive and discriminate vowel lengths in spoken German is an important phonological awareness skill required in applying the difficult German spelling rules to mark short and long vowels. However, the otherwise strong cognitive profile of the children was surprising: Given that (except for rapid automatized naming) all cognitive functioning skills were assessed in this study using standardized and norm-referenced measures, children of profile 5 seem to perform at the normative average of German third-graders. This leads to the question of whether this group might exhibit specific deficits in cognitive skills not assessed in this study, which may explain why the children developed their learning problems. Future studies should address this possibility by, for instance, including tasks pertaining to orthographic processing rather than just phonological processing.

Another important finding concerned the severity of LD: Narrow cognitive deficits (profile 4 and 5) were mostly found in single LD, whereas broad cognitive deficits (profile 1 to 3) were more likely to be found in comorbid forms of LD. This is further evidence to suggest that an accumulation of cognitive risk factors underlies comorbid LD. Nevertheless, even in the most affected cognitive profile 1, approximately half of the children showed an LD in only one academic domain. This leads to the question of whether these children possess particular (environmental) resilience factors that had prevented them from developing comorbid forms of LD despite their wide range of poor cognitive functioning skills. The same—yet in the opposite direction—, applies to children of profile 5, who showed an LD despite cognitive strengths in the functioning skills relevant in mathematics and written language: It might be that environmental risk factors such as low SES or a non-supportive educational environment in the children's home might partly be responsible for these children's learning problems.

Lastly, we also examined the role of IQ-achievement discrepancy in profile membership classification and found that IQ-discrepant children were more likely to be grouped in profile 5 displaying cognitive strengths than in profile 1 showing comprehensive cognitive deficits compared to the non-discrepant poor learners. For struggling learners, having a high IQ thus seems to be a protective factor in the cognitive functioning facets relevant in the acquisition of mathematics and written language skills (cf. van der Leij et al., 2013). At the same time, the lower association of their domain-specific and domain-general cognitive functioning with academic achievement may suggest that these children's learning problems are indeed "unexpected"—supporting the definition of ICD-11. Additional support for the validity of the IQ-achievement discrepancy criterion with respect to cognitive functioning comes from O'Brien et al. (2012)—the only other person-centered study we found in the literature examining the role of IQ-achievement discrepancy in capturing the cognitive heterogeneity underlying LD. Nevertheless, from an educational point of view, both groups of poor learners are clearly in need of special support and should, therefore, be equally eligible for respective services.

## Implications

Taken together, the finding of specific associations between the LD types and the identified cognitive profiles is not in line with a strict interpretation of the current DSM-5 classification, according to which a more even (or almost equal) distribution of the LD types would have been expected. Rather, the results show higher cognitive similarities within a particular LD group than between LD groups, which is of theoretical importance in understanding the differences between different types of LD. For instance, a cognitive deficit profile typically underlying MD-only (viz., profile 4) can be distinguished from a specific cognitive cluster predominantly associated with RD-only (profile 3). Besides its theoretical importance, this finding has implications for clinical practice. It taps into the ongoing debate in current LD research, whether or not the inclusion of cognitive functioning skills in the diagnostic process has the potential to assist in a more elaborated diagnosis of LD and in differentiating its various subtypes (e.g., Kavale et al., 2005). With respect to this debate, we suggest that our finding of specific cognitive clusters would generally support such an approach. Nonetheless, the cognitive profiles were far from being entirely consistent with the LD group, which in turn is not in line with a strict interpretation of ICD-11 either, highlighting the importance of addressing the child's individual etiology in the diagnosis of LD: Knowing the academic problems of a child (e.g., whether a child struggles with mathematics or with reading) may to some extent allow for reasonable inferences about the child's underlying cognitive deficits evoking the learning problems. Yet, those inferences may not be valid for an individual child. Rather, only a comprehensive diagnostic that incorporates the domain-specific and domain-general cognitive skills relevant in LD *in addition* to the academic skills can help practitioners to understand the individual pattern of strengths and weaknesses. This informs about the extent to which specific cognitive deficits typically associated with a specific LD subtype play a role for that particular child.

Moreover, our findings have implications for the allocation of support. Learning interventions appear not effective when they directly focus (only) on cognitive deficitis (e.g., working memory, rapid automatized naming), but rather need to address the skills and processes directly related to reading, writing, and mathematics (Hasselhorn, 2021). However, first evidence suggests that knowing the specific pattern and severity of cognitive functioning deficits of a particular child with LD could assist practitioners in providing the necessary amount of remedial support. For instance, using growth curve modeling, Frijters et al. (2011) predicted the responsiveness to intervention for children with RD and found that the inclusion of cognitive functioning skills in the prediction substantially improved the accuracy of differentiating between good and poor responders. Thus, a comprehensive diagnostic of cognitive functioning skills may assist in the allocation of educational support by informing educators and practitioners which children are likely to overcome their learning difficulties when provided additional in-class support by their teachers, and which children are in need of a more in-depth and longer support. Understanding the different competency profiles could also be helpful in selecting and shaping interventions that suit children's strengths and weaknesses by taking these into account.

## Limitations and Directions for Future Research

Although this study contributes to understanding the cognitive heterogeneity among the various LD types, the results should be interpreted in light of some limitations. First of all, since we did not have the possibility to recruit a nation-wide sample of children with LD, it might be that our results do not generalize to the whole population of third-graders with LD in Germany. Secondly, since we did not have a norm-reference measure to assess naming speed, we standardized the rapid automatized naming task on our own sample. Yet, as our sample consisted of children with LD only, the resulting T-scores cannot be interpreted in the same way as those for the other cognitive skills, which were based on representative norming samples. Instead, the children's performance in naming speed is likely to be overestimated, as a mean performance of $T = 50$ in our sample would most likely not converge with a T-score of 50 in a representative sample but would be biased downwards. This might be one of the reasons why poor naming skills (defined as T-scores $\leq 43.3$ or percentile $\leq 25$) emerged in only one of the five latent profiles. For example, we cannot rule out that profile 2 (double deficit in phonological awareness and phonological short-term memory), which showed the second lowest performance in rapid automatized naming in this study with a mean of $T = 47.84$, might in fact also have met the cut-off point of percentile $\leq 25$ if a representative norming sample had been used for standardization.

Thirdly, although we included a wide range of measures prominent in current LD research, our selection of cognitive skills entered in the LPA was still limited. Especially the inclusion of additional domain-specific measures in the mathematical domain such as magnitude comparison and basic number processing rather than only visual-spatial short-term memory would be worthy to consider in future studies as those skills have not only been found to contribute largely to mathematical skill development in general (e.g., Lonnemann et al., 2011), but also to differentiate between children with and without MD in previous person-centered approaches (e.g., de Souza Salvador et al., 2019). For instance, it seems reasonable to assume that profile 4 (single attention deficit and at risk of visual-spatial short-term memory), which was after all to 40% made up of children with MD-only, may show additional at-risk performance (or even deficits) in these domain-specific skills relevant in mathematics. Lastly, longitudinal studies assessing the cognitive functioning skills multiple times in the course of children's development are necessary to draw conclusions on the stability of the identified profiles over time. Likewise, longitudinal studies examining the persistency of the learning problems over the school career could provide additional insights into the severity of the children's learning problems and may address the research question of whether the cognitive functioning profiles are differentially associated with persistent and non-persistent LD.

## Conclusion

To sum up, the results of the present analyses corroborate the view that various types of LD are associated with distinct cognitive functioning profiles. Nonetheless, the identified profiles were not entirely consistent with LD subgroups. This might be due to reliability issues or other methodological shortcomings. However, we prefer the interpretation, that this highlights the importance of addressing the child's individual etiology in the diagnosis of LD: Knowing the academic problems of a child (e.g., whether a child struggles with mathematics or with reading) may to some extent—but not exclusively—allow making reasonable inferences with respect to the child's underlying cognitive deficits evoking the learning problems.

# DATA AVAILABILITY STATEMENT

The generated datasets are available by request to the corresponding author.

# ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

## AUTHOR CONTRIBUTIONS

JB performed the statistical analyses with the help of SH. The results were discussed and interpreted by all authors. JB wrote the first draft of the manuscript, which was revised by MH, SH, and LV with regard to content and language. All authors jointly developed the research questions of the manuscript.

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## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2021.725374/full#supplementary-material

## REFERENCES

Alloway, T. P., and Passolunghi, M. C. (2011). The relationship between working memory, IQ, and mathematical skills in children. *Learn. Individ. Differ.* 21, 133–137. doi: 10.1016/j.lindif.2010.09.013

American Psychiatric Association (2013). *Diagnostic and Statistical Manual of Mental Disorders – DSM-5*. 5th Edn. Washington, DC: American Psychiatric Association.

Archibald, L. M. D., Cardy, J. O., Ansari, D., Olino, T., and Joanisse, M. F. (2019). The consistency and cognitive predictors of children's oral language, reading, and math learning profiles. *Learn. Individ. Differ.* 70, 130–141. doi: 10.1016/j.lindif.2019.02.003

Asparouhov, T., and Muthén, B. O. (2020). "Auxiliary variables in mixture modeling: Using the BCH method in Mplus to estimate distal outcome model and an arbitrary secondary model," in *Mplus Web Notes: No. 21. May 14, 2014. Revised December 23, 2020.*

Birkel, P. (2007). *Weingartener Grundwortschatz Rechtschreib-Test für zweite und dritte Klassen – WRT 2+ [Weingarten's Spelling Test of Basic Vocabulary for Second and Third Grade]*. Göttingen, Germany: Hogrefe.

Bosse, M. L., Tainturier, M. J., and Valdois, S. (2007). Developmental dyslexia: The visual attention span deficit hypothesis. *Cognition* 104, 198–230. doi: 10.1016/j.cognition.2006.05.009

Büttner, G., and Hasselhorn, M. (2011). Learning disabilities: debates on definitions, causes, subtypes, and responses. *Int. J. Disabil. Dev. Educ.* 58, 75–87. doi: 10.1080/1034912X.2011.548476

Capin, P., Cho, E., Miciak, J., Roberts, G, and Vaughn, S. (2021). Examining the reading and cognitive profiles of students with significant reading comprehension difficulties. *Learn. Disabil. Q.* 44, 183–196. doi: 10.1177/0731948721989973

Carreti, B., Borella, E., Cornoldi, C., and de Beni, R. (2009). Role of working memory in explaining the performance of individuals with specific reading comprehension difficulties: a meta-anaylsis. *Learn. Individ. Differ.* 19, 246–251. doi: 10.1016/j.lindif.2008.10.002

Cattell, R. B., Weiß, R. H., and Osterland, J. (1997). *Grundintelligenztest Skala 1 – CFT 1 [Basic intelligence test scale 1]*. 5th Edn. Göttingen, Germany: Hogrefe.

David, C. V. (2012). Working memory deficits in math learning difficulties: a meta-analysis. *Int. J. Dev. Disabil.* 58, 67–84. doi: 10.1179/2047387711Y.0000000007

de Jong, P.F., and van der Leij, A. (2003). Developmental changes in the manifestation of a phonological deficit in dyslexic children learning to read a regular orthography. *J. Educ. Psychol.* 95, 22–40. doi: 10.1037/0022-0663.95.1.22

de Souza Salvador, L., Moura, R., Wood, G., and Geraldi Haase, V. (2019). Cognitive heterogeneity of math difficulties: a bottom-up classification approach. *J. Numerical Cogn.* 5, 55–85. doi: 10.5964/jnc.v5i1.60

den Bos, I.F-,v., van der Ven, S.H.G., Kroesbergen, E.H., and van Luit, J.E.H. (2013). Working memory and mathematics in primary school children: a meta-analysis. *Educ. Res. Rev.* 10, 29–44. doi: 10.1016/j.edurev.2013.05.003

Frijters, J. C., Lovett, M. W., Steinbach, K. A., Wolf, M., Sevcik, R. A., and Morris, R. D. (2011). Neurocognitive predictors of reading outcomes for children with reading disabilities. *J. Learn. Disabil.* 44, 150–166. doi: 10.1177/0022219410391185

Geary, D. C. (2010). Mathematical disabilities: reflections on cognitive, neuropsychological, and genetic components. *Learn. Individ. Differ.* 20, 130–133. doi: 10.1016/j.lindif.2009.10.008

Goswami, U. (1997). "Learning to read in different orthographies: Phonological awareness, orthographic representations and dyslexia," in *Dyslexia: Biology, identification and Intervention*, eds C. Hulme and M. J. Snowling (London, UK: Singular), 131–152.

Gray, S., Fox, A. B., Green, S., Alt, M., Hogan, T. P., Petscher, Y., et al. (2019). Working memory profiles of children with dyslexia, developmental language disorder, or both. *J. Speech Lang. Hear. Res.* 62, 1839–1858. doi: 10.1044/2019_JSLHR-L-18-0148

Gresham, F. M., and Vellutino, F. R. (2010). What is the role of intelligence in the identification of specific learning disabilities? Issues and clarifications. *Learn. Disabil. Res. Pract.* 25, 194–206. doi: 10.1111/j.1540-5826.2010.00317.x

Grob, A., Meyer, C. S., and Hagmann-von Arx, P. (2009). *Intelligence and Development Scales (IDS): Intelligenz- und Entwicklungsskalen für Kinder von 5-10 Jahren. [Intelligence and Developmental Sclaes for Children From 5 to 10 Years]*. Bern, Switzerland: Huber.

Hasselhorn, M. (2021). Lernstörungen: Ein unvermeidbares Schicksal? [Learning disorders: An unavoidable fate?]. *Zeitschrift für Pädagogische Psychologie*. 1–7. doi: 10.1024/1010-0652/a000324

Hasselhorn, M., Mähler, C., and Grube, D. (2008). "Lernstörungen in Teilleistungsbereichen [Learning disabilities in specific domains]," in *Entwicklungspsychologie*, eds R. Oerter and L. Montada (Weinheim, Germany: Psychologie Verlagsunion), 769–778.

Hasselhorn, M., Schumann-Hengsteler, R., Gronauer, J., Grube, D., Mähler, C., Schmid, I., et al. (2012). *Arbeitsgedächtnistestbatterie für Kinder von 5 bis 12 Jahren (AGTB 5–12) [Working memory test battery for children aged five to twelve years]*. Göttingen, Germany: Hogrefe.

Hickendorff, M., Edelsbrunner, P. A., McMullen, J., Schneider, M., and Trezise, K. (2018). Informative tools for characterizing individual differences in learning: Latent class, latent profile, and latent transition analysis. *Learn. Individ. Differ.* 66, 4–15. doi: 10.1016/j.lindif.2017.11.001

Hubbard, E. M., Piazza, M., Pinel, P., and Dehaene, S. (2005). Interactions between number and space in parietal cortex. *Nat. Rev. Neurosci.* 6, 435–448. doi: 10.1038/nrn1684

Huijsmans, M. D. E., Kleemans, T., van der Ven, S. H. G., and Kroesbergen, E. H. (2020).The relevance of subtyping children with mathematical learning disabilities. *Res. Dev. Disabil.* 104:103704. doi: 10.1016/j.ridd.2020.103704

Kavale, K. A., Holdnack, J. A., and Mostert, N. P. (2005). Responsiveness to intervention and the identification of specific learning disabilities: a critique and alternative proposal. *Learn. Disabil. Q.* 28, 2–16. doi: 10.2307/4126970

Kißler, C., Schwenck, C., and Kuhn, J.-T. (2020). Zur Additivität kognitiver Defizitprofile bei komorbiden Lernstörungen [On additivity of cognitive deficit profiles in children with comorbid learning disorders]. *Lernen und Lernstörungen*. 10, 89–101. doi: 10.1024/2235-0977/a000310

Klicpera, C., Schabmann, A., and Gasteiger-Klicpera, B. (2010). *Legasthenie – LRS: Modelle, diagnose, therapie und förderung [Dyslexia: Models, Diagnosis, Therapy and Intervention]*. München, Germany: Reinhardt.

Kohn, J., Wyschkon, A., Ballaschk, K., Ihle, W., and Esser, G. (2013). Verlauf von umschriebenen Entwicklungsstörungen: Eine 30-Monats-Follow-up-Studie. *[*Long-term course of dyslexia, dyscalculia and expressive language disorder: A 30-month follow-up study*]. Lernen und Lernstörungen* 2, 77–89. doi: 10.1024/2235-0977/a000032

Koponen, T., Georgiou, G., Salmi, P., Leskinen, M., and Aro, M. (2017). A meta-analysis of the relation between RAN and mathematics. *J. Educ. Psychol.* 109, 977–992. doi: 10.1037/edu0000182

Krajewski, K., Liehm, S., and Schneider, W. (2004). *Deutscher Mathematiktest für zweite Klassen (DEMAT 2+) [German Test of Mathematical Skills for Second Grades]*. Göttingen, Germany: Beltz.

Kudo, M. F., Lussier, C. M., and Swanson, H. L. (2015). Reading disability in children: a selective meta-anaylsis of the cognitive literature. *Res. Dev. Disabil.* 40, 51–62. doi: 10.1016/j.ridd.2015.01.002

Landerl, K. (2003). Categorization of vowel length in German poor spellers: an orthographically relevant phonological distinction. *Appl. Psycholinguist.* 24, 523–538. doi: 10.1017/S0142716403000262

Landerl, K., Fussenegger, B., Moll, K., and Willburger, E. (2009). Dyslexia and dyscalculia: two learning disorders with different cognitive profiles. *J. Exp. Child Psychol.* 103, 309–324. doi: 10.1016/j.jecp.2009.03.006

Landerl, K., and Wimmer, H. (2000). Deficits in phoneme segmentation are not the core problem of dyslexia: evidence from German and English children. *Appl. Psycholinguist.* 21, 243–262. doi: 10.1017/S0142716400002058

Lenhard, W., and Schneider, W. (2006). *Ein Leseverständnistest für Erst- bis Sechstklässler (ELFE 1–6) [A Reading Comprehension Test for First to Sixth Graders]*. Göttingen, Germany: Hogrefe.

Lonnemann, J., Linkersdörfer, J., Hasselhorn, M., and Lindberg, S. (2011). Neurokognitive Korrelate der Dyskalkulie [Neurocognitive correlates of dyscalculia]. *Kindheit und Entwicklung* 20, 13–20. doi: 10.1026/0942-5403/a000036

Meyer, M. S. (2000). The ability–achievement discrepancy: does it contribute to an understanding of learning disabilities? *Educ. Psychol. Rev.* 12, 315–337. doi: 10.1023/A:1009070006373

Moll, K., Bruder, J., Kunze, S., Neuhoff, N., and Schulte-Körne, G. (2014). Specific learning disorder: Prevalence and gender differences. *PLoS ONE* 9:e103537. doi: 10.1371/journal.pone.0103537

Moll, K., and Landerl, K. (2009). Double dissociation between reading and spelling deficits. *Sci. Stud. Read.* 13, 359–382. doi: 10.1080/10888430903162878

Muthén, L.K., and Muthén, B.O. (1998-2019). *Mplus User's Guide*. 8th Edn. Los Angeles, CA: Muthén & Muthén

Nagler, T., Lindberg, S., and Hasselhorn, M. (2018). Leseentwicklung im Grundschulalter. *Kognitive Grundlagen und Risikofaktoren*. [Reading development in children. Cognitive preconditions and risk factors]. *Lernen und Lernstörungen* 7, 33–44. doi: 10.1024/2235-0977/a000185

Niileksela, C. R., and Templin, J. (2018). Identifying dyslexia with confirmatory latent profile analysis. *Psychol. Sch.* 56, 335–359. doi: 10.1002/pits.22183

Nunnally, J. C., and Bernstein, I. H. (1994). *Psychometric Theory*. 3rd Edn. New York, NY: McGraw-Hill.

Nylund, K. L., Asparouhov, T., and Muthén, B. O. (2007). Deciding on the number of classes in latent class analysis and growth mixture modeling: a Monte Carlo simulation study. *Struct. Eq. Model. Multidiscip. J.* 14, 535–569. doi: 10.1080/10705510701575396

O'Brien, B. A., Wolf, M., and Lovett, M. W. (2012). A taxometric investigation of developmental dyslexia subtypes. *Dyslexia* 18, 16–39. doi: 10.1002/dys.1431

O'Malley, K. J., Francis, D. J., Foorman, B. R., Fletcher, J. M., and Swank, P. R. (2002). Growth in precursor and reading-related skills: do low-achieving and IQ-discrepant readers develop differently? *Learn. Disabil. Res. Pract.* 17, 19–34. doi: 10.1111/1540-5826.00029

Peng, P., and Fuchs, D. (2016). A meta-analysis of working memory deficits in children with learning difficulties: is there a difference between verbal domain and numerical domain? *J. Learn. Disabil.* 49, 3–20. doi: 10.1177/0022219414521667

Peng, P., Lin, X., Ünal, Z. E., Lee, K., Namkung, J., Chow, J., et al. (2020). Examining the mutual relations between language and mathematics: a meta-analysis. *Psychol. Bull.* 146, 595–634. doi: 10.1037/bul0000231

Petermann, F. (2010). *Sprachstandserhebungstest für Kinder im Alter zwischen 5 und 10 Jahren (SET 5-10). [Language Proficiency Test for Children Aged 5 to 10 Years]*. Göttingen, Germany: Hogrefe.

Pieters, S., Roeyers, H., Rosseel, Y., Van Waelvelde, H., and Desoete, A. (2015). Identifying subtypes among children with developmental coordination disorder and mathematical learning disabilities, using model-based clustering. *J. Learn. Disabil.* 48, 83–95. doi: 10.1177/0022219413491288

Raghubar, K. P., Barnes, M. A., and Hecht, S. A. (2010). Working memory and mathematics: A review of developmental, individual difference, and cognitive approaches. *Learn. Individ. Differ.* 20, 110–122. doi: 10.1016/j.lindif.2009.10.005

Rutter, M., Kim-Cohen, J., and Maughan, B. (2006). Continuities and discontinuities in psychopathology between childhood and adult life. *Child Psychol. Psychiatry* 47, 276–296. doi: 10.1111/j.1469-7610.2006.01614.x

Schuchardt, K., Kunze, J., Grube, D., and Hasselhorn, M. (2006). Arbeitsgedächtnisdefizite bei Kindern mit schwachen Rechen- und Schriftsprachleistungen [Working memory deficits in children with low calculating and spelling performance]. *Zeitschrift für Pädagogische Psychologie* 20, 261–268. doi: 10.1024/1010-0652.20.4.261

Share, D.L. (2008). Orthographic learning, phonological recoding, and self-teaching. *Adv. Child Dev. Behav.* 36, 31–82. doi: 10.1016/S0065-2407(08)00002-5

Snowling, M. J., Hulme, C., and Nation, K. (2020). Defining and understanding dyslexia: past, present and future. *Oxford Rev. Educ.* 46, 501–513. doi: 10.1080/03054985.2020.1765756

Snowling, M. J., and Melby-Lervåg, M. (2016). Oral language deficits in familial dyslexia: A meta-analysis and review. *Psychol. Bull.* 142, 498–545. doi: 10.1037/bul0000037

Snowling, M. J., Moll, K., and Hulme, C. (2021). Language difficulties are a shared risk factor for both reading disorder and mathematics disorder. *J. Exp. Child Psychol.* 202:105009. doi: 10.1016/j.jecp.2020.105009

Stock, C., Marx, P., and Schneider, W. (2003). *Basiskompetenzen für Lese-Rechtschreibleistungen: Ein Test zur Erfassung der phonologischen Bewusstheit vom ersten bis vierten Schuljahr (BAKO 1–4) [Basic competencies of reading and spelling skills: A test assessing phonological awareness from first to fourth grade]*. Göttingen, Germany: Beltz.

Strehlow, U., and Haffner, J. (2002). Definitionsmöglichkeiten und sich daraus ergebende Häufigkeit der umschriebenen Lese- bzw. Rechtschreibstörung – theoretische Überlegungen und empirische Befunde an einer repräsentativen Stichprobe junger Erwachsener [Alternative definitions and the resulting prevalence rates of spelling disorder – Theoretical considerations and empirical findings in an epidemiological sample of adolescents and young adults]. *Zeitschrift für Kinder- und Jugendpsychiatrie und Psychotherapie* 30, 113–126. doi: 10.1024//1422-4917.30.2.113

Stuebing, K. K., Fletcher, J. M., LeDoux, J. M., Lyon, G. R., Shaywitz, S. E., and Shaywitz, B. A. (2002). Validity of IQ-discrepancy classifications of reading disabilities: a meta-analysis. *Am. Educ. Res. J.* 39, 469–518. doi: 10.3102/00028312039002469

Swanson, H. L., and Jerman, O. (2006). Math disabilities: a selective meta-analysis of the literature. *Rev. Educ. Res.* 76, 249–274. doi: 10.3102/00346543076002249

Swanson, H. L., Zheng, X., and Jerman, O. (2009). Working memory, short-term memory, and reading disabilities: a selective meta-analysis of the literature. *J. Learn. Disabil.* 42, 260–287. doi: 10.1177/0022219409331958

Tafti, M. A., Boyle, J. R., and Crawford, C. M. (2014). Meta-analysis of visual-spatial deficits in dyslexia. *Int. J. Brain Cogn. Sci.* 3, 25–34. doi: 10.5923/j.ijbcs.20140301.03

Tannock, R. (2013). Rethinking ADHD and LD in DSM-5: proposed changes in diagnostic criteria. *J. Learn. Disabil.* 46, 5–25. doi: 10.1177/0022219412464341

Tiffin-Richards, M. C., Hasselhorn, M., Woerner, W., Rothenberger, A., and Banaschewski, T. (2007). Phonological short-term memory and central executive processing in attention-deficit/hyperactivity disorder with/without dyslexia – Evidence of cognitive overlap. *J. Neural Transm.* 115, 227–234. doi: 10.1007/s00702-007-0816-3 van der Leij, A., Van Bergen, E., van Zuijen, T., De Jong, P., Maurits, N., and Maassen, B. (2013). Precursors of developmental dyslexia: an overview of the longitudinal Dutch dyslexia programme study. *Dyslexia* 19, 191–213. doi: 10.1002/dys.1463

Wagner, R. K. (1986). Phonological processing abilities and reading: implications for disabled readers. *J. Learn. Disabil.* 19, 623–630. doi: 10.1177/002221948601901009

Wang, J., and Wang, X. (2012). *Structural Equation Modeling: Applications Using Mplus*. West Sussex, UK: John Wiley & Sons.

Wimmer, H., and Mayringer, H. (2002). Dysfluent reading in the absence of spelling difficulties: a specific disability in regular orthographies. *J. Educ. Psychol.* 94, 272–277. doi: 10.1037/0022-0663.94.2.272

Wimmer, H., and Schurz, M. (2010). Dyslexia in regular orthographies: manifestation and causation. *Dyslexia* 16, 283–299. doi: 10.1002/dys.411

Wolf, M., and Bowers, P. (1999). The "Double-Deficit Hypothesis" for the developmental dyslexia. *J. Educ. Psychol.* 91, 1–24. doi: 10.1037/0022-0663.91.3.415

World Health Organization (2021). *ICD-11 for Mortality and Morbidity Statistics*. Available online at: https://www.dimdi.de/dynamic/de/klassifikationen/icd/icd-11/ (accessed June 13, 2021).

Yang, X., Shaftel, J., Glasnapp, D., and Poggio, J. (2005). Qualitative or quantitative differences? Latent class analysis of mathematical ability for special education students. *J. Special Educ.* 38, 194–207. doi: 10.1177/00224669050380040101

Yopp, H.K. (1988). The validity and reliability of phonemic awareness tests. *Read. Res. Q.* 23, 159–177. doi: 10.2307/747800

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# Development of Numeracy and Literacy Skills in Early Childhood—A Longitudinal Study on the Roles of Home Environment and Familial Risk for Reading and Math Difficulties

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This study examines the direct and indirect effects of home numeracy and literacy environment, and parental factors (parental reading and math difficulties, and parental education) on the development of several early numeracy and literacy skills. The 265 participating Finnish children were assessed four times between ages 2.5 and 6.5. Children's skills in counting objects, number production, number sequence knowledge, number symbol knowledge, number naming, vocabulary, print knowledge, and letter knowledge were assessed individually. Parents ($N$ = 202) reported on their education level, learning difficulties in math and reading (familial risk, FR), and home learning environment separately for numeracy (HNE) and literacy (HLE) while their children were 2.5 years old and again while they were 5.5 years old. The results revealed both within-domain and cross-domain associations. Parents' mathematical difficulties (MD) and reading difficulties (RD) and home numeracy environment predicted children's numeracy and literacy skill development within and across domains. An evocative effect was found as well; children's skills in counting, number sequence knowledge, number symbol identification, and letter knowledge negatively predicted later home numeracy and literacy activities. There were no significant indirect effects from parents' RD, MD, or educational level on children's skills *via* HLE or HNE. Our study highlights that parental RD and MD, parental education, and the home learning environment form a complex pattern of associations with children's numeracy and literacy skills starting already in toddlerhood.

**Keywords: numeracy skills, literacy skills, familial risk, home numeracy environment (HNE), home literacy environment (HLE)**

## INTRODUCTION

Early childhood and toddlerhood is the developmental stage when children develop at their fastest rate and are most influenced by their environments (Gerber et al., 2010). This is also when the early literacy and numeracy skills create a foundation for future reading and mathematical skill development: Symbolic and nonsymbolic numeracy skills, assessed before school entry, have been shown to predict later mathematical skills (Watts et al., 2014; Zhang et al., 2014; Koponen et al., 2016; Koponen et al., 2019; Schneider et al., 2017; Chu et al., 2018; Geary et al., 2018), and early language and literacy skills have been shown to predict reading skills (e.g., Torppa et al., 2010; Ziegler et al., 2010; Psyridou et al., 2018; Hjetland et al., 2020). Reading and mathematical development are deeply interconnected processes, and emerging evidence reveals both shared and unshared predictors of reading and mathematical skill development (e.g., Purpura et al., 2011; Davidse et al., 2014; Purpura and Ganley, 2014; Purpura et al., 2017a; Korpipää, 2020; Vanbinst et al., 2020). At school age, the comorbidity of reading difficulties (RD) and mathematical difficulties (MD) is also common: The rate of the cooccurrence of these difficulties has been estimated to be approximately 30–70% (Landerl and Moll, 2010; Moll et al., 2019). Although the estimates vary considerably, existing evidence suggests that the likelihood of this comorbidity is significantly higher than chance. However, as we still have many unanswered questions about the very early development of reading and mathematical skills, and their co-occurrence, more research is needed.

This longitudinal study sets out to examine the development of emerging literacy and numeracy skills during early childhood to better understand the foundation for reading and mathematical skills. We examine the cross-domain associations of literacy and numeracy skills by focusing on the early development of several important literacy and numeracy skills and the family factors predicting them. We aim to add to the existing knowledge on the underpinnings of literacy and numeracy development by examining the roles of home numeracy (HNE) and literacy environment (HLE), familiar risk (FR, due to parental RD and/or MD), and parents' education in children's literacy and numeracy development from age 2.5 to 6.5. To better understand the developmental relationship between literacy and numeracy abilities and the common and unique factors associated with each domain, we will identify the within-domain and cross-domain predictive associations between children's skill development, home environment, and parental RD and MD. Considering that early experiences create a significant starting point for young children's skill development, longitudinal research beginning with toddlers is particularly warranted, and existing gaps in the literature show the need to gain new insights into early predictors of literacy and numeracy skills (e.g., Napoli and Purpura, 2018, p. 597; Esmaeeli et al., 2019, p. 2395). So far, only a few studies have examined the effects of the HNE and HLE on children's literacy and numeracy skills with the effects of FR for MD and RD from a longitudinal developmental perspective, and they have been completed among older children and adolescents (e.g., Khanolainen et al., 2020).

## Home Learning Environment and its Relation to Literacy and Numeracy Skills

The home learning environment (i.e., shared parent-child activities at home) plays an important role in developing literacy and numeracy skills (e.g., Scarborough and Dobrich, 1994; Sénéchal and LeFevre, 2002; Mol and Bus, 2011; Silver et al., 2020). The home learning environment is often conceptualized as including two domains: the home literacy environment (HLE) and home numeracy environment (HNE) (e.g., Napoli and Purpura, 2018), which have mainly been examined separately as predictors of domain-specific skills (literacy skills/reading or numeracy skills/math).

Previous research has revealed within-domain associations showing that the HLE is related to literacy outcomes (Scarborough and Dobrich, 1994; Sénéchal and LeFevre, 2002; Evans and Shaw, 2008; Mol and Bus, 2011), and the HNE is related to numeracy outcomes (e.g., Kleemans et al., 2012; Susperreguy et al., 2020; Daucourt et al., 2021). Since the number of studies on HNE and numeracy development has only sparked off over the past 10 years (Daucourt et al., 2021 for meta-analysis), research focusing on the role of HNE in children's skill development remains less clear and conclusive compared with studies on HLE. Some HNE studies have not found a significant association between HNE and children's outcomes (e.g., Missall et al., 2015), while some other studies have yielded mixed findings with positive associations between HNE and skill development for certain items, but negative associations for other items (e.g., Blevins-Knaube and Musun-Miller, 1996; Skwarchuk, 2009; DeFlorio and Beliakoff, 2015). Longitudinal studies starting in toddlerhood (Baker, 2014) and later in preschool at age 3–5 (Melhuish et al., 2008) have reported HLE predicting both reading and mathematical skills later in school, and likewise, HNE predicting numeracy and definitional vocabulary outcomes (Napoli and Purpura, 2018), suggesting that HNE and HLE also relate to children's cross-domain outcomes. However, there is currently a lack of studies examining both HLE and HNE and their within- and cross-domain associations using the same dataset (as exceptions, Khanolainen et al., 2020; Manolitsis et al., 2013; Napoli and Purpura, 2018), and thus it is impossible to say whether the found cross-domain associations are unique or whether they reflect a more general quality of home environment and vanish when within-domain activities are included. Activities at home can also be a proxy of family resources and parents' educational level. In line with this suggestion, parental education is linked not only directly to a child's literacy and numeracy skills (e.g., Purpura and Reid, 2016; Esmaeeli et al., 2018; Silinskas et al., 2020), but also to the home environment, such as to the frequency of shared numeracy or literacy activities (e.g., Thompson et al., 2017; Khanolainen et al., 2020; Silinskas et al., 2020). For instance, Thompson et al.'s (2017) study, comparing the relation between specific HNE practices and children's numeracy skills across preschool-aged children (3 and 4 years old), indicated that children from families with higher parental education may engage in more mathematical activities than children from families with lower parental education, particularly at younger ages. More studies are needed to clarify the within- and cross-domain associations between the home environment and children's mathematical and reading development. Of particular importance are longitudinal studies that start early on, including both HLE and HNE, parental education, and literacy and numeracy skills.

In the studies on HLE and HNE, activities in the home environment have been further differentiated into separate categories (e.g., Scarborough and Dobrich, 1994; Sénéchal and LeFevre, 2002; Mol and Bus, 2011; Silver et al., 2020). Sénéchal and LeFevre (2002), as part of their Home Literacy Model, have introduced two categories of activities for HLE: formal and informal. Following their work, a similar model within the context of HNE was developed and evaluated by Skwarchuk et al. (2014). Formal activities are code-related activities that aim to instruct children. Informal activities are various playful activities involving print or numbers (e.g., shared reading or measuring ingredients while cooking). Evidence is accumulating to show that formal and informal activities contribute to developing skills for both literacy and numeracy (Sénéchal and LeFevre, 2014; Soto-Calvo et al., 2020) and that different practices in the home environment may relate to children's skills at various ages (Thompson et al., 2017).

Previous studies suggest that informal HLE (e.g., shared reading) and HNE practices (e.g., children's exposure to numeracy-related and play-based experiences and contents such as playing games; counting and quantity comparison) are more meaningful in supporting skill development in early childhood (e.g., Sénéchal, 2006; LeFevre et al., 2009; Hamilton et al., 2016; Thompson et al., 2017), possibly through their associations with nonsymbolic numeracy skills (Skwarchuk et al., 2014). Longitudinal studies in kindergarten through the first years of primary school have shown that for HLEs, informal literacy activities are associated with developing vocabulary knowledge and reading comprehension (e.g., Sénéchal, 2006; Torppa et al., 2007; Sénéchal et al., 2008; Sénéchal and LeFevre, 2014). Simultaneously for HNE, in two cross-sectional studies with 5 to 6 year olds, informal home numeracy practices (i.e., children's exposure to numeracy-related content such as playing games) were shown to predict children's nonsymbolic arithmetic performance (e.g., Skwarchuk et al., 2014; Mutaf Yildiz et al., 2020).

Only a handful of studies have included measures of informal HNE and HLE as predictors of literacy and numeracy skill development (e.g., Manolitsis et al., 2013; Susperreguy et al., 2020), and none have begun the investigation with toddlers. In the present study, we investigate the associations of informal HNE and HLE with children's literacy and numeracy development in a longitudinal sample in early childhood (ages 2.5 through 6.5) to examine whether the within-domain and cross-domain effects appear before children begin school in the Finnish system.

## Familial Risk for Reading and Mathematical Difficulties and Relations to Literacy and Numeracy Skills

Both RD and MD run in families (e.g., Snowling and Melby-Lervåg, 2016). This means that the children born in families where parents have difficulties in reading or mathematical skills are at higher risk to develop such difficulties themselves. The group of children with parental RD or MD are therefore often referred to as familial risk (FR) group. RD is up to 4–10 times more likely to occur in children with FR than in children without it (Puolakanaho et al., 2007; van Bergen et al., 2014; Hulme et al., 2015; Torppa et al., 2015; Esmaeeli et al., 2019). Parental MD seems to influence children's development in a similar manner, although relevant research remains scarce (Shalev and Gross-Tsur, 2001; Soares et al., 2018). It is possible that genetic FR has a direct influence on children's skills, but parental skills in reading and math may also interact with the home learning environment (Hamilton et al., 2016; Dilnot et al., 2017; Esmaeeli et al., 2018). Without sufficient parental skills, the home learning environment may not be as supportive (e.g., fewer activities where children can learn literacy or numeracy skills) in the FR families. Parental RD and MD have been shown to be transmitted through environmental factors in some studies (Petrill et al., 2005; Niklas and Scheinder, 2014; de Zeeuw et al., 2015; Hart et al., 2016; van Bergen et al., 2017), while some other studies have not found differences between the home environments of FR and non-FR families (e.g., Elbro et al., 1998; Torppa et al., 2007; Caglar-Ryeng et al., 2020). Although studies on the interaction of FR and the HLE are emerging (e.g., Esmaeeli et al., 2019), comparable research investigating the influence of FR on the HNE is almost nonexistent, and the few existing studies (Silinskas et al., 2010; Niklas and Scheinder, 2014; Khanolainen et al., 2020) were conducted with kindergarten and primary school-aged children and showed somewhat mixed results. In the study by Khanolainen et al. (2020), neither MD nor RD predicted the frequency of shared reading or parental teaching activities at home when parental education was controlled for. At the same time, Niklas and Schneider's (2014) study showed that certain informal HNE activities (e.g., playing dice, counting, and calculation games) occurred less frequently in families with MD compared with families without MD. Additionally, Silinskas et al.'s (2010) study showed that mothers' but not fathers' MD predicted their formal teaching of math in the first grade, suggesting also the need to incorporate measures of FR for both parents into studies investigating home environment effects on children's skill development (van Bergen et al., 2017). Our study focuses on the early years because that is when the associations between FR, HLE, HNE, and children's skills are likely to emerge (e.g., Hart et al., 2009; Hart et al., 2016).

## Children's Skills and Evocative Effects With Home Learning Environment

While it is widely acknowledged that both HLE and HNE contribute to children's literacy and mathematical outcomes, children's individual characteristics (i.e., their emerging literacy and mathematical skills) may also shape the home learning environment (Scarr and McCartney, 1983; Pomerantz and Eaton, 2001). The term "evocative effect" refers to adults' responses arising from their children's characteristics, such as skills or academic performance (Plomin et al., 1977; Scarr and McCartney, 1983; Rutter et al., 2006; Silinskas et al., 2013). Previous research among school-aged children has shown that the child's poorer academic skills and achievements may evoke more parental academic involvement in both HLE and HNE (Levin et al., 1997; Pomerantz and Eaton, 2001; Silinskas et al., 2020). Additionally, children with higher pre-reading skills have been shown to attract more frequent at-home reading activities by parents (Silinskas et al., 2012).

As FR operates through genes, it is also plausible that FR impacts children's skills and *via* children's skills in the home environment (e.g., Plomin et al., 1977; Rutter et al., 2006; Knafo and Jaffee, 2013; van Bergen et al., 2014). The child's skills are likely to impact how often the child participates in various learning activities (active effects on environment) and how often parents engage in shared learning activities with the child (evocative effects on environment). However, these effects of children's emerging skills have been mainly examined at the age of kindergarten or school entry (e.g., Silinskas et al., 2010), leaving early childhood an understudied area.

## THE PRESENT STUDY

This longitudinal study focuses on literacy and numeracy development during early childhood (from age 2.5–6.5). We aim to add to existing knowledge on the underpinnings of early literacy and numeracy development by examining the roles of HNE, HLE, and FR for RD and MD, and parents' education in children's literacy and numeracy development in early childhood. To better understand the developmental relationship between literacy and numeracy skills and the common and unique factors associated with each domain, we will identify the within-domain and cross-domain predictive associations between children's skill development, home environment, and parental factors (education, RD, and MD).

The research questions being studied are: 1) To what extent do parental MD and RD and their education level predict a) their children's numeracy and literacy development in early childhood, and b) HLE and HNE? 2) To what extent do HLE and HNE predict children's numeracy and literacy development in early childhood? 3) To what extent do children's early numeracy and literacy skills predict HLE and HNE? 4) Are there indirect effects from parental RD and MD and their educational level on children's numeracy and literacy development through the home environment?

## METHODS

### Participants and Procedure

The data were collected as part of the VUOKKO follow-up study (Lerkkanen and Salminen, 2015–2019). A sample of children born in 2013 ($N$ = 265; 138 male, 127 female), with their parents and early childhood education and care (ECEC) educators were recruited from one middle-sized city in Central Finland. Children's emerging math and literacy skills were assessed four times during the follow-up: Twice at toddler age T1 ($M_{Age}$ 28.73 months, $N$ = 228) and T2 ($M_{Age}$ 34.69 months, $N$ = 206), and twice further in later childhood T3 ($M_{Age}$ 64.71 months, $N$ = 188); and T4 ($M_{Age}$ 70.83 months, $N$ = 175). Parents reported on their education level and learning difficulties in mathematics and reading (familial risk, FR) and replied twice: T1 ($N$ = 202) and T3 ($N$ = 130). They also responded to several questions on the home learning environment, including items for numeracy (HNE) and literacy (HLE).

## Measures

### Emerging Numeracy Skills

The following two tasks were administered at the first two time points: counting objects and number production. These three tasks were administered at all four time points: number sequence knowledge, number symbol knowledge, and number naming.

#### *Counting Objects*

The child's counting skills (i.e., order of the number words, mastering the counting principles) were assessed with a simple counting task (modified from Hannula and Lehtinen, 2005). The task began with placing four wooden buttons on the table in front of the child, with a piece of paper blocking the visual field. The paper was removed, and the child was asked to count how many buttons there were. If the answer was correct, the child would be given 5, then 6, 8, 10, and 12 buttons to be counted. If the child counted four buttons incorrectly, the next trial was two, and if the child further failed on two, the next trial was one button. Each item included two trials. The highest number of correctly counted buttons was used as the score for the counting objects task (maximum nine points).

#### *Number Producing*

The "Give me X" task (Wynn, 1990; Wynn, 1992) was used to tap children's number concept skill. In this task, the child was asked to pick up an amount of plastic figures from a box with a lid on (e.g., Give me four strawberries). Before removing the lid and giving the child a turn, the child was asked to confirm how many strawberries they were supposed to give. The test included eight items with increasing difficulty, and each item included two trials. If the child failed in both trials for the specific item, the task was terminated. The highest number of correctly produced items produced the score used in the analysis (maximum 19 points).

#### *Number Sequences*

The child's skill in producing number sequences was measured with a verbal task (Hannula and Lehtinen, 2005). The child was asked "How long can you count?" and the child was allowed to enumerate as many numbers as possible, starting from one. If the child was reluctant or unable to start, the researcher modeled numbers from one to twelve and gave a turn to the child. The child had two trials, and the longer number sequence without mistakes was considered the score for number sequence skills in the analysis (maximum 50 points).

#### *Number Symbol Identification*

The child's number symbol identification skill was assessed with a task (Wright et al., 2006) in which the child was shown an A4-sized paper with numbers 1–10 on it in a mixed order. The child was asked to point where the requested number was. The test proceeded in segments of three numbers; if the child knew at least two number symbols, another set of three numbers was introduced. If these were correct, the child was introduced with a paper with numbers from 11 to 20 on it. The third paper included numbers from 22 to 50. If the child did not recognize at least two numbers per sheet, the task was terminated. The number of correct responses determined the score used for the analysis (maximum 12 points).

#### *Number Naming*

Number naming skills were assessed with a task (Wright et al., 2006) in which a deck of twelve cards with numbers on them was spread on the table before the child. One number at a time was pointed at, and the child was asked to tell the researcher what the number was called. The task proceeded in segments of three numbers. If the child knew two out of three numbers, three more questions were introduced. If not, the task was terminated. The number of correct responses determined the score used for the analysis (maximum 12 points).

### Emerging Literacy Skills

The following three measures on emerging literacy skills were administered at all four time points: vocabulary, print knowledge, and letter knowledge.

#### *Vocabulary*

The breadth of the child's vocabulary was assessed with the Peabody Picture Vocabulary Test-R (PPVT-Short: Dunn and Dunn, 1981). In this task, the child was shown a set of 30 A4-sized papers with four pictures on each. For each sheet of paper, the child was told a word and asked to point out which picture included the target word. The test included two practice items and 30 test items. Different words were used for T1 and T2 from T3 and T4 to better fit the measure for different age groups. The number of correct responses was used as the score for the analysis (maximum 30 points).

#### *Print Knowledge*

The child's print knowledge was assessed with the print awareness subtest of the Test of Preschool Early Literacy (TOPEL; Lonigan et al., 2007). The child was shown a set of 12 A4-sized papers with four pictures on each. Pictures could represent e.g., four different book covers, one with title written with words, one with a price tag (number symbols), and two with picture on the cover. The child's task was to point a picture with letters on it. There were twelve items in the actual test, and the child went through them all in sequence, regardless of performance. Number of correct responses was used as the score for the print knowledge task (maximum 12 points, $\alpha = 0.56, 0.74, 0.71$, and 0.66 for T1, T2, T3, and T4, respectively).

#### *Letter Knowledge*

Letter knowledge was assessed with two tasks: in T1 and T2 with the VIIVI test (Torppa et al., 2006; Lohvansuu et al., 2021) and in T3 and T4 with the ARMI test (Lerkkanen et al., 2006). In the VIIVI letter naming task, the child was asked to name letters written in capitals and presented one at a time on their own page. The child was presented with 29 letters organized in four sets (6 + 6+4 + 13 letters). The child received one point for each correct response (use of a phoneme or a letter name were both coded as correct responses). The testing always began by presenting the child with the letter expected to be most familiar to the child: the first letter of the child's own first name (maximum 29 points). The ARMI test battery includes a naming test of all 29 letters in the Finnish alphabet. The letters were presented as uppercase letters in three rows and were shown to the child one row at a time. The total score corresponded to the number of correctly named items (maximum 29 points, $\alpha = 0.51, 0.72, 0.92$, and 0.94 for T1, T2, T3, and T4, respectively).

### Parent Reported Learning Difficulties in Reading and Mathematics

One parent per each participating child responded to the questionnaire. These parents were asked to fill in a questionnaire asking if they and/or the other parent of the child had experienced learning difficulties 1) in reading or writing, and 2) in mathematics or calculation. The questionnaire included one question about their own difficulties in reading or writing, one about their own difficulties in mathematics or calculation, and the same two items concerning the other parent. The parents answered each question on a 3-point Likert scale (1 = no difficulties, 2 = some difficulties, and 3 = clear difficulties). Variables for the analysis were created based on recoding the self-reports and those of the other parent into fathers' and mothers' RD and MD according to a variable indicating which parent had completed the questionnaire (mother or father). RD and MD variables were then dichotomized so that parents who indicated either some or clear difficulties were placed in the same group with difficulties. 20 (out of 208) mothers had reading difficulties and 32 (out of 207) had mathematical difficulties. 21 (out of 202) fathers had reading difficulties and 14 (out of 200) had mathematical difficulties.

### Parent Reported Education

Parents were asked to indicate the level of their own vocational education and that of the other parent on a five-point scale {1 = no vocational education [3.4% ($N = 7$) of mothers and 9.4% ($N = 19$) of fathers], 2 = vocational school degree [30.4% ($N = 63$) of mothers and 37.9% ($N = 77$) of fathers], 3 = vocational college degree [3.4% ($N = 7$) of mothers and 6.4% ($N = 13$) of fathers], 4 = polytechnic degree [31.4% ($N = 65$) of mothers and 22.7% ($N = 46$) of fathers], 5 = university degree [31.4% ($N = 65$) of mothers and 23.6% ($N = 48$) of fathers]}. Variables for the analysis were created based on recoding the self-reports and those of the other parent into fathers' and mothers' vocational education, according to a variable indicating which parent had completed the questionnaire (mother or father).

### Parent Reported Home Learning Environment

#### *Home Literacy Environment*

Informal HLE was documented with four shared reading items in accordance with the Home Literacy Model (Sénéchal and LeFevre, 2002). The parents were asked to report how often they participated in the following activities: "viewing illustrations in a book with the child," "reading books to the child when they were going to bed," "mother reading a book or magazine with the child," "father reading a book or magazine with the child." They responded to the items using a Likert scale (1 = Not at all or rarely; 5 = Several times a day). Cronbach's alpha reliability coefficients indicated that the internal consistency of shared reading was .84 at T1 and .81 at T3.

***Home Numeracy Environment***

Parents were asked to complete the home numeracy questionnaire developed by LeFevre et al. (2009). There were seventeen items on the scale to which parents responded using a Likert scale (1 = Not at all or rarely; 5 = Several times a day). They were asked to respond to the following question: "In the past month, how often did you and your child engage in the following activities?" Not all the items functioned well across the time points of the study. Therefore, like LeFevre et al. (2009) and Mutaf Yıldız et al. (2018) we dealt with numeracy environment items by eliminating those that were rarely reported at each time point by the parents (all items to which at least 80% replied "never"). At T1, these seven items were excluded (in parentheses, the percentage of "never" responses): "Printing numbers" (87%), "Connect-the-dot activities" (100%), "Using number activity books" (88%), "Being timed" (80%), "Having your child wear a watch" (95%), "Talking about money when shopping" (84%), and "Playing with calculators" (88%). At T3, two items were discarded: "Having your child wear a watch" (88%) and "Playing with calculators" (84%). Internal consistency of the retained items was .77 (10 items) at T1 and .86 (15 items) at T3. Following the example of earlier research (LeFevre et al., 2009; Mutaf Yıldız et al., 2018), we then conducted principal component analysis (PCA) with a varimax rotation to verify the factor structure of the HNE. PCA at T1 generated a single factor, but the PCA generated a two-factor solution in T3, which accounted for 46% of the explained variance. This two-factor solution resembled the factor structure identified by Hart et al. (2016). The only difference from Hart et al. (2016) was that "being timed" loaded on a different factor. Because of this, the same labels were used as Hart et al. (2016): 1) formal numeracy environment and 2) informal numeracy environment. In this study, we focused on informal learning activities specifically, and we excluded the other items from further analysis for this reason. For consistency, we included the same HNE items at both time points. Therefore, the informal numeracy activities included these five items at T1: "Playing card games," "Making collections," "Playing board games with die or spinner," "Measuring ingredients when cooking," and "Using calendars and dates." At T3, the same items were included along with an additional item, "Talking about money when shopping" (which was too rare to be included at T1). The Cronbach's alpha reliability coefficient was 0.60 at T1 and 0.70 at T3.

## Statistical Analysis

The data were then analyzed as longitudinal path models using Mplus Version 7.3. With these models, we can examine stability over time, as well as the within-domain and cross-domain predictive direct and indirect associations between the measures, including both autoregressors and parental variables as predictors.

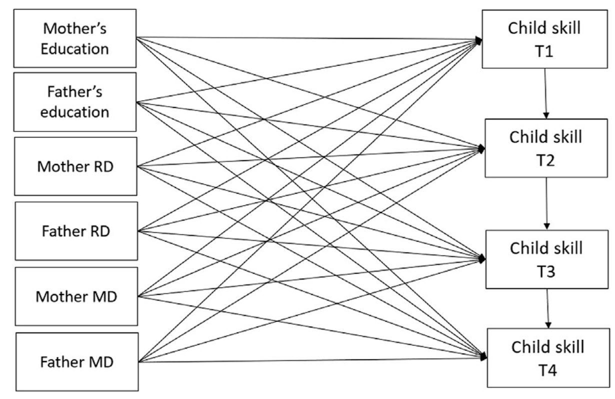


**FIGURE 1 |** The base-model for parental measures predicting children's skills.

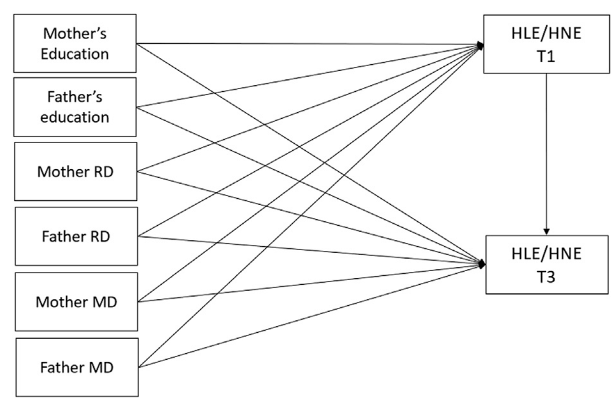


**FIGURE 2 |** The base-model for parental measures predicting HLE and HNE.

Our analysis had two main steps. In the first step, we ran models with only direct effect of parental variables on children's skills (research question 1a; **Figure 1**) and on environmental variables (research question 1b; **Figure 2**).

In the second step, we included direct and indirect effects of environmental factors and children's skills simultaneously (**Figure 3**). Eight models were fitted to the data in the second analysis step, one for each skill assessed: counting objects, number producing, number symbol identification, naming numbers, number sequences, print knowledge, vocabulary, and letter knowledge. We report models for each of the children's skills separately because the developing skills did not form a stable factor structure across time. To minimize measurement error, latent variables were created for the informal HLE and informal HNE items. All four shared reading items were loaded as indicators of the informal HLE latent factor at T1 and T3. The five HNE items at T1 and the six HNE items at T3 were loaded as indicators of the informal HNE latent factor.

The loadings for the HLE factors ranged between 0.665 and 0.858 at T1 and 0.597–0.806 at T3. The loadings for the HNE factors varied between 0.298 and 0.686 at T1 and 0.503–0.806 at

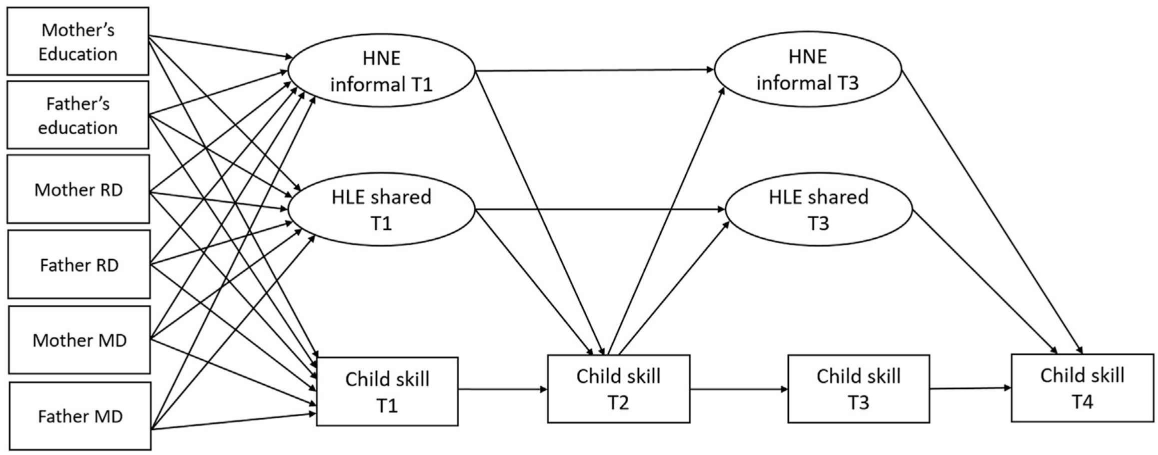


**FIGURE 3 |** The base-model for each numeracy and language skill with direct and indirect paths. Note: In addition to the regression paths depicted, the models included residual correlations between the variables in T1 and T3. In addition, specific paths from parental skills to children's skills were added for each individual skill model based on the step 1 models (**Figures 1**, **2**, and **Tables 3**, **4**).

T3. The skill assessments and parental variables were added as observed variables.

In the hypothesized model (**Figure 3**) we included stability paths between each skill and between the HLE and HNE factors, paths from parental variables to all T1 measures, and all cross-lagged paths between measures at subsequent time-points. In addition, specific paths from parental skills to children's skills were added for each individual skill model based on the step 1 models (please see **Figures 1**, **2**, and **Tables 3**, **4**). After fitting the hypothesized model (**Figure 3**) the modification indices provided by Mplus were inspected to identify possible reasons for a model misfit. All paths with modification indices above 10.00 where theoretically relevant were added to the models. Finally, we performed mediation analysis by using the delta method (MacKinnon, 2008).

# RESULTS

## Descriptive Statistics

Descriptive statistics for children's skills and parental questionnaires are reported for all the participants in **Table 1**. The table shows the rapid development of the skills during the follow-up period for all skills measured. It also shows the considerable variability between children in the sample. Among the youngest children (T1 and T2), three symbolic measure distributions (letter knowledge, number naming, and number symbol identification) were skewed to the right, as many children did not yet have the knowledge or were still at the very beginning of grasping symbolic knowledge. Therefore, in the model estimation, we used the MLR estimator, which is robust to the skewness of the distributions.

We began our analysis by checking for entry errors and outliers. No errors were found, and the few identified outliers (over three standard deviations from the mean) were windsorized. We then examined the patterns of missing data. Little's MCAR tests were conducted with all measures, and the missing data were found to be missing completely at random $x^2$ (1,097) = 1,085.52, $p$ = 0.592. In the models the missing values were handled using maximum likelihood with robust standard errors (MLR) in Mplus. Reliance on robust standard errors provides more accurate results when data are incomplete and non-normal (Savalei, 2010; Maydeu-Olivares, 2017). $N$ = 196 in all step 2 models with direct and indirect paths.

**Table 2** reports Pearson correlation coefficients between all study variables. Numeracy and literacy skills were found to be significantly correlated within and across domains from T1 onward, but the correlations became stronger over time. Similarly, HNE and HLE variables were significantly correlated with each other, and there were significant correlations with skill assessments both within and across domains. Finally, there were some significant, albeit weak, correlation coefficients between parental variables (education, parental RD, and MD), children's skills, and home environment variables.

## The Longitudinal Models

In the models constructed at the first step of our analysis (reported in **Tables 3**, **4**), different parental variables (education, RD, and MD) were significant predictors of both children's skills and environmental factors at different time points. The models also showed significant stability correlations in children's skills and in HNE and HLE across time. For research question 1a on the effect of parental variables on children's skill, please see more details for each skill in their respective models below.

Regarding the effect of parental variables (education, RD, and MD) on HLE and HNE (research question 1b), three types of effects were found. First, mothers' education positively predicted T3 HLE (over and above HLE at T1), suggesting that the higher the mother's education level was, the more they increased shared reading with their children from age 2.5–5.5 years. Second, the fathers' RD predicted less shared reading at home at T1. Third, a

**TABLE 1 |** Descriptive statistics for all variables across time.

| | N | Minimum | Maximum | Mean | Sd | Skewness | Kurtosis |
|---|---|---|---|---|---|---|---|
| Numeracy skills (raw scores) | | | | | | | |
| Counting objects | | | | | | | |
| T1: 2.5 years | 226 | 0 | 8 | 1.87 | 1.87 | 0.77 | −0.55 |
| T2: 3.5 years | 203 | 0 | 9 | 3.31 | 3.31 | 0.41 | −0.68 |
| Number production | | | | | | | |
| T1: 2.5 years | 228 | 0 | 8 | 1.19 | 1.44 | 1.30 | 2.80 |
| T2: 3.5 years | 204 | 0 | 9 | 2.12 | 1.85 | 0.97 | 1.82 |
| Number sequences | | | | | | | |
| T1: 2.5 years | 225 | 0 | 11 | 2.52 | 3.02 | 1.23 | −0.53 |
| T2: 3.5 years | 204 | 0 | 19 | 4.09 | 4.45 | 1.21 | −0.98 |
| T3: 5.5 years | 186 | 0 | 50 | 29.43 | 15.63 | 0.20 | −1.38 |
| T4: 6.5 years | 173 | 5 | 50 | 34.49 | 14.00 | −0.19 | −1.46 |
| Number symbol identification | | | | | | | |
| T1: 2.5 years | 226 | 0 | 9 | 0.38 | 1.08 | 4.98 | 30.92 |
| T2: 3.5 years | 204 | 0 | 10 | 0.72 | 1.66 | 3.59 | 14.69 |
| T3: 5.5 years | 188 | 0 | 12 | 8.19 | 3.57 | −0.74 | −0.57 |
| T4: 6.5 years | 175 | 0 | 12 | 9.65 | 2.86 | −1.26 | 0.75 |
| Number naming | | | | | | | |
| T1: 2.5 years | 226 | 0 | 6 | 0.43 | 1.04 | 3.30 | 11.88 |
| T2: 3.5 years | 204 | 0 | 7 | 0.82 | 1.38 | 2.39 | 6.13 |
| T3: 5.5 years | 187 | 0 | 12 | 8.19 | 3.50 | −0.64 | −0.69 |
| T4: 6.5 years | 174 | 0 | 12 | 9.76 | 2.84 | −1.20 | 0.56 |
| Literacy skills (raw scores) | | | | | | | |
| Vocabulary | | | | | | | |
| T1: 2.5 years | 227 | 0 | 18 | 9.57 | 3.00 | −0.01 | 0.69 |
| T2: 3.5 years | 204 | 2 | 22 | 11.57 | 3.30 | 0.32 | 0.44 |
| T3: 5.5 years | 188 | 5 | 25 | 15.52 | 3.40 | 0.18 | 0.06 |
| T4: 6.5 years | 175 | 9 | 25 | 18.03 | 3.34 | 0.18 | −0.27 |
| Print knowledge | | | | | | | |
| T1: 2.5 years | 227 | 0 | 9 | 3.17 | 2.06 | 0.64 | 0.20 |
| T2: 3.5 years | 206 | 0 | 12 | 3.72 | 2.27 | 0.79 | 0.73 |
| T3: 5.5 years | 188 | 3 | 12 | 9.65 | 2.25 | −0.87 | −0.09 |
| T4: 6.5 years | 175 | 6 | 12 | 10.90 | 1.56 | −1.54 | 1.39 |
| Letter knowledge | | | | | | | |
| T1: 2.5 years | 227 | 0 | 22 | 0.87 | 3.46 | 5.08 | 25.98 |
| T2: 3.5 years | 205 | 0 | 27 | 1.51 | 4.55 | 4.35 | 19.14 |
| T3: 5.5 years | 188 | 0 | 29 | 16.62 | 9.60 | −0.39 | −1.28 |
| T4: 6.5 years | 175 | 0 | 29 | 19.28 | 9.16 | −0.68 | −0.94 |
| Informal home numeracy environment (sum scores) | | | | | | | |
| T1: 2.5 years | 202 | 1 | 3.33 | 1.44 | 0.42 | 1.23 | 1.97 |
| T3: 5.5 years | 130 | 1.17 | 4.67 | 2.02 | 0.54 | 1.36 | 4.15 |
| Informal home literacy environment (shared reading) (sum scores) | | | | | | | |
| T1: 2.5 years | 202 | 1.25 | 5 | 3.35 | 0.91 | −0.23 | −0.72 |
| T3: 5.5 years | 123 | 1 | 5 | 2.90 | 0.80 | −0.12 | −0.21 |

very weak effect (which in some of the step 2 models was barely significant, and in some models fell just beneath the significance level of 0.05) was found from mothers' RD predicting less HNE activities.

For the research question 2 on association between the home environment and children's skills and for the research question 3 on association between children's skills and the home environment, please see more details for each skill in their respective models below.

## The Model for Counting Objects

The model for counting objects (**Figure 4**) had an acceptable fit with the data: $x^2$ (199) = 240.60, $p = 0.02$, RMSEA = 0.03 (90% CI 0.01–0.05), CFI = 0.95, SRMR = 0.06. Of the parental variables, having a mother with MD predicted faster development in counting objects from T1 to T2. Of the home environment factors, having more informal HNE activities at T1 predicted faster development in counting objects from T1 to T2. Also, children's poorer performance in counting objects at T2 predicted an increase in shared reading from T1 to T3.

## The Model for Number Producing

The model for number producing (**Figure 5**) had a good fit with the data: $x^2$ (196) = 230.17, $p = 0.05$, RMSEA = 0.03 (90% CI 0.00–0.04), CFI = 0.96, SRMR = 0.05. None of the parental variables predicted their children's number producing. However, of the home environment factors, more frequent informal HNE activities at T1 predicted faster development of number-producing skills from T1 to T2. Children's number-producing skills did not predict home environment factors.

**TABLE 2 |** Correlations between all variables.

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Skills T1: 2.5 years | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1. Count obj | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2. Num prod | 0.27 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 3. Num seq | 0.55 | 0.31 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 4. Num id | 0.20 | 0.15 | 0.27 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 5. Num nam | 0.41 | 0.24 | 0.36 | 0.61 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 6. Vocab | 0.31 | 0.37 | 0.29 | 0.11 | 0.17 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 7. Print know | 0.32 | 0.21 | 0.31 | 0.24 | 0.26 | 0.33 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 8. Letter know | 0.23 | 0.17 | 0.18 | 0.58 | 0.69 | 0.12 | 0.24 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Skills T2: 3.5 years | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 9. Count obj | 0.44 | 0.34 | 0.46 | 0.28 | 0.39 | 0.25 | 0.25 | 0.21 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 10. Numb prod | 0.42 | 0.46 | 0.41 | 0.34 | 0.37 | 0.30 | 0.34 | 0.26 | 0.42 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 11. Numb seq | 0.36 | 0.21 | 0.41 | 0.29 | 0.31 | 0.30 | 0.27 | 0.24 | 0.45 | 0.28 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 12. Numb id | 0.21 | 0.27 | 0.25 | 0.68 | 0.64 | 0.16 | 0.21 | 0.55 | 0.24 | 0.38 | 0.26 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | |
| 13. Numb nam | 0.31 | 0.21 | 0.33 | 0.57 | 0.65 | 0.11 | 0.28 | 0.55 | 0.35 | 0.39 | 0.28 | 0.65 | 1 | | | | | | | | | | | | | | | | | | | | | | | | |
| 14. Vocab | 0.27 | 0.30 | 0.27 | 0.20 | 0.28 | 0.45 | 0.30 | 0.24 | 0.28 | 0.25 | 0.36 | 0.27 | 0.25 | 1 | | | | | | | | | | | | | | | | | | | | | | | |
| 15. Print know | 25 | 0.12 | 0.25 | 0.29 | 0.24 | 0.21 | 0.35 | 0.24 | 0.18 | 0.28 | 0.32 | 0.33 | 0.38 | 0.29 | 1 | | | | | | | | | | | | | | | | | | | | | | |
| 16. Letter know | 0.26 | 0.17 | 0.28 | 0.72 | 0.75 | 0.13 | 0.28 | 0.76 | 0.25 | 0.38 | 0.28 | 0.73 | 0.68 | 0.25 | 0.35 | 1 | | | | | | | | | | | | | | | | | | | | | |
| Skills T3: 5.5 years | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 17. Numb seq | 0.30 | 0.30 | 0.23 | 0.20 | 0.21 | 0.21 | 0.29 | 0.23 | 0.38 | 0.30 | 0.37 | 0.34 | 0.31 | 0.26 | 0.17 | 0.28 | 1 | | | | | | | | | | | | | | | | | | | | |
| 18. Numb id | 0.31 | 0.23 | 0.17 | 0.17 | 0.17 | 0.21 | 0.26 | 0.19 | 0.28 | 0.32 | 0.31 | 0.28 | 0.33 | 0.25 | 0.24 | 0.24 | 0.68 | 1 | | | | | | | | | | | | | | | | | | | |
| 19. Numb nam | 0.26 | 0.23 | 0.18 | 0.14 | 0.17 | 0.23 | 0.22 | 0.14 | 0.26 | 0.27 | 0.33 | 0.26 | 0.28 | 0.25 | 0.22 | 0.22 | 0.68 | 0.89 | 1 | | | | | | | | | | | | | | | | | | |
| 20. Vocab | 0.28 | 0.31 | 0.20 | 0.13 | 0.14 | 0.37 | 0.30 | 0.02 | 0.07 | 0.24 | 0.29 | 0.24 | 0.12 | 0.43 | 0.23 | 0.12 | 0.22 | 0.22 | 0.25 | 1 | | | | | | | | | | | | | | | | | |
| 21. Print know | 0.24 | 0.20 | 0.19 | 0.13 | 0.13 | 0.21 | 0.32 | 0.14 | 0.07 | 0.20 | 0.22 | 0.17 | 0.24 | 0.19 | 0.25 | 0.19 | 0.34 | 0.46 | 0.51 | 0.37 | 1 | | | | | | | | | | | | | | | | |
| 22. Letter know | 0.25 | 0.30 | 0.33 | 0.20 | 0.26 | 0.20 | 0.22 | 0.24 | 0.23 | 0.29 | 0.26 | 0.30 | 0.33 | 0.19 | 0.21 | 0.31 | 0.50 | 0.64 | 0.65 | 0.33 | 0.44 | 1 | | | | | | | | | | | | | | | |
| Skills T4: 6.5 years | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 23. Numb seq | 0.20 | 0.25 | 0.13 | 0.13 | 0.12 | 0.27 | 0.26 | 0.11 | 0.21 | 0.32 | 0.35 | 0.26 | 0.28 | 0.27 | 0.26 | 0.19 | 0.69 | 0.64 | 0.65 | 0.25 | 0.41 | 0.57 | 1 | | | | | | | | | | | | | | |
| 24. Numb id | 0.28 | 0.26 | 0.16 | 0.10 | 0.17 | 0.28 | 0.30 | 0.16 | 0.21 | 0.24 | 0.30 | 0.18 | 0.29 | 0.18 | 0.19 | 0.20 | 0.57 | 0.78 | 0.79 | 0.27 | 0.49 | 0.63 | 0.67 | 1 | | | | | | | | | | | | | |
| 25. Numb nam | 0.20 | 0.23 | 0.13 | 0.11 | 0.15 | 0.28 | 0.27 | 0.14 | 0.12 | 0.14 | 0.29 | 0.21 | 0.31 | 0.25 | 0.20 | 0.23 | 0.57 | 0.70 | 0.76 | 0.24 | 0.44 | 0.55 | 0.64 | 0.84 | 1 | | | | | | | | | | | | |
| 26. Vocab | 0.41 | 0.32 | 0.28 | 0.08 | 0.20 | 0.35 | 0.22 | 0.09 | 0.26 | 0.34 | 0.32 | 0.07 | 0.11 | 0.39 | 0.16 | 0.15 | 0.18 | 0.29 | 0.28 | 0.57 | 0.34 | 0.36 | 0.25 | 0.32 | 0.19 | 1 | | | | | | | | | | | |
| 27. Print know | 0.07 | 0.13 | 0.08 | 0.03 | 0.03 | 0.16 | 0.14 | 0.01 | 0.19 | 0.08 | 0.18 | 0.07 | 0.19 | 0.22 | 0.19 | 0.07 | 0.22 | 0.31 | 0.27 | 0.26 | 0.49 | 0.26 | 0.27 | 0.36 | 0.31 | 0.32 | 1 | | | | | | | | | | |
| 28. Letter know | 0.32 | 0.27 | 0.34 | 0.16 | 0.24 | 0.21 | 0.26 | 0.21 | 0.24 | 0.30 | 0.34 | 0.25 | 0.31 | 0.21 | 0.25 | 0.27 | 0.52 | 0.67 | 0.68 | 0.34 | 0.47 | 0.95 | 0.58 | 0.69 | 0.59 | 0.41 | 0.28 | 1 | | | | | | | | | |
| Home environment and familial risk measures | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 29. HNE T1 | 0.26 | 0.15 | 0.27 | 0.17 | 0.28 | 0.05 | 0.21 | 0.30 | 0.31 | 0.32 | 0.26 | 0.19 | 0.28 | 0.23 | 0.17 | 0.25 | 0.09 | 0.09 | 0.05 | 0.08 | 0.09 | 0.06 | 0.05 | 0.12 | 0.04 | 0.15 | 0.13 | 0.08 | 1 | | | | | | | | |
| 30. HNE T3 | 0.12 | −0.02 | 0.10 | −0.07 | 0.10 | 0.07 | 0.06 | 0.05 | 0.02 | −0.06 | 0.14 | −0.08 | −0.07 | 0.18 | 0.12 | −0.00 | 0.02 | 0.03 | 0.05 | 0.15 | 0.04 | 0.00 | 0.01 | 0.06 | 0.12 | 0.13 | 0.11 | 0.01 | 0.34 | 1 | | | | | | | |
| 31. HLE T1 | 0.04 | 0.09 | 0.06 | 0.01 | 0.11 | 0.06 | −0.04 | 0.10 | 0.06 | 0.10 | 0.15 | −0.01 | 0.01 | 0.11 | 0.07 | 0.00 | 0.02 | 0.12 | 0.12 | 0.05 | 0.05 | 0.21 | 0.16 | 0.13 | 0.10 | 0.16 | −0.18 | 0.22 | 0.24 | 0.18 | 1 | | | | | | |
| 32. HLE T3 | 0.03 | 0.08 | −0.06 | 0.08 | 0.20 | 0.08 | −0.04 | 0.17 | −0.12 | 0.14 | −0.08 | 0.15 | 0.01 | −0.00 | 0.06 | 0.17 | −0.06 | −0.00 | 0.01 | 0.17 | −0.10 | 0.20 | 0.09 | 0.09 | 0.06 | 0.16 | −0.01 | 0.20 | 0.12 | 0.29 | 0.61 | 1 | | | | | |
| 33. FR Mo Re | −0.07 | −0.09 | −0.07 | 0.12 | −0.02 | −0.12 | −0.03 | 0.04 | −0.07 | −0.15 | −0.01 | 0.02 | 0.00 | −0.12 | 0.03 | 0.01 | −0.13 | −0.18 | −0.14 | −0.04 | −0.02 | −0.05 | −0.20 | −0.19 | −0.19 | −0.15 | −0.03 | −0.10 | −0.06 | −0.02 | 0.02 | 0.10 | 1 | | | | |
| 34. FR Mo Ma | −0.07 | −0.15 | −0.07 | 0.06 | −0.03 | −0.11 | 0.01 | −0.01 | 0.08 | −0.06 | 0.01 | 0.01 | 0.01 | −0.04 | −0.06 | −0.04 | −0.08 | −0.09 | −0.08 | −0.12 | −0.14 | −0.05 | −0.16 | −0.13 | −0.13 | −0.13 | −0.00 | −0.08 | −0.09 | 0.02 | −0.09 | −0.13 | 0.40 | 1 | | | |
| 35. FR Fa Re | −0.05 | −0.10 | −0.09 | −0.04 | −0.10 | −0.06 | 0.01 | −0.08 | −0.03 | −0.09 | −0.11 | −0.10 | −0.03 | 0.04 | −0.02 | −0.11 | −0.11 | −0.10 | −0.11 | −0.08 | −0.09 | −0.19 | −0.20 | −0.17 | −0.16 | −0.05 | 0.15 | −0.19 | 0.00 | −0.11 | −0.18 | −0.23 | −0.05 | 0.19 | 1 | | |
| 36. FR Fa Ma | −0.15 | −0.14 | −0.10 | −0.10 | −0.04 | −0.11 | −0.13 | −0.06 | 0.03 | −0.08 | −0.03 | −0.05 | −0.04 | −0.10 | −0.12 | −0.07 | −0.15 | −0.22 | −0.23 | −0.13 | −0.18 | −0.27 | −0.18 | −0.33 | −0.30 | −0.13 | −0.07 | −0.27 | −0.02 | 0.06 | −0.06 | −0.09 | 0.12 | 0.29 | 0.29 | 1 | |
| 37. Mo Ed | 0.09 | 0.14 | 0.05 | 0.05 | 0.12 | 0.16 | 0.08 | 0.16 | 0.15 | 0.09 | 0.19 | 0.08 | 0.09 | 0.17 | 0.13 | 0.09 | 0.14 | 0.08 | 0.09 | 0.22 | 0.06 | 0.22 | 0.19 | 0.11 | 0.07 | 0.22 | 0.18 | 0.25 | 0.08 | 0.00 | 0.16 | 0.28 | −0.24 | −0.46 | −0.17 | −0.12 | 1 |
| 38. Fa Ed | 0.13 | 0.00 | 0.09 | 0.00 | 0.07 | 0.19 | 0.10 | −0.00 | 0.08 | 0.13 | 0.22 | 0.05 | 0.02 | 0.11 | 0.16 | 0.02 | 0.11 | 0.08 | 0.10 | 0.20 | 0.11 | 0.15 | 0.28 | 0.17 | 0.17 | 0.16 | 0.10 | 0.18 | 0.05 | −0.09 | 0.09 | 0.09 | −0.08 | −0.15 | −0.18 | −0.17 | 0.53 |

*Note. Count obj = counting objects; Num prod = number producing; Num seq = number sequences; Num id = number symbol identification; Num nam = number naming; Vocab = vocabulary; Print know = print knowledge; Letter know = letter knowledge. Significance levels: rs > 16,* p *< 0.05, rs > 17,* p *< 0.01, rs > 0.26,* p *< 0.001.*

### The Model for Number Sequence Skill

The model for number sequence skill (**Figure 6**) had a good fit with the data: $x^2$ (241) = 263.30, $p$ = 0.15, RMSEA = 0.02 (90% CI 0.00–0.04), CF I = 0.98, SRMR = 0.06. Of the parental variables, fathers' RD predicted significantly, albeit weakly, slower number sequence development from T3 to T4. No predictive associations were found between home environment factors and number sequencing skill. Children's poorer number sequence skill at T2, however, predicted an increase in shared reading from T1 to T3.

### The Model for Number Symbol Identification

The model for number symbol identification (**Figure 7**) had a good fit with the data: $x^2$ (238) = 266.95, $p$ = 0.10, RMSEA = 0.02 (90% CI 0.00–0.04), CFI = 0.97, SRMR = 0.06. Of the parental variables, fathers' MD predicted significantly, albeit weakly, their children's number symbol identification skills. The children of the fathers who reported MD had poorer number symbol identification skills at T1 than the children whose fathers did not report MD. No predictive associations were found between home environment factors and number symbol identification. Poorer number symbol identification skills at T2, however, predicted an increase in informal HNE activities from T1 to T3.

### The Model for Number Naming

The model for number naming (**Figure 8**) had a good fit with the data: $x^2$ (238) = 263.67, $p$ = 0.12, RMSEA = 0.02 (90% CI 0.00–0.04), CFI = 0.97, SRMR = 0.06. Of the parental variables, fathers' and mothers' RD predicted significantly, albeit weakly, their children's number naming at T1. The path estimates were negative, suggesting that the children with parental RD had poorer skills in number naming than their peers whose parents did not have RD. Also, fathers' MD predicted poorer development in their children's number naming from T3 to T4. No predictive associations were found between home environment factors and number naming skill assessments. Children's number naming skills did not predict home environment factors.

### The Model for Vocabulary

The model for vocabulary (**Figure 9**) had a good fit with the data: $x^2$ (242) = 279.49, $p$ = 0.05, RMSEA = 0.03 (90% CI 0.00–0.04), CFI = 0.96, SRMR = 0.06. There were no significant associations between vocabulary and the other variables in the model.

### The Model for Print Knowledge

The path model for print knowledge (**Figure 10**) had a good fit with the data: $x^2$ (241) = 266.94, $p$ = 0.12, RMSEA = 0.02 (90% CI 0.00–0.04), CFI = 0.97, SRMR = 0.06. Of the parental variables, mothers' RD predicted significantly, albeit weakly, their children's print knowledge at T1. The path estimate was negative, suggesting that with mothers' RD, the children had poorer print knowledge than their peers whose mothers did not have RD. However, fathers' RD predicted faster development in print knowledge from T3 to T4. No predictive associations were found between home environment factors and print knowledge. Children's print knowledge did not predict home environment factors.

### The Model for Letter Knowledge

The path model for letter knowledge (**Figure 11**) had an acceptable fit with the data: $x^2$ (237) = 306.26, $p$ = 0.002, RMSEA = 0.04 (90% CI 0.02–0.05), CFI = 0.95, SRMR = 0.06. Of the parental variables, mothers' education, fathers' MD, and both fathers' and mothers' RD predicted significantly, albeit weakly, their children's letter knowledge at T1. Fathers' MD negatively predicted children's letter knowledge at T3, while mothers' MD negatively predicted children's letter knowledge at T2. The children whose parents reported difficulties were more likely to perform worse in letter knowledge than their peers with parental RD or MD. No predictive associations were found between home environment factors and letter knowledge assessments. Children's poorer letter knowledge at T2, however, predicted more numeracy activities at home at T3.

### Indirect Paths

Regarding the indirect effects from parental variables on children's numeracy and literacy development through the home environment (Research question 4), we did not find any significant mediation effects. In the step 2 models (**Figures 4–11**), all significant paths identified in step 1 from any of the parental measures to letter knowledge at T2-T4 became nonsignificant after adding the HLE and HNE factors at step 2. Similarly, the effects of mother's RD on number production, number identification, and number sequences became nonsignificant after adding the HLE and HNE factors. The same was true for the effect of father's RD on number sequences and for the effect of mother's education on counting objects. These findings suggest that the small impact of parental measures on children's skills may be mediated via home environment. However, none of the indirect effects from parental measures via HLE or HNE to children's skills were found to be significant (research question 4, **Table 5**), which suggests that the impact of parental measures of children's skills through home environment was not significant.

## DISCUSSION

The main objective of this study was to gain more understanding of the underpinnings of children's early literacy and numeracy development by examining the roles of the home numeracy (HNE) and literacy (HLE) environment, parental RD and MD, and parents' education in an early onset longitudinal sample of Finnish children (followed from age 2.5–6.5). The results showed that of the parental measures, parental RD and MD significantly, albeit weakly, predicted several of their children's skills at different ages and both within and across domains, while parental education weakly predicted only early letter knowledge. Parental RD and MD had significantly weak negative associations with the home environment measures, while mother's education positively predicted HLE. The HNE and HLE activities were reciprocally associated with children's skills both within and across domains. This suggests both a supportive role for the HNE and HLE activities but underlines the role of children's skills in arousing the activities with their parents (potentially reflecting both active and evocative gene-environment correlations).

## Parental Math and Reading Difficulties and Their Education Level Predicted Children's Numeracy and Literacy Skills

Regarding research question 1a on the role of parental measures on children's skills, our models revealed both within-domain and cross-domain effects of parental RD and MD on children's skills. All but two skills (number producing and vocabulary) were predicted by parental RD and/or MD. Some associations emerged as early as age 2.5: namely, mother's RD predicting children's T1 print knowledge, letter knowledge, and number naming skills, and father's MD predicting T1 number symbol identification skills. At the same time, mothers' and fathers' RD predicted number naming at age 2.5 and fathers' RD predicted number sequence knowledge at age 6.5. Age 2.5 letter knowledge was predicted not only by the mother's RD but also by the father's RD and MD. The impact of parental RD on children's literacy skills lends support for prior studies on the significant role of FR with RD (Puolakanaho et al., 2007; Torppa et al., 2010; van Bergen et al., 2014; Esmaeeli et al., 2019). In line with Torppa et al. (2010), the results of the current study imply that the predictive role of parental RD on emerging literacy skills already exists in toddlerhood, adding a risk for children's skill development during a sensitive period of language development. Parental MD predicted their children's poorer symbolic numeracy processing, which is in line with prior studies (Shalev and Gross-Tsur, 2001; Soares et al., 2018). The results, however, add to the prior literature by showing a cross-domain association between parental RD and MD and emerging numeracy and literacy skills, suggesting that RD and MD have both common and distinct underpinnings (e.g., Landerl and Moll, 2010) with an early onset. Literacy and numeracy development rely on many of the same cognitive processes (Korpipää et al., 2017), but their intergenerational transfer has hardly been examined and explained.

Some effects between parental MD and children's skills emerged later in development. Mothers' MD predicted children's counting skills at age 3.5, while fathers' MD predicted children's letter knowledge at ages 2.5 and 6.5. The results show significant within and cross-domain associations between MD and numeracy and literacy skills, which have also been found with a sample of children in primary school: In their study, Khanolainen et al. (2020) showed that parental MD predicted both children's reading comprehension and arithmetic fluency. The findings of the current study emphasize that similar cross-domain FR might already be true before school age with children's emerging literacy (letter and print knowledge) and numeracy (counting skills and number sequence skills). The predictive association between parental skills and children's letter name knowledge is interesting, as letter name knowledge has been identified as a strong predictor of RD (e.g., Pennington and Lefly, 2001; Puolakanaho et al., 2007). Together, the results point to the importance of FR in children's literacy and numeracy development well ahead of school entry, and more research is warranted on the mechanisms through which such effects emerge, particularly for the effects of parental MD, which is yet hardly investigated.

Regarding parental education, there was only one significant association with children's skills: that of mother's education to age 2.5 letter knowledge. This finding is in line with prior studies (e.g., Esmaeeli et al., 2018) reporting an association between parental education and children's emergent literacy. Also, a prior Finnish study by Silinskas et al. (2020) suggested that maternal education is linked with child outcomes. In our sample, there were also other significant correlation coefficients between parental education and children's skills, but in the models where parental RD and MD were also included, the effects of parental education became nonsignificant. This finding points to the direction that the often-reported association between parental education and their children's skill development may be explained by parental skills, that is, the intergenerational transmission of RD and MD (e.g., van Bergen et al., 2017). In a recent study by Khanolainen et al. (2020) among school-aged children, however, parental education remained a significant predictor of children's skill even with parental MD and RD variables in the models. Like ours, Khanolainen et al.'s (2020) study was also conducted in Finland, but the differences in sample, age, or the skills assessed may explain the difference and further studies are needed. Such studies should preferably have parental skills directly assessed instead of self-reported like the studies so far. Based on the findings, it thus appears that, of the parental measures, it is parental skills rather than their educational level underlying their children's early skill development.

## Parental Reading Difficulties and Their Education Level Predicted Home Literacy and Numeracy Environments

Regarding research question 1b, parental RD negatively predicted both HNE and HLE. The associations between fathers' RD and the home learning environment were within-domain, whereas association for mothers' RD appeared to impact across domains. Also, mothers' level of education positively predicted HLE activities at T3.

First, fathers' RD predicted less shared reading at home, thus resonating with some studies showing that children whose parents have FR of RD might be exposed to more unsupportive home environments (e.g., less shared reading) than children with parents without FR of RD (e.g., van Bergen et al., 2014; Dilnot et al., 2017). The finding can be explained by the lack of access to print materials because of parents reading less themselves, but parental attitudes or dispositions (e.g., reading anxiety) may also play a role. A recent study in foreign-language learning suggested that parents with higher levels of anxiety might engage less in HLE activities with children, thus minimizing their child's experience in using a foreign language (Chow et al., 2017). Furthermore, studies that look closely at the reading interactions are, however, needed to understand the reasons for this association more deeply.

Second, a weak effect (which in some models was barely significant and in others fell just beneath the significance level of 0.05) was found from the mother's RD predicting fewer HNE activities. This finding is among the first to show a predictive cross-domain association between RD and HNE. A possible explanation for the finding is that, albeit relating to numeracy in terms of content, several of the informal HNE activities used in the current study also included activities that would simultaneously

**TABLE 3 |** The standardized model estimates for parental measures predicting children's skills.

| | Skill T1 | Skill T2 | Skill T3 | Skill T4 | Model fit |
|---|---|---|---|---|---|
| Counting objects (effective $N$ = 188) | | | | | |
| Autoregressor T1 | — | 0.48*** | — | — | Saturated model |
| Mother's education | 0.00 | 0.21* | — | — | |
| Father's education | 0.11 | −0.08 | — | — | |
| Mother RD | −0.09 | −0.09 | — | — | |
| Father RD | −0.00 | −0.06 | — | — | |
| Mother MD | 0.01 | 0.23** | — | — | |
| Father MD | −0.08 | 0.09 | — | — | |
| Number production (effective $N$ = 190) | | | | | |
| Autoregressor T1 | — | 0.47*** | — | — | Saturated model |
| Mother's education | 0.17 | −0.08 | — | — | |
| Father's education | −0.11 | 0.15 | — | — | |
| Mother RD | −0.04 | −0.15** | — | — | |
| Father RD | −0.07 | −0.06 | — | — | |
| Mother MD | 0.02 | 0.03 | — | — | |
| Father MD | −0.07 | 0.03 | — | — | |
| Number sequences (effective $N$ = 192) | | | | | |
| Autoregressor T1 | — | 0.43*** | — | — | $\chi^2$ (3) = 2.52, $p$ = 0.47, RMSEA = 0.00, CFI = 1.00 |
| Autoregressor T2 | — | — | 0.37*** | — | |
| Autoregressor T3 | — | — | — | 0.61*** | |
| Mother's education | −0.07 | 0.15 | 0.00 | −0.12 | |
| Father's education | 0.11 | 0.06 | 0.04 | 0.20* | |
| Mother RD | −0.09 | −0.04 | −0.16* | −0.12* | |
| Father RD | −0.08 | −0.05 | −0.08 | −0.11* | |
| Mother MD | 0.01 | 0.09 | 0.07 | −0.05 | |
| Father MD | −0.02 | 0.01 | −0.07 | −0.01 | |
| Number identification (effective $N$ = 192) | | | | | |
| Autoregressor T1 | — | 0.62*** | — | — | $\chi^2$ (3) = 0.76, $p$ = 0.86, RMSEA = 0.00, CFI = 1.00 |
| Autoregressor T2 | — | — | 0.29*** | — | |
| Autoregressor T3 | — | — | — | 0.73*** | |
| Mother's education | 0.07 | −0.01 | −0.04 | −0.00 | |
| Father's education | −0.09 | 0.05 | 0.05 | 0.07 | |
| Mother RD | 0.03 | −0.12* | −0.24 | −0.05 | |
| Father RD | −0.01 | −0.08 | −0.09 | −0.06 | |
| Mother MD | 0.00 | −0.03 | 0.10 | 0.02 | |
| Father MD | −0.10** | 0.08 | −0.17 | −0.12 | |
| Number naming (effective $N$ = 192) | | | | | |
| Autoregressor T1 | — | 0.67*** | — | — | $\chi^2$ (3) = 7.06, $p$ = 0.07, RMSEA = 0.08, CFI = 0.98 |
| Autoregressor T2 | — | — | 0.30*** | — | |
| Autoregressor T3 | — | — | — | 0.71*** | |
| Mother's education | 0.11 | 0.00 | −0.03 | −0.10 | |
| Father's education | −0.01 | −0.02 | 0.08 | 0.11 | |
| Mother RD | −0.12** | 0.02 | −0.19 | −0.06 | |
| Father RD | −0.10* | 0.07 | −0.10 | −0.04 | |
| Mother MD | 0.03 | −0.00 | 0.11 | −0.03 | |
| Father MD | 0.03 | −0.09 | −0.15 | −0.14* | |
| Vocabulary (effective $N$ = 193) | | | | | |
| Autoregressor T1 | — | 0.46*** | — | — | $\chi^2$ (2) = 3.71, $p$ = 0.16, RMSEA = 0.07, CFI = 0.99 |
| Autoregressor T2 | — | — | 0.45*** | — | |
| Autoregressor T3 | — | — | — | 0.42*** | |
| Mother's education | 0.04 | 0.14 | 0.04 | 0.11 | |
| Father's education | 0.15 | −0.07 | 0.14 | −0.00 | |
| Mother RD | −0.09 | −0.10 | 0.00 | −0.12 | |
| Father RD | −0.00 | 0.12 | −0.04 | −0.04 | |
| Mother MD | −0.00 | 0.05 | 0.01 | 0.07 | |
| Father MD | −0.05 | −0.12 | −0.08 | 0.01 | |
| Print knowledge (effective $N$ = 193) | | | | | |
| Autoregressor T1 | — | 0.32*** | — | — | $\chi^2$ (2) = 0.00, $p$ = 0.99, RMSEA = 0.00, CFI = 1.00 |
| Autoregressor T2 | — | — | 0.23* | — | |
| Autoregressor T3 | — | — | — | 0.45*** | |
| Mother's education | 0.06 | 0.00 | −0.07 | 0.11 | |
| Father's education | 0.07 | 0.12 | 0.07 | 0.05 | |
| Mother RD | −0.13* | 0.08 | −0.02 | −0.00 | |
| Father RD | 0.03 | 0.06 | −0.07 | 0.24*** | |

(Continued on following page)

**TABLE 3 |** (*Continued*) The standardized model estimates for parental measures predicting children's skills.

| | Skill T1 | Skill T2 | Skill T3 | Skill T4 | Model fit |
|---|---|---|---|---|---|
| Mother MD | 0.11 | –0.09 | –0.10 | 0.07 | |
| Father MD | –0.11 | –0.08 | –0.05 | –0.11 | |
| Letter knowledge (effective *N* = 193) | | | | | |
| Autoregressor T1 | — | 0.76*** | — | — | $\chi^2$ (3) = 4.08, *p* = 0.25, RMSEA = 0.04, CFI = 0.99 |
| Autoregressor T2 | — | — | 0.26*** | — | |
| Autoregressor T3 | — | — | — | –0.93*** | |
| Mother's education | 0.27** | –0.20 | 0.20* | –0.02 | |
| Father's education | –0.18 | 0.15* | 0.01 | 0.04 | |
| Mother RD | –0.05* | –0.04* | –0.07 | –0.05 | |
| Father RD | –0.06** | –0.04 | –0.13 | –0.00 | |
| Mother MD | 0.06 | –0.13** | 0.19 | –0.02 | |
| Father MD | –0.03 | 0.01 | –0.23* | –0.01 | |

*Note. To improve the model fit the following paths were added to the relevant models: Vocabulary T4 was regressed on Vocabulary T2 (0.28***) and Print knowledge T3 was regressed on Print knowledge T1 (0.27**).*

**TABLE 4 |** The standardized model estimates for parental measures predicting HLE and HNE.

| | HNE T1 | HNE T3 | Model fit |
|---|---|---|---|
| HNE (effective *N* = 196) | | | |
| Autoregressor T1 | — | 0.43* | χ2 (52) = 43.89, *p* = 0.78, RMSEA = 0.00, CFI = 1.00 |
| Mother's education | 0.03 | –0.06 | |
| Father's education | 0.03 | –0.08 | |
| Mother RD | –0.13* | –0.02 | |
| Father RD | 0.07 | –0.15 | |
| Mother MD | –0.10 | 0.10 | |
| Father MD | 0.00 | –0.01 | |
| HLE (effective *N* = 196) | | | |
| Autoregressor T1 | — | 0.71*** | χ2 (40) = 78.33, *p* = 0.00, RMSEA = 0.07, CFI = 0.94 |
| Mother's education | 0.18 | 0.23* | |
| Father's education | –0.07 | –0.07 | |
| Mother RD | 0.07 | 0.19 | |
| Father RD | –0.19** | 0.11 | |
| Mother MD | 0.02 | –0.10 | |
| Father MD | 0.03 | –0.02 | |

*Note. To improve the model fit indicators of latent environmental variables were allowed to correlate. Specifically: 1) the item "Using calendars and dates" at T1 was correlated with other HNE items (indicators), and 2) all HLE items at T1 were correlated with all HLE items at T3.*

require the parent to engage with and understand text or written instructions (e.g., playing board games). It was interesting to note that parental MD was not associated with HNE or HLE. Prior studies lend support for this finding; for instance, in a study by Khanolainen et al. (2020) neither RD nor MD predicted at home teaching (math and reading) or shared reading. Silinskas et al. (2010) showed that mothers' MD predicted more frequent teaching of math (formal HNE) but not their teaching of reading (formal HLE) during the first grade in primary education. It is thus possible that also in the present sample the association would have emerged between parental MD and formal HNE had we included the formal HNE measure.

Third, mother's education positively predicted HLE in the third time point at age 5.5 (over and above HLE at T1), suggesting that the higher the mother's education level was, the more they increased shared reading with their children from age 2.5–5.5 years. The finding may mean that parents with higher education are themselves more accustomed to reading and find reading more pleasurable, and therefore might also be more willing to read with their children than less educated parents. Parents may also be more prone to recognize the value of reading to children. The finding is in line with a prior Finnish study linking mothers' higher education with more shared reading and lower education with more teaching children to read (Khanolainen et al., 2020). However, their study additionally showed that lower parental education also predicted more math-related teaching at home, whereas in the current study parents' education did not predict HNE. This finding also conflicts with that of Thompson et al. (2017), suggesting that more highly educated parents engage more frequently in numeracy activities with their 3-year-olds than parents with lower education. The lack of associations, however, could be explained again by our lack of formal teaching items and focus on informal HLE and HNE only.

## Home Numeracy Environment Predicted Children's Numeracy and Literacy Skills

As for research question 2 on the associations between HNE, HLE, and children's skill development, our results suggested that informal HNE supports the development of several skills. However, HLE predicted neither literacy nor numeracy skills. The informal HNE at

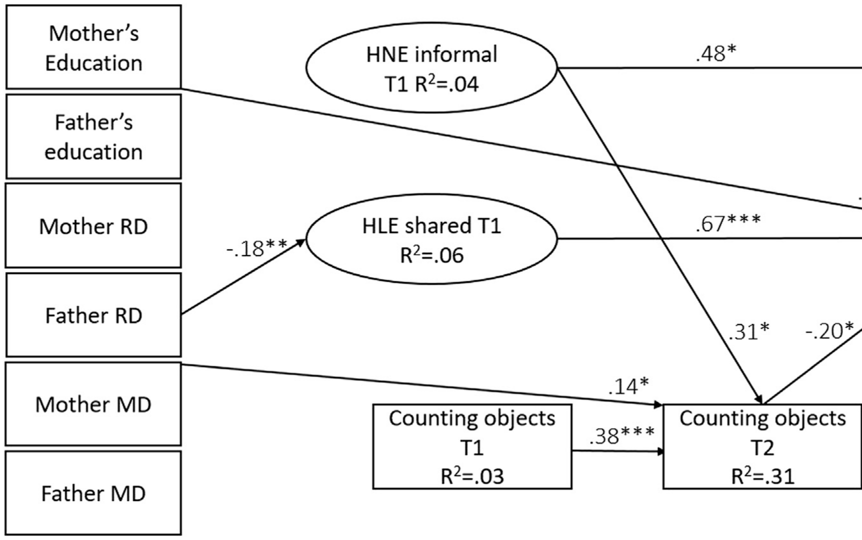


**FIGURE 4 |** The model for counting objects skill with significant standardized estimates. Note: In addition to the regression paths depicted, there were two significant residual correlations: between HNE and HLE at T1 (stand. estimate = 0.38***) and between HNE and counting objects at T1 (stand. estimate = 0.31**).

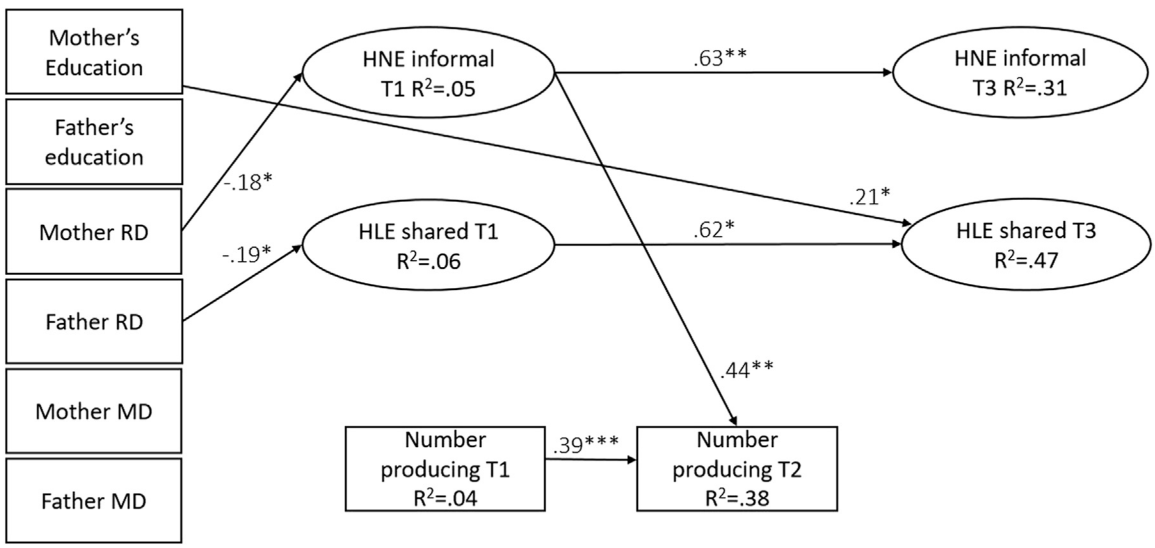


**FIGURE 5 |** The model for number production with significant standardized estimates. Note: In addition to the regression paths depicted, there was one significant residual correlation: between HNE and HLE at T1 (stand. estimate = 0.41***).

the first time point, age 2.5, positively predicted children's counting objects skill and number producing skill at the second time point, age 3.5, even after controlling for the prior skill level at age 2.5. Similar results have been derived from recent studies about slightly older children: Skwarchuk et al. (2014) reported informal HNE predicting 5-year-old children's nonsymbolic arithmetic, namely their abilities to manipulate quantities. However, their study was cross-sectional in terms of children's skills. The results of the current study among younger children and with including autoregressors confirm this finding and suggest that frequently engaging in informal HNE activities, such as being exposed to numeracy-related contents in board games or measuring ingredients while cooking (e.g., Vandermaas-Peeler et al., 2012) while already in toddlerhood, may help children to gain understanding of quantity manipulation without the deliberate instruction of a symbolic number system. As nonsymbolic arithmetic skills have further been associated with better calculation and number system knowledge in later childhood (LeFevre et al., 2010), these activities may have long-standing impacts.

Unexpectedly, the home literacy environment predicted neither literacy nor numeracy skills, indicating that cross-domain associations were identified for HNE, but not for HLE. Our findings are therefore in contrast to many previous within-

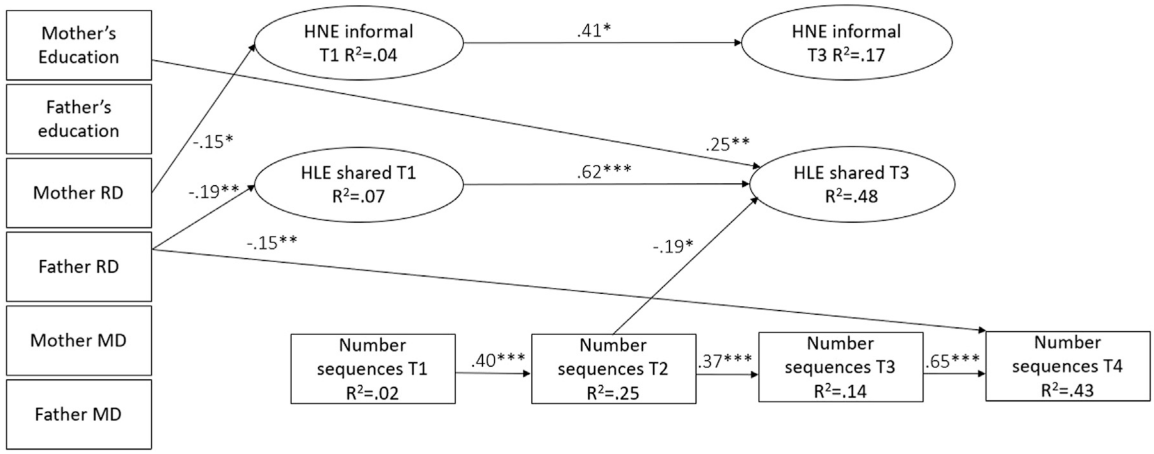


**FIGURE 6 |** The model for number sequence skill with the significant standardized estimates. Note. In addition to the regression paths depicted, there were two significant residual correlations: between HNE and HLE at T1 (stand. estimate = 0.38***) and between HNE and number sequence skill at T1 (stand. estimate = 0.35**).

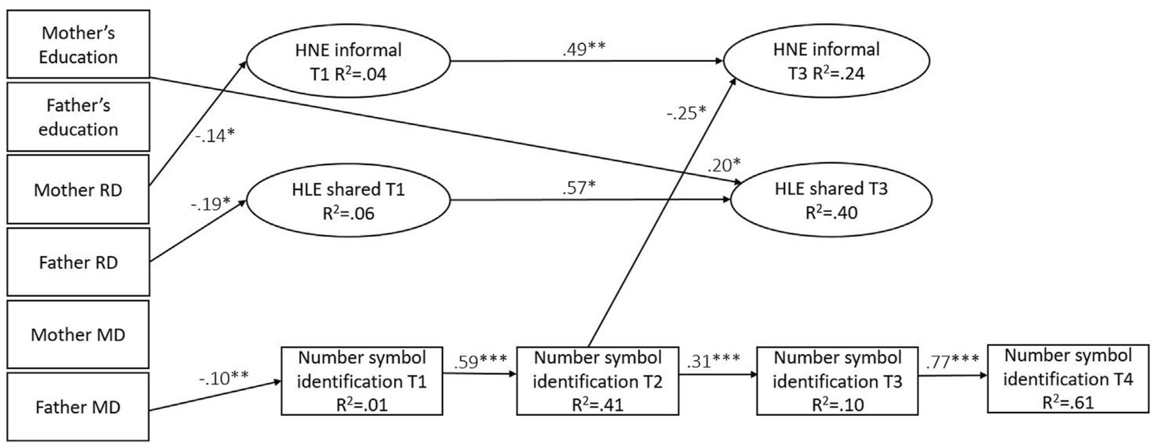


**FIGURE 7 |** The model for number symbol identification with the significant standardized estimates. Note: In addition to the regression paths depicted, there was one significant residual correlation: between HNE and HLE at T1 (stand. estimate = 0.42***).

domain studies exploring the association between HLE and literacy skills, which suggested that more parent-child shared reading supports children's language and literacy skills, oral language in particular (e.g., Mol and Bus, 2011:; Sénéchal and LeFevre, 2002; Torppa et al., 2007). The research also conflicts with the accumulating body of studies where both HLE and HNE, along with numeracy and literacy skills, have been inspected (e.g., Manolitsis et al., 2013; Napoli and Purpura, 2018; Khanolainen et al., 2020; Soto-Calvo et al., 2020). These studies have systematically reported significant associations between HLE and literacy and numeracy outcomes, providing well-established evidence for shared reading predicting literacy and/or numeracy outcomes, rather than the other way around. Though they showed that storybook reading predicted children's definitional vocabulary, Napoli and Purpura (2018) also observed that the same was not true for numeracy skills: storybook reading predicted numeracy outcomes only until HNE was included in the models. Therefore, the results of their study lend only partial support to the current study in terms of explaining the importance of HNE for skill development. Many of the previous studies have not included autoregressive controls in their models (as an exception, see Khanolainen et al., 2020). Our models gave a stringent test to the hypothesis by controlling for the skill level at the previous time point. Here, we are examining if shared reading affects developing faster in each skill, not merely examining uni-directional associations.

## Children's Early Numeracy and Language Skills Predicted Home Literacy and Numeracy Environment

With respect to research question 3, our analysis revealed evocative/active effects running from children's skills to activities with parents

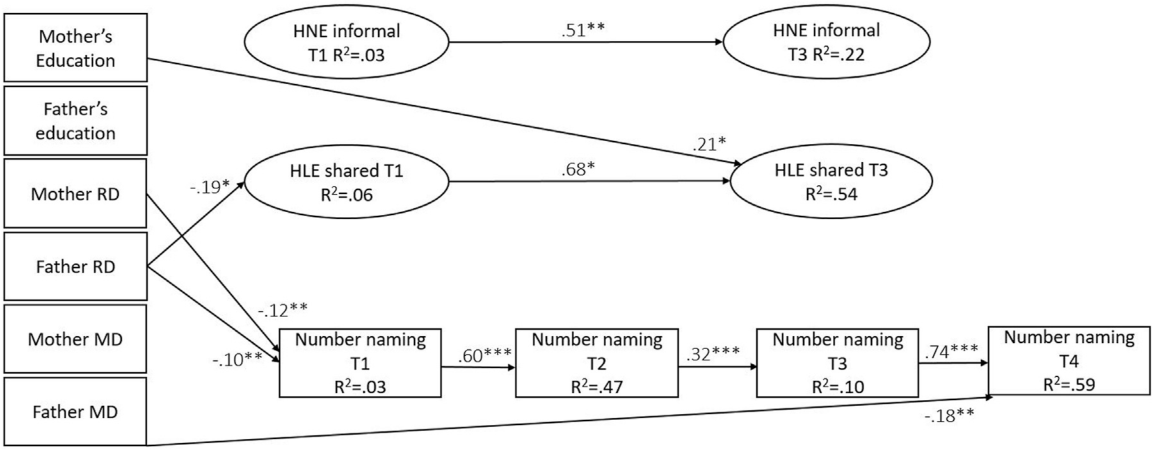


**FIGURE 8 |** The model for number naming with the significant standardized estimates. Note: In addition to the regression paths depicted, there were two significant residual correlations: between HNE and HLE at T1 (stand. estimate = 0.41***) and between HNE and number naming skill at T1 (stand. estimate = 0.39**).

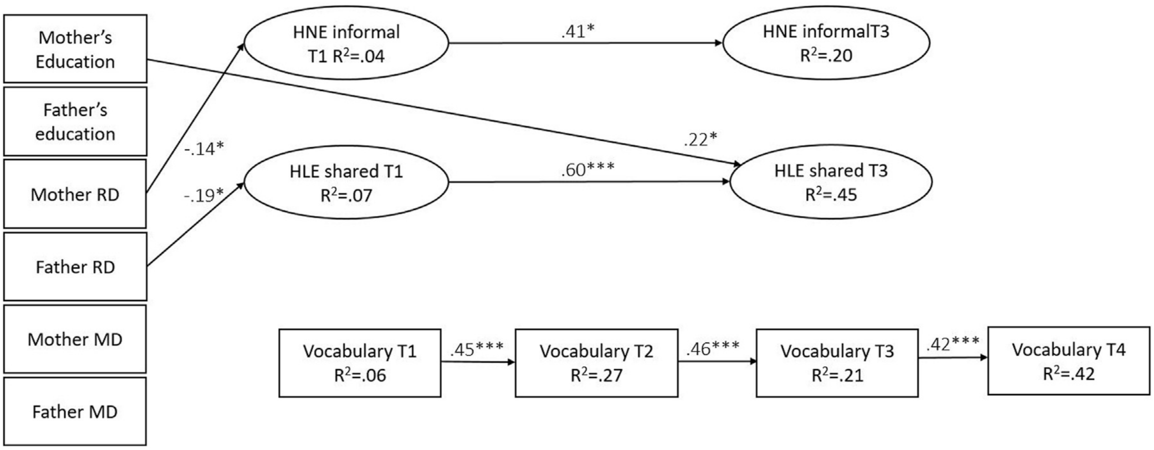


**FIGURE 9 |** The model for vocabulary with the significant standardized estimate. Note: In addition to the regression paths depicted, there was one significant residual correlation: between HNE and HLE at T1 (stand. estimate = 0.42***).

at home (e.g., Plomin et al., 1977; Scarr and McCartney, 1983; Pomerantz and Eaton, 2001; Rutter et al., 2006). These results add to the scarce studies by increasing understanding on how young children actively shape their learning environments by attracting responses in their home environments.

The results confirmed within-domain association, as children's number symbol identification skill at the second time point (age 3.5) negatively predicted HNE activities at the third time point (5.5). There are three viable ways to explain the negative association. First, the results might imply that if children have poor numeracy skills, their parents are observant to this and want to do more to support the skill development (i.e., increase the frequency of informal, shared numeracy-related activities that are easily integrated into daily activities and parent-child interaction: an evocative effect on environment). A similar association has been identified in a follow-up from kindergarten through first grade: Parents of children with low math skills increased the frequency of their home numeracy activities more than others (Silinskas et al., 2020). Second, the findings could also be explained by children's early vs. late emerging number symbol identification skills. It is noteworthy that there is a two-year gap between measuring children's skills in time points 2 and 3. This could mean that for those children whose skills were poorer at time point 2, the skill could have emerged later during the two-year timeframe, increasing their motivation and interest toward numeracy, to which parents responded by increasing the frequency of informal HNE activities, as suggested by Silinskas et al. (2020). Third, the results could also be interpreted from the opposite perspective, implying that more skilled children (i.e., children who already identify number symbols) might lose their interest in informal HNE and attract their parents to do more complex at-home numeracy activities and formal teaching of math (e.g.,

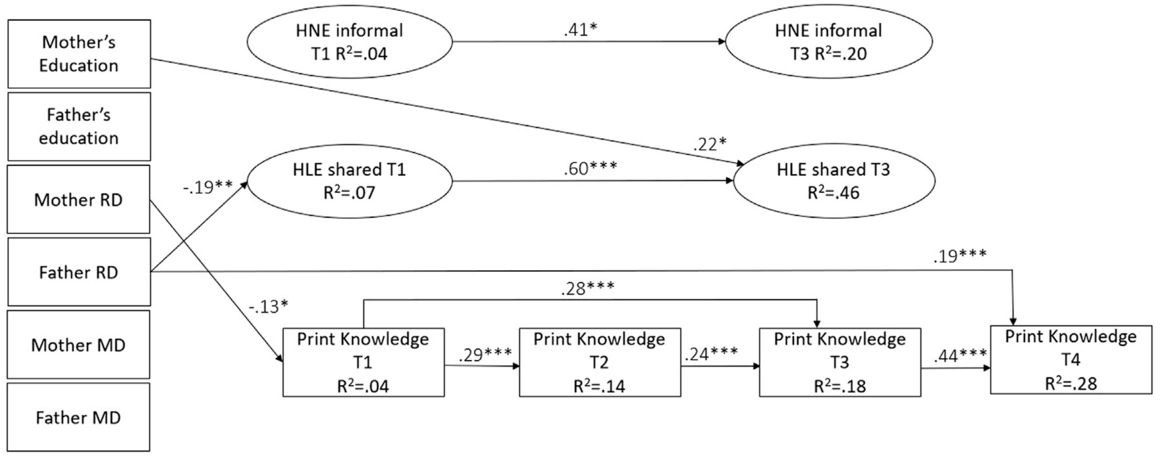


**FIGURE 10 |** The model for print knowledge with the significant standardized estimates. Note: In addition to the regression paths depicted, there were three significant residual correlations: between HNE and HLE at T1 (stand. estimate = 0.38***) and between HNE and print knowledge at T1 (stand. estimate = 0.24*), and between HLE and print knowledge at T3 (stand. estimate = –0.27**).

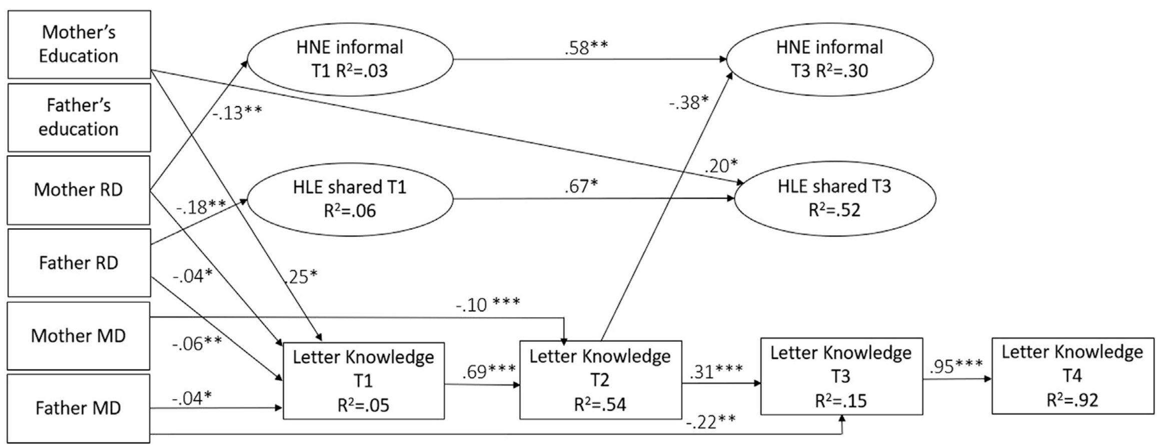


**FIGURE 11 |** The model for letter knowledge with the significant standardized estimates. Note: In addition to the regression paths depicted, there were two significant residual correlations: between HNE and HLE at T1 (stand. estimate = 0.42***) and between HNE and letter knowledge at T1 (stand. estimate = 0.49**).

teaching simple sums), which could explain the decrease in the frequency of informal HNE. This explanation can be bolstered with the findings of Thompson et al. (2017), showing that parents engage in complex, direct activities with higher frequency with 4-year-olds than 3-year-olds, suggesting that the complexity of HNE increases as children grow older. Furthermore, albeit in HLE, a similar mechanism of active effects, that is, parents teaching those children who mastered the basics of reading more often than others, was identified in a study by Silinskas et al. (2010). The results of the current study imply that a similar effect could apply to emerging numeracy skills and HNE. However, this explanation would need further research, as the current study did not include numeracy teaching items at home.

Cross-domain findings were identified for both early numeracy and literacy skills. First, children's letter knowledge at the second time point (age 3.5) negatively predicted HNE activities at the third time point (5.5). Also, children's skills in counting objects and number sequencing at the second time point (age 3.5) negatively predicted shared reading (HLE) at the third time point (age 5.5). A negative association could again be explained through children's active evocative role and interest: The children whose letter knowledge skills are good might show more interest and motivation toward literacy-related tasks in the home environment, leading parents to provide less support on numeracy-related tasks and instead put more effort on literacy-related activities at home. In line with this proposition, children who are strong in number sequencing might attract more frequent numeracy-related activities with their parents and engage less in at-home activities with literacy content. Although there is an evident lack of studies having identified evocative cross-domain effects between children's

**TABLE 5 |** All indirect paths for models provided in **Figures 4–11** (mediation analysis results).

| Path estimates | Model for counting objects: estimate (s.e.) | Model for number producing: estimate (s.e.) | Model for number sequencing: estimate (s.e.) | Model for number naming: estimate (s.e.) | Model for vocabulary: estimate (s.e.) | Model for print knowledge: estimate (s.e.) | Model for letter knowledge: estimate (s.e.) |
|---|---|---|---|---|---|---|---|
| Mothers' education → HNE at T1 → Child skill at T2 | 0.03 (0.05) | 0.00 (0.06) | 0.00 (0.02) | 0.01 (0.03) | 0.01 (0.03) | 0.00 (0.02) | 0.00 (0.01) |
| Mothers' education → HLE at T1 → Child skill at T2 | –0.01 (0.02) | –0.02 (0.02) | 0.03 (0.03) | –0.02 (0.02) | 0.01 (0.02) | 0.01 (0.02) | –0.01 (0.02) |
| Fathers' education → HNE at T1 → Child skill at T2 | 0.00 (0.04) | 0.02 (0.06) | 0.00 (0.01) | 0.00 (0.02) | 0.00 (0.02) | 0.00 (0.02) | 0.00 (0.01) |
| Fathers' education → HLE at T1 → Child skill at T2 | 0.00 (0.01) | 0.01 (0.01) | –0.01 (0.02) | 0.01 (0.01) | –0.00 (0.01) | 0.00 (0.01) | 0.00 (0.01) |
| Mothers' reading difficulties → HNE at T1 → Child skill at T2 | –0.04 (0.03) | –0.08 (0.05) | –0.02 (0.02) | –0.02 (0.02) | –0.03 (0.02) | –0.02 (0.02) | –0.00 (0.02) |
| Mothers' reading difficulties → HLE at T1 → Child skill at T2 | –0.00 (0.01) | –0.01 (0.01) | 0.01 (0.01) | –0.01 (0.01) | 0.00 (0.01) | 0.01 (0.01) | –0.01 (0.01) |
| Fathers' reading difficulties → HNE at T1 → Child skill at T2 | 0.00 (0.03) | –0.02 (0.05) | 0.00 (0.01) | 0.00 (0.02) | 0.01 (0.02) | 0.01 (0.02) | –0.00 (0.01) |
| Fathers' reading difficulties → HLE at T1 → Child skill at T2 | 0.01 (0.02) | 0.02 (0.02) | –0.03 (0.02) | 0.02 (0.02) | –0.01 (0.02) | –0.01 (0.02) | 0.01 (0.02) |
| Mothers' math difficulties → HNE at T1 → Child skill at T2 | –0.01 (0.03) | –0.02 (0.04) | –0.01 (0.01) | 0.01 (0.02) | –0.01 (0.02) | –0.01 (0.02) | –0.00 (0.01) |
| Mothers' math difficulties → HLE at T1 → Child skill at T2 | –0.00 (0.00) | –0.00 (0.01) | 0.00 (0.01) | –0.00 (0.01) | 0.00 (0.00) | 0.00 (0.01) | –0.00 (0.01) |
| Fathers' math difficulties → HNE at T1 → Child skill at T2 | 0.01 (0.03) | 0.01 (0.03) | 0.00 (0.01) | 0.01 (0.02) | 0.00 (0.02) | –0.00 (0.01) | –0.00 (0.01) |
| Fathers' math difficulties → HLE at T1 → Child skill at T2 | –0.00 (0.00) | –0.00 (0.01) | 0.00 (0.01) | –0.00 (0.01) | 0.00 (0.00) | 0.00 (0.01) | 0.00 (0.00) |
| HLE at T1 → Child skill at T2 → HLE at T3 | 0.01 (0.02) | –0.00 (0.01) | –0.03 (0.03) | 0.00 (0.01) | –0.00 (0.00) | 0.01 (0.01) | 0.00 (0.01) |
| HNE at T1 → Child skill at T2 → HLE at T3 | –0.06 (0.04) | 0.01 (0.04) | –0.02 (0.03) | –0.00 (0.02) | –0.01 (0.02) | 0.01 (0.02) | –0.00 (0.01) |
| HLE at T1 → Child skill at T2 → HNE at T3 | 0.01 (0.02) | 0.05 (0.05) | 0.00 (0.02) | 0.02 (0.03) | 0.00 (0.01) | 0.01 (0.02) | 0.03 (0.04) |
| HNE at T1 → Child skill at T2 → HNE at T3 | –0.05 (0.08) | –0.16 (0.13) | 0.00 (0.01) | –0.04 (0.05) | 0.02 (0.03) | 0.02 (0.02) | –0.03 (0.08) |
| Child skill at T2 → HNE at T3 → Child skill at T4 | — | — | 0.00 (0.00) | –0.01 (0.01) | –0.01 (0.01) | 0.02 (0.03) | 0.00 (0.01) |
| Child skill at T2 → HLE at T3 → Child skill at T4 | — | — | –0.00 (0.02) | 0.00 (0.00) | –0.00 (0.02) | –0.01 (0.01) | 0.00 (0.00) |

*Note. No significant mediation paths were found (with* p *< 0.05).*

literacy and numeracy skills and HNE and HLE, this explanation of the current study could be connected to prior findings through the mechanism of parents teaching more skilled children (e.g., Silinskas et al., 2012), which with these results would extend its effects on decrease in the home activities on the other domain. These cross-domain findings imply that parents react by doing what better supports the development of their children, and that children's active, evocative role in steering the parent's activities is evident, although more research is needed.

## No Indirect Effects From Parental RD, MD, or Educational Level on Children's Numeracy and Literacy Development Through the Home Environment

Albeit the mediation analysis revealed that significant effects from parental measures to children's skills (in the case of letter knowledge, number production, number identification, number sequences, and counting objects) became nonsignificant after adding the HLE and HNE factors, suggesting the impact of parental measures on children's skill development *via* home environment, neither parental education nor parental RD or MD had significant indirect effects on children's skill development via HNE or HLE (research questions 4). Consequently, our findings did not provide support for the mechanism that parental factors influence via differential home environments on children's skill development in these families (in line with Caglar-Ryeng et al., 2020; Elbro et al., 1998; Khanolainen et al., 2020; Torppa et al., 2007; van Bergen et al., 2014). However, as our study focuses only on the frequency of informal HNE and HLE activities, it is possible there are other differences between the families with and without parental RD or MD. All the predictive effects from parental variables accounted for only a little of the variance in children's skills, ranging from below one percent to little over four percent. Despite the small effects, the effects were still present for many skills and emerged over and above autoregressive and home environment controls, which suggests a unique role for parental RD and MD in children's skill development. However, future studies should aim to include latent variables for all measures to manage measurement error, assess parental skills with actual skill tests, and include a broader assessment of HNE and HLE. It is also worthy of consideration to explore the role of other environments, such as enrollment in institutional ECEC, where emerging literacy skills and abilities in integrating numeracy into several daily activities are more systematically emerging in children's lives.

## Limitations and Future Directions

This study is not without its limitations, with most relating to measures used. First, for children's emerging numeracy skills, we did not have nonsymbolic measures albeit evidence exists on the importance of approximate number system, for development of symbolic numerical skills (e.g., Feigenson et al., 2013). Despite that our existing symbolic measures yielded significant associations with FR, HLE, and HNE measures, it would nevertheless be important to include nonsymbolic tasks to future studies. Furthermore, we were not able to calculate reliabilities for all of the children's measures, particularly so for the numeracy measures. This is because the tasks items become increasingly difficult as the test progresses, and due to the discontinuation rules in place, not all the children completed all the items. Therefore, calculation of the Cronbach alpha, which is a measure of item cohesion within a test, is not meaningful and becomes impossible to calculate due to missingness by test design. If we only use the items that all children have responses, we do not have enough variation to calculate meaningful reliability indices. In our data, the time-gap is also too long for the calculation of test-re-test reliabilities. Second, this study deployed single measures for parental RD and MD and children's literacy and numeracy skills. Although we included HNE and HLE into the models as latent factors and thus minimized measurement error, the same was thus impossible for the other constructs. For children's skills, it was impossible to form similar latent factors across time because of varying correlation patterns. This was also expected, as we assessed several early number skills that theoretically emerge as more distinct skills in the early development with integration occurring later in development (e.g., Purpura et al., 2017b). As we wished to control for the autoregressive effects, the estimation of separate models for each skill seemed inevitable. Third, the assessment of parental RD and MD was based on single-item self-reports. This is not ideal, as self-reports may be affected by the individual's reference group, his or her educational and occupational pathways, or the positivity/negativity of views on self the individual has in general. Therefore, in future studies, we recommend the use of direct parental skill assessments, as they have been shown to predict children's skill development (e.g., Puglisi et al., 2017). If that is impossible, use of a more detailed questionnaire with multiple items on the specific difficulties one may face with RD or MD is recommended (e.g., Pennington and Lefly, 2001).

Fourth, HNE and HLE measures were based on parental reported activities at home. Questionnaire-based assessments are limited and threatened by bias due to over-reporting of activities, but parents may also have difficulties accurately identifying the frequency of these activities in the home (Elliot and Bachman, 2018). All HNE and HLE activities were focused on the informal home environment, and we recognize that there may be other environmental influences at home affecting children's skills. Such factors could be the direct teaching of numeracy and literacy skills, which in prior studies have been associated with both literacy (e.g., Sénéchal and LeFevre, 2002; Sénéchal and LeFevre, 2014) and numeracy skills (e.g., Skwarchuk et al., 2014), especially with older children. Future studies should also include complex formal teaching activities to better understand the full impact of home environment activities, especially because studies combining formal and informal HNE and HLE in an early onset study are basically nonexistent. Also, all the items of HLE and HNE were based on shared parent-child activities. Such items are the most influential regarding children's skill development (Melhuish et al., 2008), but it may be that access to literacy and numeracy content (e.g., frequency of library visits, amount of books, and other play materials) should have also been assessed. Nevertheless, the current sample comes from Finland and participated in ECEC, where children have solid access to print and numbers. However, in some other contexts or samples, children may be more deprived of opportunities to get access to materials (no access to a library, no games or books at home), and that can be detrimental to their learning opportunities. The sheer access or even frequency of interactions may not be enough if the quality of interactions is not sufficient. In this study, we did not include interaction quality measures, which could provide a better understanding of what aspects of HLE and HNE support children's skill development. Future studies should therefore complement the inspection of the home learning environment with observations (e.g., Totsika and Sylva, 2004) focusing on the quality of the home environment alongside the quantity. Fifth, children and families were recruited from a relatively limited geographical area (one municipality), with a rather high proportion of highly educated parents; therefore, it would be preferable to replicate the study in a more representative sample.

Future studies examining the underpinnings of early literacy and numeracy development should also consider the impact of literacy and numeracy environments in formal ECEC. Although the number of ECEC children under 3 years old is lower in Finland than in the OECD countries on average (European Commission/EACEA/Eurydice/Eurostat, 2019), exposure to a more formal instructional environment alongside the home environment plays an important supportive role in developing both emerging literacy and numeracy skills (Anders et al., 2012). Based on the findings of the current study, this might be important for children with FR for RD or MD.

## CONCLUSION

Overall, the current study suggests that the associations between parental measures, home environments, and young children's developing literacy and numeracy skills emerge as early as toddlerhood. It is also of importance to note that at this important developmental stage, the associations between the growing child and his or her home environment were reciprocal and not limited to within-domain effects. It thus appears that the early risk factors for RD and MD regarding measures of home environment and parental skills are at least partially shared years before school entry and might give at least a partial explanation for the rather high covariance and comorbid problems in reading and math later on.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

## ETHICS STATEMENT

The studies involving human participants were conducted under the regimes and regulations of the Ethical Committee of the University of Jyväskylä and the Finnish Advisory Board on Research Integrity (2012). Written informed consent to participate in this study was provided by the children's legal guardian/next of kin. Parents gave informed consent regarding their own participation.

## AUTHOR CONTRIBUTIONS

JS wrote the first draft of the manuscript. DK and MT conducted the data analysis, and TK and JS contributed to planning and preparing the data for analysis. JS and M-KL were responsible for the research design and data collection. All authors actively contributed to deciding the research design, the manuscript writing and editing, and all authors read and approved the submitted version.

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## REFERENCES

Anders, Y., Rossbach, H.-G., Weinert, S., Ebert, S., Kuger, S., Lehrl, S., et al. (2012). Home and Preschool Learning Environments and Their Relations to the Development of Early Numeracy Skills. *Early Child. Res. Q.* 27 (2), 231–244. doi:10.1016/j.ecresq.2011.08.003

Baker, C. E. (2014). African American Fathers' Contributions to Children's Early Academic Achievement: Evidence from Two-Parent Families from the Early Childhood Longitudinal Study-Birth Cohort. *Early Educ. Develop.* 25, 19–35. doi:10.1080/10409289.2013.764225

Blevins-Knabe, B., and Musun-Miller, L. (1996). Number Use at home by Children and Their Parents and its Relationship to Early Mathematical Performance. *Early Develop. Parenting: Int. J. Res. Pract.* 5 (1), 35–45. doi:10.1002/(SICI)1099-0917(199603)5:1<35:AID-EDP113>3.0.CO;2-0

Caglar-Ryeng, Ø., Eklund, K., and Nergård-Nilssen, T. (2020). The Effects of Book Exposure and reading Interest on Oral Language Skills of Children with and without a Familial Risk of Dyslexia. *Dyslexia* 26 (4), 394–410. doi:10.1002/dys.1657

Chow, B. W.-Y., Chui, B. H.-T., Lai, M. W.-C., and Kwok, S. Y. C. L. (2017). Differential Influences of Parental home Literacy Practices and Anxiety in English as a Foreign Language on Chinese Children's English Development. *Int. J. Bilingual Educ. Bilingualism* 20, 625–637. doi:10.1080/13670050.2015.1062468

Chu, F. W., vanMarle, K., Rouder, J., and Geary, D. C. (2018). Children's Early Understanding of Number Predicts Their Later Problem-Solving Sophistication in Addition. *J. Exp. Child. Psychol.* 169, 73–92. doi:10.1016/j.jecp.2017.12.010

Daucourt, M. C., Napoli, A., Quinn, J. M., Wood, S. G., and Hart, S. A. (2021, The Home Math Environment and Children's Math Achievement: A Meta-Analysis). PsyArXiv. May 25. doi:10.31234/osf.io/n4b2a

Davidse, N. J., De Jong, M. T., and Bus, A. G. (2014). Explaining Common Variance Shared by Early Numeracy and Literacy. *Read. Writ* 27, 631–648. doi:10.1007/s11145-013-9465-0

de Zeeuw, E. L., de Geus, E. J. C., and Boomsma, D. I. (2015). Meta-analysis of Twin Studies Highlights the Importance of Genetic Variation in Primary School Educational Achievement. *Trends Neurosci. Educ.* 4, 69–76. doi:10.1016/j.tine.2015.06.001

DeFlorio, L., and Beliakoff, A. (2015). Socioeconomic Status and Preschoolers' Mathematical Knowledge: The Contribution of home Activities and Parent Beliefs. *Early Educ. Develop.* 26 (3), 319–341. doi:10.1080/10409289.2015.968239

Dilnot, J., Hamilton, L., Maughan, B., and Snowling, M. J. (2017). Child and Environmental Risk Factors Predicting Readiness for Learning in Children at High Risk of Dyslexia. *Dev. Psychopathol* 29, 235–244. doi:10.1017/S0954579416000134

Dunn, L., and Dunn, L. (1981). *The Peabody Picture Vocabulary Test-Revised.* Circle Pines, MN: American Guidance Service.

Elbro, C., Borstrøm, I., and Petersen, D. K. (1998). Predicting Dyslexia from Kindergarten: The Importance of Distinctness of Phonological Representations of Lexical Items. *Reading Res. Q.* 33, 36–60. doi:10.1598/RRQ.33.1.3

Elliott, L., and Bachman, H. J. (2018). How Do Parents foster Young Children's Math Skills? *Child. Dev. Perspect.* 12, 16–21. doi:10.1111/cdep.12249

Esmaeeli, Z., Lundetrae, K., and Kyle, F. E. (2018). What Can Parents' Self-Report of Reading Difficulties Tell Us about Their Children's Emergent Literacy at School Entry? *Dyslexia* 24, 84–105. doi:10.1002/dys.1571

Esmaeeli, Z., Kyle, F. E., and Lundetræ, K. (2019). Contribution of Family Risk, Emergent Literacy and Environmental Protective Factors in Children's reading Difficulties at the End of Second-Grade. *Read. Writ* 32 (9), 2375–2399. doi:10.1007/s11145-019-09948-5

European Commission/EACEA/Eurydice (2019). *Key Data on Early Childhood Education and Care in Europe*. Eurydice Report. 2019 Edition. Luxembourgh: Publications Office of the European Union. Available at: https://ec.europa.eu/eurostat/documents/3217494/5785249/EC-01-14-484-EN.PDF/cbdf1804-a139-43a9-b8f1ca5223eea2a1.

Evans, M. A., and Shaw, D. (2008). Home Grown for reading: Parental Contributions to Young Children's Emergent Literacy and Word Recognition. *Can. Psychology/Psychologie Canadienne* 49, 89–95. doi:10.1037/0708-5591.49.2.89

Feigenson, L., Libertus, M. E., and Halberda, J. (2013). Links between the Intuitive Sense of Number and Formal Mathematics Ability. *Child. Dev. Perspect.* 7 (2), 74–79. doi:10.1111/cdep.12019

Geary, D. C., vanMarle, K., Chu, F. W., Rouder, J., Hoard, M. K., and Nugent, L. (2018). Early Conceptual Understanding of Cardinality Predicts Superior School-Entry Number-System Knowledge. *Psychol. Sci.* 29, 191–205. doi:10.1177/0956797617729817

Gerber, R. J., Wilks, T., and Erdie-Lalena, C. (2010). Developmental Milestones: Motor Development. *Pediatr. Rev.* 31, 267–277. doi:10.1542/pir.31-7-267

Hamilton, L. G., Hayiou-Thomas, M. E., Hulme, C., and Snowling, M. J. (2016). The home Literacy Environment as a Predictor of the Early Literacy Development of Children at Family-Risk of Dyslexia. *Sci. Stud. Read.* 20 (5), 401–419. doi:10.1080/10888438.2016.1213266

Hannula, M. M., and Lehtinen, E. (2005). Spontaneous Focusing on Numerosity and Mathematical Skills of Young Children. *Learn. Instruction* 15 (3), 237–256. doi:10.1016/j.learninstruc.2005.04.005

Hart, S. A., Ganley, C. M., and Purpura, D. J. (2016). Understanding the Home Math Environment and its Role in Predicting Parent Report of Children's Math Skills. *PloS one* 11, e0168227. doi:10.1371/journal.pone.0168227

Hart, S. A., Petrill, S. A., DeThorne, L. S., Deater-Deckard, K., Thompson, L. A., Schatschneider, C., et al. (2009). Environmental Influences on the Longitudinal Covariance of Expressive Vocabulary: Measuring the home Literacy Environment in a Genetically Sensitive Designfluences on the Longitudinal Covariance of Expressive Vocabulary: Measuring the home Literacy Environment in a Genetically Sensitive Design. *J. Child. Psychol. Psychiatry* 50, 911–919. doi:10.1111/j.1469-7610.2009.02074.x

Hjetland, H. N., Brinchmann, E. I., Scherer, R., Hulme, C., and Melby-Lervåg, M. (2020). Preschool Pathways to reading Comprehension: A Systematic Meta-Analytic Review. *Educ. Res. Rev.* 30, 100323. doi:10.1016/j.edurev.2020.100323

Hulme, C., Nash, H. M., Gooch, D., Lervåg, A., and Snowling, M. J. (2015). The Foundations of Literacy Development in Children at Familial Risk of Dyslexia. *Psychol. Sci.* 26 (12), 1877–1886. doi:10.1177/0956797615603702

Khanolainen, D., Psyridou, M., Silinskas, G., Lerkkanen, M. K., Niemi, P., Poikkeus, A. M., et al. (2020). Longitudinal Effects of the Home Learning Environment and Parental Difficulties on Reading and Math Development across Grades 1-9. *Front. Psychol.* 11, 577981. doi:10.3389/fpsyg.2020.577981

Kleemans, T., Peeters, M., Segers, E., and Verhoeven, L. (2012). Child and home Predictors of Early Numeracy Skills in Kindergarten. *Early Child. Res. Q.* 27 (3), 471–477. doi:10.1016/j.ecresq.2011.12.004

Knafo, A., and Jaffee, S. R. (2013). Gene-environment Correlation in Developmental Psychopathology. *Dev. Psychopathol* 25, 1–6. doi:10.1017/S0954579412000855

Koponen, T., Aunola, K., and Nurmi, J.-E. (2019). Verbal Counting Skill Predicts Later Math Performance and Difficulties in Middle School. *Contemp. Educ. Psychol.* 59, 101803. doi:10.1016/j.cedpsych.2019.101803

Koponen, T., Salmi, P., Torppa, M., Eklund, K., Aro, T., Aro, M., et al. (2016). Counting and Rapid Naming Predict the Fluency of Arithmetic and reading Skills. *Contemp. Educ. Psychol.* 44-45, 83–94. doi:10.1016/j.cedpsych.2016.02.004

Korpipää, H., Koponen, T., Aro, M., Tolvanen, A., Aunola, K., Poikkeus, A.-M., et al. (2017). Covariation between reading and Arithmetic Skills from Grade 1 to Grade 7. *Contemp. Educ. Psychol.* 51, 131–140. doi:10.1016/j.cedpsych.2017.06.005

Korpipää, H., Moll, K., Aunola, K., Tolvanen, A., Koponen, T., Aro, M., et al. (2020). Early Cognitive Profiles Predicting reading and Arithmetic Skills in Grades 1 and 7. *Contemp. Educ. Psychol.* 60, 101830. doi:10.1016/j.cedpsych.2019.101830

Landerl, K., and Moll, K. (2010). Comorbidity of Learning Disorders: Prevalence and Familial Transmission. *J. Child. Psychol. Psychiatry* 51 (3), 287–294. doi:10.1111/j.1469-7610.2009.02164.x

LeFevre, J.-A., Skwarchuk, S.-L., Smith-Chant, B. L., Fast, L., Kamawar, D., and Bisanz, J. (2009). Home Numeracy Experiences and Children's Math Performance in the Early School Years. *Can. J. Behav. Science/Revue canadienne des Sci. du comportement* 41, 55–66. doi:10.1037/a0014532

LeFevre, J. A., Fast, L., Skwarchuk, S. L., Smith-Chant, B. L., Bisanz, J., Kamawar, D., et al. (2010). Pathways to Mathematics: Longitudinal Predictors of Performance. *Child. Dev.* 81 (6), 1753–1767. doi:10.1111/j.1467-8624.2010.01508.x

Lerkkanen, M.-K., Poikkeus, A.-M., and Ketonen, R. (2006). *ARMI—Luku- Ja Kirjoitustaidon Arviointimateriaali 1.Luokalle [ARMI—A Tool for Assessing reading and Writing Skills in Grade 1*. Helsinki, Finland: WSOY.

Lerkkanen, M.-K., and Salminen, J. (2015–2019). *Interaction, Development & Learning (VUOKKO) Study*. Unpublished data. Finland: University of Jyväskylä.

Levin, I., Levy-Shiff, R., Appelbaum-Peled, T., Katz, I., Komar, M., and Meiran, N. (1997). Antecedents and Consequences of Maternal Involvement in Children's Homework: A Longitudinal Analysis. *J. Appl. Dev. Psychol.* 18, 207–227. doi:10.1016/S0193-3973(97)90036-8

Lohvansuu, K., Torppa, M., Ahonen, T., Eklund, K., Hämäläinen, J. A., Leppänen, P. H. T., et al. (2021). Unveiling the Mysteries of Dyslexia-Lessons Learned from the Prospective Jyväskylä Longitudinal Study of Dyslexia. *Brain Sci.* 11, 427. doi:10.3390/brainsci11040427

Lonigan, C. J., Wagner, R. K., Torgesen, J. K., and Rashotte, C. A. (2007). *TOPEL: Test of Preschool Early Literacy*. Austin: TX: Pro.

MacKinnon, D. P. (2008). *Introduction to Statistical Mediation Analysis*. New York: Lawrence Erlbaum Associates.

Manolitsis, G., Georgiou, G. K., and Tziraki, N. (2013). Examining the Effects of home Literacy and Numeracy Environment on Early reading and Math Acquisition. *Early Child. Res. Q.* 28 (4), 692–703. doi:10.1016/j.ecresq.2013.05.004

Maydeu-Olivares, A. (2017). Maximum Likelihood Estimation of Structural Equation Models for Continuous Data: Standard Errors and Goodness of Fit. *Struct. Equation Model. A Multidisciplinary J.* 24, 383–394. doi:10.1080/10705511.2016.126960610.1080/10705511.2016.1269606

Melhuish, E. C., Phan, M. B., Sylva, K., Sammons, P., Siraj-Blatchford, I., and Taggart, B. (2008). Effects of the home Learning Environment and Preschool center Experience upon Literacy and Numeracy Development in Early Primary School. *J. Soc. Issues* 64, 95–114. doi:10.1111/j.1540-4560.2008.00550.x

Missall, K., Hojnoski, R. L., Caskie, G. I. L., and Repasky, P. (2015). Home Numeracy Environments of Preschoolers: Examining Relations Among Mathematical Activities, Parent Mathematical Beliefs, and Early Mathematical Skills. *Early Educ. Develop.* 26, 356–376. doi:10.1080/10409289.2015.968243

Mol, S. E., and Bus, A. G. (2011). To Read or Not to Read: a Meta-Analysis of Print Exposure from Infancy to Early Adulthood. *Psychol. Bull.* 137, 267–296. doi:10.1037/a0021890

Moll, K., Landerl, K., Snowling, M. J., and Schulte-Körne, G. (2019). Understanding Comorbidity of Learning Disorders: Task-dependent Estimates of Prevalence. *J. Child. Psychol. Psychiatry* 60 (3), 286–294. doi:10.1111/jcpp.12965

Mutaf Yıldız, B., Sasanguie, D., De Smedt, B., and Reynvoet, B. (2018). Frequency of home Numeracy Activities Is Differentially Related to Basic Number Processing and Calculation Skills in Kindergartners. *Front. Psychol.* 9, 340. doi:10.3389/fpsyg.2018.00340

Mutaf-Yıldız, B., Sasanguie, D., De Smedt, B., and Reynvoet, B. (2020). Probing the Relationship between home Numeracy and Children's Mathematical Skills: A Systematic Review. *Front. Psychol.* 11, 2074. doi:10.3389/fpsyg.2020.02074

Napoli, A. R., and Purpura, D. J. (2018). The home Literacy and Numeracy Environment in Preschool: Cross-Domain Relations of Parent-Child Practices and Child Outcomes. *J. Exp. Child. Psychol.* 166, 581–603. doi:10.1016/j.jecp.2017.10.002

Niklas, F., and Schneider, W. (2014). Casting the die before the die is cast: The importance of the home numeracy environment for preschool children. *Eur. J. Psychol. Educ.* 29 (3), 327–345. doi:10.1007/s10212-013-0201-6

Pennington, B. F., and Lefly, D. L. (2001). Early reading Development in Children at Family Risk for Dyslexia. *Child. Dev.* 72, 816–833. doi:10.1111/1467-8624.00317

Petrill, S. A., Deater-Deckard, K., Schatschneider, C., and Davis, C. (2005). Measured Environmental Influences on Early reading: Evidence from an Adoption Study. *Scientific Stud. Reading* 9 (3), 237–259. doi:10.1207/s1532799xssr0903_4

Plomin, R., DeFries, J. C., and Loehlin, J. C. (1977). Genotype-environment Interaction and Correlation in the Analysis of Human Behavior. *Psychol. Bull.* 84 (2), 309–322. doi:10.1037/0033-2909.84.2.309

Pomerantz, E. M., and Eaton, M. M. (2001). Maternal Intrusive Support in the Academic Context: Transactional Socialization Processes. *Dev. Psychol.* 37 (2), 174–186. doi:10.1037/0012-1649.37.2.174

Psyridou, M., Eklund, K., Poikkeus, A. M., and Torppa, M. (2018). Reading Outcomes of Children with Delayed Early Vocabulary: A Follow-Up from Age 2-16. *Res. Dev. Disabil.* 78, 114–124. doi:10.1016/j.ridd.2018.05.004

Puglisi, M. L., Hulme, C., Hamilton, L. G., and Snowling, M. J. (2017). The Home Literacy Environment Is a Correlate, but Perhaps Not a Cause, of Variations in Children's Language and Literacy Development. *Sci. Stud. Read.* 21, 498–514. doi:10.1080/10888438.2017.1346660

Puolakanaho, A., Ahonen, T., Aro, M., Eklund, K., Leppänen, P. H., Poikkeus, A. M., et al. (2007). Very Early Phonological and Language Skills: Estimating Individual Risk of reading Disability. *J. Child. Psychol. Psychiatry* 48 (9), 923–931. doi:10.1111/j.1469-7610.2007.01763.x

Purpura, D. J., and Ganley, C. M. (2014). Working Memory and Language: Skill-specific or Domain-General Relations to Mathematics? *J. Exp. Child. Psychol.* 122, 104–121. doi:10.1016/j.jecp.2013.12.009

Purpura, D. J., Hume, L. E., Sims, D. M., and Lonigan, C. J. (2011). Early Literacy and Early Numeracy: the Value of Including Early Literacy Skills in the Prediction of Numeracy Development. *J. Exp. Child. Psychol.* 110, 647–658. doi:10.1016/j.jecp.2011.07.004

Purpura, D. J., Logan, J. A. R., Hassinger-Das, B., and Napoli, A. R. (2017b). Why Do Early Mathematics Skills Predict Later reading? the Role of Mathematical Language. *Dev. Psychol.* 53 (9), 1633–1642. doi:10.1037/dev0000375

Purpura, D. J., Schmitt, S. A., and Ganley, C. M. (2017a). Foundations of Mathematics and Literacy: The Role of Executive Functioning Components. *J. Exp. Child. Psychol.* 153, 15–34. doi:10.1016/j.jecp.2016.08.010

Purpura, D. J., and Reid, E. E. (2016). Mathematics and Language: Individual and Group Differences in Mathematical Language Skills in Young Children. *Early Child. Res. Q.* 36, 259–268. doi:10.1016/j.ecresq.2015.12.020

Rutter, M., Moffitt, T. E., and Caspi, A. (2006). Gene-environment Interplay and Psychopathology: Multiple Varieties but Real Effects. *J. Child. Psychol. Psychiatry* 47, 226–261. doi:10.1111/j.1469-7610.2005.01557.x

Savalei, V. (2010). Expected versus Observed Information in SEM with Incomplete normal and Nonnormal Data. *Psychol. Methods* 15, 352–367. doi:10.1037/a0020143

Scarborough, H. S., and Dobrich, W. (1994). On the Efficacy of reading to Preschoolers. *Dev. Rev.* 14 (3), 245–302. doi:10.1006/drev.1994.1010

Scarr, S., and McCartney, K. (1983). How People Make Their Own Environments: a Theory of Genotype Greater Than Environment Effects. *Child. Dev.* 54 (2), 424–435. doi:10.2307/112970310.1111/j.1467-8624.1983.tb03884.x

Schneider, M., Beeres, K., Coban, L., Merz, S., Susan Schmidt, S., Stricker, J., et al. (2017). Associations of Non-symbolic and Symbolic Numerical Magnitude Processing with Mathematical Competence: a Meta-Analysis. *Dev. Sci.* 20, 3. doi:10.1111/desc.12372

Sénéchal, M., and Lefevre, J. A. (2014). Continuity and Change in the home Literacy Environment as Predictors of Growth in Vocabulary and reading. *Child. Dev.* 85, 1552–1568. doi:10.1111/cdev.12222

Sénéchal, M., and Lefevre, J. A. (2002). Parental Involvement in the Development of Children's reading Skill: a Five-Year Longitudinal Studyfive-Year Longitudinal Study. *Child. Dev.* 73, 445–460. doi:10.1111/1467-8624.00417

Sénéchal, M., Pagan, S., Lever, R., and Ouellette, G. P. (2008). Relations Among the Frequency of Shared Reading and 4-Year-Old Children's Vocabulary, Morphological and Syntax Comprehension, and Narrative Skills. *Early Educ. Develop.* 19, 27–44. doi:10.1080/10409280701838710

Sénéchal, M. (2006). Testing the Home Literacy Model: Parent Involvement in Kindergarten Is Differentially Related to Grade 4 Reading Comprehension, Fluency, Spelling, and Reading for Pleasurefferentially Related to Grade 4 reading Comprehension Fluency, Spelling and reading for Pleasure. *Scientific Stud. Reading* 10, 59–87. doi:10.1207/s1532799xssr1001_4

Shalev, R. S., and Gross-Tsur, V. (2001). Developmental Dyscalculia. *Pediatr. Neurol.* 24, 337–342. doi:10.1016/s0887-8994(00)00258-7

Silinskas, G., Di Lonardo, S., Douglas, H., Xu, C., LeFevre, J.-A., Garckija, R., et al. (2020). Responsive home Numeracy as Children Progress from Kindergarten through Grade 1. *Early Child. Res. Q.* 53, 484–495. doi:10.1016/j.ecresq.2020.06.003

Silinskas, G., Leppänen, U., Aunola, K., Parrila, R., and Nurmi, J.-E. (2010). Predictors of Mothers' and Fathers' Teaching of reading and Mathematics during Kindergarten and Grade 1. *Learn. Instruction* 20, 61–71. doi:10.1016/j.learninstruc.2009.01.002

Silinskas, G., Lerkkanen, M.-K., Tolvanen, A., Niemi, P., Poikkeus, A.-M., and Nurmi, J.-E. (2012). The Frequency of Parents' reading-related Activities at home and Children's reading Skills during Kindergarten and Grade 1. *J. Appl. Dev. Psychol.* 33 (6), 302–310. doi:10.1016/j.appdev.2012.07.004

Silinskas, G., Niemi, P., Lerkkanen, M.-K., and Nurmi, J.-E. (2013). Children's Poor Academic Performance Evokes Parental Homework Assistance-But Does it Help? *Int. J. Behav. Develop.* 37, 44–56. doi:10.1177/0165025412456146

Silver, A. M., Elliott, L., Imbeah, A., and Libertus, M. E. (2020). Understanding the Unique Contributions of home Numeracy, Inhibitory Control, the Approximate Number System, and Spontaneous Focusing on Number for Children's Math Abilities. *Math. Think Learn.* 22 (4), 296–311. doi:10.1080/10986065.2020.1818469

Skwarchuk, S.-L. (2009). How Do Parents Support Preschoolers' Numeracy Learning Experiences at Home? *Early Child. Educ J* 37 (3), 189–197. doi:10.1007/s10643-009-0340-1

Skwarchuk, S. L., Sowinski, C., and LeFevre, J. A. (2014). Formal and Informal home Learning Activities in Relation to Children's Early Numeracy and Literacy Skills: the Development of a home Numeracy Model. *J. Exp. Child. Psychol.* 121, 63–84. doi:10.1016/j.jecp.2013.11.006

Snowling, M. J., and Melby-Lervåg, M. (2016). Oral Language Deficits in Familial Dyslexia: A Meta-Analysis and Review. *Psychol. Bull.* 142 (5), 498–545. doi:10.1037/bul0000037

Soares, N., Evans, T., and Patel, D. R. (2018). Specific Learning Disability in Mathematics: a Comprehensive Review. *Transl Pediatr.* 7, 48–62. doi:10.21037/tp.2017.08.03

Soodla, P., Lerkkanen, M.-K., Niemi, P., Kikas, E., Silinskas, G., and Nurmi, J.-E. (2015). Does Early Reading Instruction Promote the Rate of Acquisition? A Comparison of Two Transparent Orthographies. *Learn. Instruction* 38, 14–23. doi:10.1016/j.learninstruc.2015.02.002

Soto-Calvo, E., Simmons, F. R., Adams, A.-M., Francis, H. N., and Giofre, D. (2020). Pre-Schoolers' Home Numeracy and Home Literacy Experiences and Their Relationships with Early Number Skills: Evidence from a UK Study. *Early Educ. Develop.* 31, 113–136. doi:10.1080/10409289.2019.1617012

Susperreguy, M. I., Di Lonardo Burr, S., Xu, C., Douglas, H., and LeFevre, J. A. (2020). Children's Home Numeracy Environment Predicts Growth of Their Early Mathematical Skills in Kindergarten. *Child. Dev.* 91 (5), 1663–1680. doi:10.1111/cdev.13353

Thompson, R. J., Napoli, A. R., and Purpura, D. J. (2017). Age-related Differences in the Relation between the home Numeracy Environment and Numeracy Skills. *Inf. Child. Dev.* 26, e2019. doi:10.1002/icd.2019

Torppa, M., Eklund, K., van Bergen, E., and Lyytinen, H. (2015). Late-emerging and Resolving Dyslexia: A Follow-Up Study from Age 3 to 14. *J. Abnorm Child. Psychol.* 43 (7), 1389–1401. doi:10.1007/s10802-015-0003-1

Torppa, M., Lyytinen, P., Erskine, J., Eklund, K., and Lyytinen, H. (2010). Language Development, Literacy Skills, and Predictive Connections to reading in Finnish Children with and without Familial Risk for Dyslexia. *J. Learn. Disabil.* 43 (4), 308–321. doi:10.1177/0022219410369096

Torppa, M., Poikkeus, A. M., Laakso, M. L., Eklund, K., and Lyytinen, H. (2006). Predicting Delayed Letter Knowledge Development and its Relation to Grade 1 reading Achievement Among Children with and without Familial Risk for Dyslexia. *Dev. Psychol.* 42 (6), 1128–1142. doi:10.1037/0012-1649.42.6.1128

Torppa, M., Poikkeus, A.-M., Laakso, M.-L., Tolvanen, A., Leskinen, E., Leppänen, P. H. T., et al. (2007). Modeling the Early Paths of Phonological Awareness and Factors Supporting its Development in Children with and without Familial Risk of Dyslexia. *Scientific Stud. Reading* 11, 73–103. doi:10.1080/10888430709336554

Totsika, V., and Sylva, K. (2004). The home Observation for Measurement of the Environment Revisited. *Child. Adolesc. Ment. Health* 9, 25–35. doi:10.1046/j.1475-357X.2003.00073.x

van Bergen, E., van der Leij, A., and de Jong, P. F. (2014). The Intergenerational Multiple Deficit Model and the Case of Dyslexia. *Front. Hum. Neurosci.* 8, 346. doi:10.3389/fnhum.2014.00346

van Bergen, E., van Zuijen, T., Bishop, D., and de Jong, P. F. (2017). Why Are home Literacy Environment and Children's reading Skills Associated? what Parental Skills Reveal. *Read. Res. Q.* 52 (2), 147–160. doi:10.1002/rrq.160

Vanbinst, K., van Bergen, E., Ghesquière, P., and De Smedt, B. (2020). Cross-domain Associations of Key Cognitive Correlates of Early reading and Early Arithmetic in 5-Year-Olds. *Early Child. Res. Q.* 51, 144–152. doi:10.1016/j.ecresq.2019.10.009

Vandermaas-Peeler, M., Boomgarden, E., Finn, L., and Pittard, C. (2012). Parental Support of Numeracy during a Cooking Activity with Four-Year-Olds. *Int. J. Early Years Educ.* 20, 78–93. doi:10.1080/09669760.2012.663237

Watts, T. W., Duncan, G. J., Siegler, R. S., and Davis-Kean, P. E. (2014). What's Past Is Prologue: Relations between Early Mathematics Knowledge and High School Achievement. *Educ. Res.* 43, 352–360. doi:10.3102/0013189X14553660

Wright, R. J., Martland, J., and Stafford, A. K. (2006). *Early Numeracy: Assessment for Teaching and Intervention*. Thousand Oaks, CA: Sage.

Wynn, K. (1990). Children's Understanding of Counting. *Cognition* 36, 155–193. doi:10.1016/0010-0277(90)90003-3

Wynn, K. (1992). Children's Acquisition of the Number Words and the Counting System. *Cogn. Psychol.* 24 (2), 220–251. doi:10.1016/0010-0285(92)90008-P

Zhang, X., Koponen, T., Räsänen, P., Aunola, K., Lerkkanen, M. K., and Nurmi, J. E. (2014). Linguistic and Spatial Skills Predict Early Arithmetic Development via Counting Sequence Knowledge. *Child. Dev.* 85 (3), 1091–1107. doi:10.1111/cdev.12173

Ziegler, J. C., Bertrand, D., Tóth, D., Csépe, V., Reis, A., Faísca, L., et al. (2010). Orthographic Depth and its Impact on Universal Predictors of reading: A Cross-Language Investigation. *Psychol. Sci.* 21, 551–559. doi:10.1177/0956797610363406

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# Early Numeracy and Literacy Skills Among Monolingual and Bilingual Kindergarten Children

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Early numeracy and literacy skills are all the knowledge that children acquire spontaneously and independently before entering school and beginning formal learning. This knowledge is essential and forms the basis for the acquisition of reading and arithmetic in school. A bilingual child is a child who is fluent in two languages, as opposed to a monolingual child who is exposed to only one language. Bilingualism has been found to affect verbal and mathematical abilities in children, but only a few studies have focused on the early numeracy and literacy skills of preschoolers. This study examined the connection between early numeracy and literacy skills and among monolingual children as compared to bilingual children in preschool. Three hundred and two children aged 5–6 years old were recruited from 74 kindergartens. Participants were divided into two groups: 151 monolingual children who spoke and were exposed to only one language (Hebrew) and 151 bilingual children who spoke and were exposed to two languages (the bilingual children spoke different languages). Monolingual children performed better than the bilingual children in most of the literacy tasks, except for phonological awareness, in which no differences were found between the groups. In addition, in the early numeracy tasks, a difference was found only in the task, which included linguistic knowledge, number knowledge, and counting tasks, in which the monolingual children performed better. Furthermore, stronger correlations were found between the early numeracy and literacy skills among the monolingual group compared to the bilingual group. The study findings stress the importance of strengthening linguistic abilities, such as vocabulary expansion in kindergarten among populations in which more than one language is spoken. Supporting these abilities can reduce the gap between bilingual children and their monolingual classmates before entering school.

**Keywords: early literacy, early numeracy, kindergarten children, monolingualism, bilingualism**

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## INTRODUCTION

### Bilingualism

Most children around the world are exposed to more than one language. Bilingualism or multilingualism develops from learning two languages simultaneously or from initial learning of one language to which another language is added (McCardle and Hoff, 2006). Bilinguals are a heterogeneous group. There are many ways to acquire two languages: different contexts, different ages, simultaneous acquisition of two languages or in sequence, and different language pairs. It has been found that when children are exposed to two languages from infancy (early bilingualism), languages are generally better mastered than with late bilingual exposure (Kuhl and Ramirez, 2016). It is important to carefully characterize the language learning of infants and children in order to clearly understand and describe the differences in bilingual development. Identifying a profile of bilinguals that is different from monolinguals may help in tailoring their learning to help them gain needed skills, such as developing literacy in both languages (McCardle and Hoff, 2006).

The exposure of children from an early age to two languages at the same time poses challenges in language acquisition. Children are exposed to these languages from different sources (e.g., parents, other family members, friends, and the environment; Fennell et al., 2007). Studies show that acquiring and maintaining proficiency in two languages may reduce proficiency in the dominant language, whether it is the first language acquired or the second language (Misdraji-Hammond et al., 2014). Bilinguals who speak two languages sometimes must suppress one of their languages, while speaking a second language (Volmer et al., 2018).

Despite these challenges, there are also benefits of acquiring a second language. Studies have found that bilingual children have better abilities in executive functions and meta-linguistic skills (Adesope et al., 2010; Blom et al., 2014). Bilingual children have been found to have better selective attention and cognitive flexibility (Adi-Japha et al., 2010) during language use due to extensive practice of two languages. Because words in both languages are activated when one is used, bilinguals become accustomed to focusing their attention on relevant information (Bialystok, 2001). One example of this is the Stroop task, in which bilingual children performed significantly better (Poulin-Dubois et al., 2011); it should be noted that not all studies have found these advantages (for review see: Giovannoli et al., 2020).

In addition to the cognitive benefits of executive functions, there are also linguistic benefits for the bilingual group. Early studies have shown that bilingual children performed better than monolingual children on a variety of meta-linguistic awareness tests (Ben-Zeev, 1977; Bialystok, 1987). In a study that examined learning new words, which were not phonologically similar to any of the languages of the participants, an advantage in acquisition of new words was found in favor of the bilinguals (Kaushanskaya and Marian, 2009). The acquisition of languages begins at a young age, and spoken language forms the basis for the acquisition of the early literacy skills. Furthermore, bilingualism has been found to affect verbal and mathematical abilities in children; therefore, the current study will examine both of these domains.

## The Connection Between Linguistic and Numerical Abilities

Mathematical skills are closely related to language skills, which help children learn mathematics through the expression of mathematical thinking and understanding of mathematical concepts (Méndez et al., 2018). The development of the early knowledge of numbers is influenced by several non-mathematical factors, particularly by language skills (Purpura and Reid, 2016). It is suggested that simple numerical processing (calculation) depends on language, and therefore, early mathematical abilities are directly affected by language skills (Méndez et al., 2018).

Linguistic knowledge, such as general vocabulary and phonological awareness, has been found to be the most consistent and powerful predictor of early numerical abilities (Purpura and Reid, 2016). In everyday language learning, children use their knowledge of a word to learn new meanings and ideas, and a strong vocabulary may help them learn new numerical concepts in the early stages of numeracy learning (Méndez et al., 2018).

The strong connection between linguistic and numerical abilities is expressed at an early stage in children's academic development. Children who have difficulty in both areas tend to encounter significant and ongoing challenges compared to those who have difficulty in one ability only. A study found that the link between language and mathematics was stronger among native speakers than among second language speakers (Peng et al., 2020). Another study, which examined the relationship between numeracy tasks and early verbal tasks among monolingual and bilingual children in kindergarten, found that the processing of letter and number symbols shared a common cognitive component independent of specific knowledge in literacy or numeracy (Bonifacci et al., 2016).

Although a consistent relationship between general language skills and mathematical abilities has been found from early childhood, improving general language does not always lead to a positive effect on mathematical ability, which may lead to the conclusion that the relationship between these two abilities is more complex (Purpura and Reid, 2016). Therefore, the aim of this study was to examine the relationship between these two skills in depth and to investigate whether these relationships are the same among monolingual children compared to bilingual children and whether bilingualism affects the connection between language and mathematics.

## Early Literacy

Early childhood is a critical stage for the development of the early literacy skills. Studies have found that the level and quality of language that a child experiences during early childhood has a significant impact on school readiness and academic performance. Early literacy is acquired spontaneously from exposure to language in the child's environment and from learning activities such as book reading (Li et al., 2014). Sénéchal and LeFevre (2014) found that home literacy environment (HLE) has a significant role in developing early literacy abilities and in promoting reading. These findings accentuate HLE as an important factor in the development of reading abilities and linguistic skills. Moreover, it appears that forming a "language-rich environment" advances vocabulary and linguistic skills and is an important factor in promoting the early literacy abilities of preschoolers.

Exposure to preschool literacy knowledge is an important basis for developing later academic skills (Duncan et al., 2007).

Early literacy is also characterized by an interest in written things, including an awareness of letters, words, sounds, and forms that appear in language. This interest is manifested in the preoccupation with books and texts and initial attempts at reading and writing, not necessarily in accordance with the language conventions accepted by adults (Whitehurst and Lonigan, 1998). When children are exposed to new situations and new information, opportunities for cognitive and social development are created, including the development of literacy (Lukie et al., 2014).

Early literacy encompasses several areas of knowledge: phonological awareness, orthographic knowledge, morphological awareness, and vocabulary.

*Phonological awareness* refers to the ability to recognize spoken words and break them down into their sounds, such as phonemes and syllables (Abu-Rabia et al., 2013), and the understanding that a word is composed of sounds and that the letters represent different sounds (Ehri, 2005). This awareness of the connection between phonemes and the sounds of the letters is a basic ability, which develops reading and writing and is considered to predict reading in alphabetic languages, not only in the mother tongue but also in a second language (Abu-Rabia et al., 2013). Though phonological awareness underlies reading development, it does not depend on the specific language spoken by bilingual children (Leikin et al., 2010).

*Orthographic knowledge (print conventions)* refers to knowledge of the written structure of a particular language and consists of orthographic (visual) symbols in written words that help to identify words (Abu-Rabia et al., 2013). The ability to recognize letters based on visual aspects affects the development of early literacy, and exposure to words is enough to bring about orthographic learning (Schmitterer and Schroeder, 2018). It has been found that children learn to identify visual features of letters from the age of three, and when asked to write at this age, they usually do not use drawings as a form of writing (Gombert and Fayol, 1992). One of the hallmarks of reading acquisition among novice readers is familiarity with letter names. Knowing the names of letters often helps in accessing their sounds. To create effective second language word processing, mastery of orthographic knowledge must reach the level of first language automaticity (Abu-Rabia et al., 2013).

*Morphological awareness* refers to the knowledge needed in order to recognize a word, understand the forms, which create it, and produce morphologically complex words. Morphology is essential for the acquisition of reading skills because it contributes to the expansion of vocabulary and as vocabulary grows knowledge about the internal structure of words increases (Bar-On and Ravid, 2011). Studies have shown that morphological awareness affects reading comprehension and acquisition of spelling skills (Abu-Rabia et al., 2013).

*Vocabulary and morphological knowledge* refers to knowledge about words and word parts. Vocabulary is divided into two parts: depth of knowledge and breadth of knowledge. Breadth of knowledge refers to the number of words learned, and depth of knowledge refers to the quantity and quality of a person's knowledge of individual words. Knowing a word includes more than its definition. Most of the learning of words occurs when the word is encountered several times, and for this to happen, the student must be exposed to large amounts of input. Second language learners usually need to learn at a faster rate than was necessary during the acquisition of their first language, because the second language is usually taught and not acquired gradually in a developmental manner through exposure (Nagy, 1995).

Studies conducted among school-aged children suggest that vocabulary skills are a significant predictor of reading and academic achievement in monolingual children (Lee, 2011). It was also found that bilingual children's vocabulary in each of their languages is smaller than the vocabulary of monolingual children (De Houwer, 2007; Oller et al., 2007). Vocabulary is known to be significant for the development of mathematical skills as well, such as understanding mathematical concepts (Purpura et al., 2011), and it predicts computational skills at a later age (Purpura and Ganley, 2014).

The development of young children's literacy skills includes learning the system of reading and writing, as well as the components of oral language – the phonological, morphological, syntactic, and lexical aspects that characterize texts of that language. Kindergarten children with developed literacy skills have been found to experience success in acquiring the alphabetic code and becoming skilled readers at the beginning of formal reading instruction. In contrast, children with low literacy skills will most likely face difficulties during the acquisition of reading in first grade (Arafat et al., 2017).

## Bilingualism and Verbal Abilities

Bilingualism affects verbal abilities in both the first and second language. It has been found that bilingual children with reading difficulties in their mother tongue also showed difficulty in the second language. The connection between reading and writing skills in the first language and the second language is explained by oral language abilities, such as phonological, orthographic, and morphological awareness, which form the base of reading. If linguistic skills are strong in the first language, we observe the same level in the second language (Abu-Rabia et al., 2013).

Bilingual children often have difficulty acquiring early literacy skills compared to their monolingual peers (Hur et al., 2020). They often show lower achievement in school compared to their monolingual peers, which may result from the fact that the instruction at school occurs in a different language to which they speak at home. A study that examined early literacy skills among monolingual (English) and bilingual children in preschool found an improvement in early English literacy skills among bilinguals who took part in a language intervention program, which focused on vocabulary enrichment. The researchers conclude that it is important to address the unique characteristics of each child (e.g., language proficiency and language exposure), in order to promote each child's ability and strengthen their weakness (Hur et al., 2020). The literature also shows that the phonological processing skill that underlies reading development does not depend on the specific language that bilingual children speak (Leikin et al., 2010).

In addition, mastery of more than one language has been found to affect naming, which is related to language skills (Misdraji-Hammond et al., 2014). Naming and reading are interrelated in that they both depend, among other things, on the rapid execution of basic processes (Cui et al., 2017). Studies have found that bilingualism affects naming skill due to the competition between the retrieval of the word in both languages, and therefore, the naming skill of monolinguals is better than that of bilinguals, which are slower in their naming speed (Misdraji-Hammond et al., 2014).

Another study, which examined the differences in verbal abilities of English-speaking monolingual children compared to English-Spanish bilingual children, found similar performance in basic reading tasks, but there was a significant difference in the vocabulary task. The bilingual children knew fewer words in each one of the languages as compared to the monolingual children (Oller et al., 2007).

The studies above demonstrate that bilingualism can influence the acquisition of children's language skills, which later affect literacy abilities. It seems that bilingual children have longer trajectories for language acquisition and development, which may affect the timing of school-based learning of skills like literacy. The question is whether this tendency will be found also in the different aspects of early literacy skills of bilingual children.

## Early Numeracy

The development of early numeracy in children occurs during the kindergarten years, before the beginning of the formal education (Méndez et al., 2018). The development of these early quantitative abilities is a complex and ongoing process; researchers noted three routes by which children typically acquire numerical abilities: linguistic knowledge, executive functions, and numeracy knowledge (Starkey et al., 2004; Sarama and Clements, 2009; Purpura and Reid, 2016). Early numeracy skills include counting, identification of quantities, and the initial ability of addition and subtraction. These abilities develop gradually over time (Méndez et al., 2018). Early numeracy skills in kindergarten predict mathematical achievement years later: in elementary school, middle school, and even high school (Duncan et al., 2007). The process of development of numerical abilities does not occur independently (Purpura and Reid, 2016). Like early literacy, it is influenced by the environment and learned from exposure and various quantitative activities at home and in the environment.

Early numeracy includes several areas of knowledge: number knowledge, comparison of quantities, simple calculation, and verbal problem-solving.

*Number Knowledge.* Early number knowledge usually begins when young children learn to recite a list of numbers while counting. Learning to how to count and the correct order of numbers helps to build the understanding that the smaller numbers come before the bigger numbers. The knowledge that the order of numbers represent their amount forms the basis for symbolic representation of quantities at a later stage (Méndez et al., 2018). Number knowledge is one of the strongest predictors of mathematical achievement at school (Viesel-Nordmeyer et al., 2019). Findings from a meta-analysis suggested that early mathematical concepts, such as knowledge of numbers and their order were strong predictors of late mathematical learning (Duncan et al., 2007).

*Comparison of Quantities.* Understanding mathematical language is probably also related to comparing groups, in which children look at groups of dots and determine which group has the larger or smaller amount of dots, and digit comparison, in which children identify which numbers are larger or smaller (Hornburg et al., 2018).

*Simple Calculation.* This knowledge is built from the ability to disassemble and assemble quantities, as well as an early understanding of the concepts of addition and subtraction (Clements and Sarama, 2007). It has been found that infants are not only sensitive to numbers, but they can also even perform calculation operations (Mix et al., 1997).

*Verbal Problem-Solving.* This task requires complex processes above computational skills, such as reading comprehension, using linguistic information, identifying relevant information, and creating an appropriate arithmetic exercise (Swanson et al., 2021). According to mathematical development, number-related skills are necessary for solving problems that are more complex. Without concepts, children will have difficulty in more complex understanding of mathematics, for example, in applying numerical knowledge to solving verbally presented word problems (Viesel-Nordmeyer et al., 2019).

Of particular importance is the development of a variety of mathematical skills in kindergarten, such as understanding cardinality, counting, size comparison, and basic arithmetic calculation. Recent studies suggest an association between low early numeracy skills and mathematical difficulties that persist even during schooling (Viesel-Nordmeyer et al., 2019). Several studies found that number recognition abilities, distinguishing between quantities, and identifying missing numbers in certain sequences predict mathematical abilities at the end of first grade (Clarke and Shinn, 2004; Chard et al., 2005). Another study found a strong, significant, and ongoing predictive relationship of early numeracy skills from the kindergarten period to later math's skills the third grade. These findings show the importance of early mathematical abilities as a basis for later success in elementary school mathematics (Jordan et al., 2009).

### *Bilingualism and Mathematical Abilities*

The relationship of bilingualism to verbal ability has been investigated over the years, but the effect of bilingualism on mathematical abilities has been less examined. The relationship between linguistic and numeric skills has been established by many studies (e.g., Van Rinsveld et al., 2016). In a study, which examined the learning of multiplication facts among bilingual children, the children were tested in both languages. They performed the task better when the language of instruction matched the language of the test; hence, the language of instruction of mathematics affects situations where knowledge needs to be applied in a new context, as is often required in the classroom (Volmer et al., 2018).

Another study, which examined the differences in numerical abilities between bilingual and monolingual preschool children, found no significant differences between the two groups (Iglesias, 2012). In contrast, another study, which followed bilinguals from kindergarten to elementary school years, found benefits for bilinguals in mathematical abilities from basic skills in kindergarten to elementary school mathematical knowledge (Hartanto et al., 2018). Furthermore, a study, which examined the early numeracy abilities of bilingual and monolingual preschool children found differences in favor of the monolingual children in the numeracy tasks with a verbal component, such as number knowledge, but no differences in the tasks with non-verbal components, such as comparing quantities (Bonifacci et al., 2016).

It can be concluded that bilingualism can also affect numeracy skills, ranging from mastering early basic skills in preschool to developing these skills in formal school learning. There are not many studies that have examined the differences in mathematical abilities between bilingual and monolingual children in kindergarten except for the few, which are mentioned above, mathematical skills, have been explored mainly among older children. However, at the preschool level, different findings have been observed regarding the differences between the groups as presented above. Further research is needed to examine this topic and investigate whether the differences between bilingual and monolingual children appear from an early age and in which skills.

## The Current Research

A single study was found that examined the relationship between verbal abilities and early numeracy abilities between monolingual (Italian) and bilingual children in early childhood. The study examined the differences in numeracy and linguistic abilities between the two groups, as well as the linguistic predictors for early numeracy skills. This study found that the monolingual children performed better than the bilingual children did in most of the early literacy skills as well as in numeracy tasks with a verbal component only. In addition, different predictors were found for the early numeracy skills, while letter knowledge was found to be a significant predictor of numeracy tasks with a verbal component in both groups of children, phonological awareness was a predictor of numerical ability only among the monolingual children (Bonifacci et al., 2016).

Studies further suggest that the most powerful predictor of later mathematical performance is prior mathematical knowledge. Nevertheless, linguistic abilities also affect the learning of mathematics. The linguistic abilities found to influence math performance include spoken language skills, such as vocabulary and verbal comprehension, while phonological processing has been linked to the development of mathematical skills (Foster et al., 2015). Therefore, an examination of the relationship between these two areas is extremely important.

In addition, bilingualism has been found to affect verbal and mathematical abilities in children, but the findings are not uniform, and different studies have found different associations between these abilities. Most of the studies have investigated older children, and very few studies have examined both linguistic and numeric abilities in parallel on the same population. Moreover, due to the effect of bilingualism on the development pace of different linguistic abilities, which are related to different mathematical abilities, the question that arises is whether there are differences between monolingual and bilingual children in performing different skills of early literacy and numeracy in kindergarten. In addition to whether there are differences in the relationship between linguistic and numeric abilities in bilingual children as compared to monolingual children in kindergarten.

### Research Questions

1. Is there a difference between monolingual and bilingual children in the different early literacy skills (phonology, print conventions, morphology, and oral language)?

It is hypothesized that differences will be found between the different groups, and bilingual children will perform the tasks less well than monolingual children will; the differences will be stronger in orthographic and language knowledge due to the different exposure to the two languages (Prevoo et al., 2016). However, difference in the phonological awareness task will be smaller since this task has been found to be independent of the specific language (Leikin et al., 2010).

2. Is there a difference between monolingual and bilingual children in the different early numeracy skills (counting, comparison, stock, and simple calculations)?

Although some studies have found that bilinguals were better than monolinguals in the numeracy field (Hartanto et al., 2018), most of the literature suggests that the monolinguals perform better in different numeric tasks, especially the tasks, which involve linguistic abilities, such as counting and verbal problems. It is hypothesized that differences will be found between the two groups and that the difference will be larger between the groups on the language-based tasks as compared to tasks based solely on mathematical knowledge (Iglesias, 2012).

3. What is the association between early literacy and numeracy skills among monolingual children and is it different among bilingual children? It is expected, based on previous studies that a link will be found between linguistic and numeric abilities among monolingual children and among bilinguals, although it is estimated that the connection will be weaker among bilinguals due to the lower verbal abilities but not mathematical.

# MATERIALS AND METHODS

## Participants

The study examined 302 kindergarteners, 5–6 years old, who were recruited from 74 different kindergartens in different areas. The children were from a variety of socioeconomic status backgrounds (low to high). SES was determined according to parent's education and income as well as the neighborhood in which the kindergarten was situated. The distribution of the SES's was similar in both groups: monolingual children 14.3% low SES, 64.6% medium SES, and 21.1% high SES. The bilingual group: 11.4% low SES, 56.5% medium SES, and 32.1% high SES. It is important to note that there was no significant interaction between SES and the groups of children and SES effected both groups of children in the same way with high SES performing better than low SES in all early literacy and numeracy measures.

Participants were divided into two different groups: 151 monolingual children with an average age of 5 years and 8 months (68 boys and 83 and girls), who spoke only one language (Hebrew) and were not exposed to other languages at home, and 151 bilingual children with an average age of 5 and 9 months (77 boys and 74 girls) who spoke Hebrew as well as one of the following languages: Russian, English, Spanish, Japanese, German, Arabic, Ukrainian, Hungarian, Portuguese, Romanian, Persian, Italian, Armenian, Amharic, Georgian, or French. The children in the bilingual group were all exposed to two languages but were fluent in the Hebrew language. All the children in both groups understood all the instructions of the different tasks and performed all the linguistic and numeric tasks in Hebrew. In addition, all the children were in a Hebrew-speaking kindergartens and communicated with the teachers and other children only in Hebrew.

Both monolingual and bilingual children were chosen from each kindergarten in order to neutralize the effect of the quality of the teaching as well as the socioeconomic status of the children. Data were collected after receiving a consent form signed by the parents of the children who participated in the study. All children were in regular education and did not have any developmental or neurological problems.

## Research Tool

Demographic questionnaire: All parents filled out a questionnaire regarding details about the place of birth, the language spoken at home, and the child's mastery of the different languages in order to verify the child's bilingualism.

### Early Literacy Skills

1. Orthographic Knowledge (based on Schwartz, 2004, unpublished).

    - Letter naming. The child was asked to name 10 letters in the Hebrew language, which were presented to him or her. The total amount of letters named correctly was scored ($\alpha = 0.87$).
    - Letter identification. The child was asked to identify a specific letter from four letters, which were visually displayed to him or her. The total amount of letters recognized correctly was scored ($\alpha = 0.82$).
    - Orthographic identification of words (Shaul, 2015, unpublished). This task is based on a similar Dutch test (Van der Kooy-Hofland et al., 2012). A word is presented to the child orally, and he or she has to identify it from four printed words. The distractors from the target word differ by one letter, two letters, or all the letters. The final score consists of the sum of the points received from the 10 items displayed ($\alpha = 0.75$).

2. Phonological Awareness (Share and Gott, 2018, unpublished).

    - Isolation of opening syllable. The test included 12 items in which the child was asked to say a word and then isolate the opening syllable and say the single syllable. The total number of correct isolations was scored ($\alpha = 0.84$).
    - Isolation of a closing consonant. The test includes 12 items in which the child was asked to say a word and then isolate the closing consonant and say the constant. The total number of correct isolations was scored ($\alpha = 0.81$).

3. Linguistic Knowledge and Vocabulary (Share and Gott, 2018, unpublished).

    - Vocabulary. The picture-naming task is based on the vocabulary subtest from a language screening test for preschool Hebrew-speaking children. The test contained 14 colored pictures. The children were asked to name each picture out loud following the examiner's instructions (e.g., "What is this?" and "What is he doing?"). The score was based on the total number of pictures named correctly ($\alpha = 0.84$).
    - Morpho-syntactic skills: nonwords derivation task (Shalev-Laifer and Share, 2016, unpublished). The test included 10 sentences that were presented orally by the examiner. Each sentence contains a novel verb (a combination of root and conjugation) which represents a nonsense word in the Hebrew language. The children were required to complete the sentences by modifying and producing the verb in the correct inflection and derivation according to the Hebrew morpho-syntactic structures ($\alpha = 0.65$).
    - Noun plural production. Children were shown colored pictures. One picture contained a singular count noun item, and the second contained four of that same item. The child was asked to produce the noun in plural. The total of correct answers was calculated (maximum = 15; $\alpha = 0.74$).
    - Consequential adjective production. The test contained 10 items. Children were shown two colored pictures. While pointing to the first picture the examiner said a sentence with a target verb, for example: "They broke the window." Then, the examiner pointed to the second picture (with a broken window) and asked the children to complete the sentence by deriving the consequential adjectives from the verb ($\alpha = 0.74$).
    - Consequential verb production. The test includes eight sentences read aloud by the examiner. The children were required to complete the sentence by deriving the consequential verb from a noun. The total of correct answers was calculated ($\alpha = 0.74$).

### Early Numeracy Skills

Early numeracy skills tasks were built based on tests of Purpura et al. (2011, 2015, 2017).

1. Number Knowledge

- Verbal counting (forward and backward). Measured by two subtests in which children were asked to count aloud forward from 1 to 20 and backward from 10 to 1 or 0. Each pair of consecutive number words correctly pronounced received one point up to the number correctly counted according to the sequence.
- Number naming. Children were required to verbally name 13 Arabic numerals (from 0 to 12). The numbers were presented in random order. Each number named correctly received one point ($\alpha = 0.89$).

2. Quantities Comparison
   - Symbolic and non-symbolic magnitude comparison from the numeracy screener test (Nosworthy et al., 2013). In the symbolic magnitude comparison, the children were asked to decide which of the numbers was larger in each single-digit numerical pair. In the non-symbolic magnitude comparison, the children were required to recognize the larger magnitude of two arrays of dots without counting. A total number of the correct answer within a 1-min time limit was calculated for each subtest ($\alpha = 0.95$).
3. Simple Calculations
   - Basic arithmetic task with the numbers 1–5. The child was presented with 10 simple addition and subtraction exercises, five of each type, using numbers up to 5, and he or she was asked to solve them orally. (e.g., 2 + 1, 2 + 2, 4–1) Measured: The number of correct answers out of 10 ($\alpha = 0.79$).
4. Verbal Problems
   - Arithmetic story problems. The test consisted of four addition and subtraction word problems (with numbers between 1 and 5). Each item was read to the child, who was then asked to solve the problem by stating a number word verbally. One point was given for each correct answer ($\alpha = 0.64$).

## Procedure

Prior to the collection of the data, the required approvals were obtained from the Ministry of Education and the Ethics Committee of the university. In addition, consent forms were signed by the parents of the children examined. All the tests were administered to the participants individually during kindergarten class time but in a separate room, in two or three separate sessions of about 20 min each.

# RESULTS

## Preliminary Analysis

In order to reduce the number of variables, two principal component analyses with varimax rotation on the measures of early literacy and numeracy measures were conducted.

All literacy measures included in the factor analysis yielded three major factors: oral language knowledge accounted for 28.67% of the variance, phonological awareness accounted for 21.63%, and alphabetic and orthographic knowledge accounted for 20.67%. All these factors together explained 71% of the variance in early literacy. The loadings of the different tests on the factors are presented in **Table 1**.

All math measures included in the factor analysis are reported in **Table 2**, the measures yielded three factors: number knowledge (Factor 1), comparison of quantities (Factor 2), and arithmetic operations (Factor 3). Factor 3 included both simple calculation and verbal problems, but these were not merged due to the different forms of presentations (verbal vs. numbers) and were divided into basic arithmetic calculations and verbal problems separately due to the linguistic factor.

The first factor, which included number naming and counting (forward and backward), accounted for 26.29% of the variance. The second factor, which included arithmetic facts, calculation, and arithmetic story problems, accounted for 23.60% of the variance. The third factor, which included quantity comparison (symbolic and non-symbolic) measures, accounted for 19.70% of the variance. All three factors together explained 69.6% of the variance. The loadings of the different tests on the factors are presented in **Table 2**.

**TABLE 1** | Loadings and factor division findings for the different literacy tests.

| Name of the test | 1<br>Orthographic ability | 3<br>Linguistic abilities | 3<br>Phonological awareness |
|---|---|---|---|
| Letter naming | 0.90 | | |
| Letter identification | 0.89 | | |
| Word identification | 0.66 | | |
| Producing verbs | | 0.56 | |
| Producing plural | | 0.82 | |
| Vocabulary | | 0.81 | |
| Producing adjectives | | 0.81 | |
| Inflecting verbs | | 0.81 | |
| Isolation of initial sound | | | 0.87 |
| Isolation of final sound | | | 0.73 |

**TABLE 2** | Loadings and factor division findings for the different numeracy tests.

| | Component | | |
|---|---|---|---|
| | Factor 1: Number knowledge | Factor 2: Quantity comparison | Factor 3: Arithmetic operations |
| Number naming | 0.580 | | |
| Ascending counting | 0.837 | | |
| Descending counting | 0.811 | | |
| Arithmetic facts | | | 0.683 |
| Arithmetic story problems | | | 0.866 |
| Non-symbolic magnitude comparison | | 0.919 | |
| Symbolic magnitude comparison | | 0.866 | |

Based on the factor analysis aggregated variables were computed for each factor, and the average was computed on the percent of the correct answers n each task in each factor.

## First Research Question

The first research question examined whether there were differences in the various early literacy skills between monolingual and bilingual children. In order to answer this question, a MANOVA with SES as a controlled covariant was conducted for all the literacy measures. **Table 3** and **Figure 1** present the averages and SDs of the early literacy factors of each group of children.

A significant effect for group was found for the overall early literacy measures, $F_{(3,211)} = 30.87$, $p < 0.001$. Significant differences were found between monolingual children and bilingual children in the measures of orthography, $F_{(1,211)} = 21.49$, $p < 0.05$. The monolingual children performed better in orthographic knowledge ($M = 73.15$; $SD = 20.61$) than the bilingual children ($M = 61.14$; $SD = 22.55$). In addition, a significant effect for group was found for linguistic knowledge, $F_{(1,211)} = 83.46$, $p < 0.001$. The same pattern was found in the linguistic knowledge of monolingual children with lower performance ($M = 65.26$; $SD = 13.44$) as compared to the bilingual children ($M = 46.38$; $SD = 20.39$). In the phonological awareness factor, no significant differences were found between the two groups of children.

## Second Research Question

The second research question examined whether there were differences in different early numeracy skills between monolingual and bilingual children. In order to answer this question, a MANOVA with SES as a controlled covariant was conducted for all the numeracy measures. **Table 4** and **Figure 2** present the averages and SDs of the early numeracy factors of each group of children.

A significant effect for group was found for the overall early numeracy measures, $F_{(4,222)} = 2.97$, $p < 0.05$. Significant differences were found between monolingual children and bilingual children only in the number knowledge factor, $F_{(1,211)} = 5.32$, $p < 0.05$, with the monolingual children performing better than the bilingual children ($M = 85.49$; $SD = 22.79$) as compared to the bilingual children ($M = 77.13$; $SD = 25.95$). In all other factors, no significant differences were found between the two groups.

## Third Research Question

The third research question examined the association between early literacy and numeracy skills among monolingual children and whether the connection is different among bilingual children. In order to examine this question, Pearson correlations were conducted between the various indices within each group. **Table 5** shows the results of the correlations between each of the three linguistic factors and each of the four numeric factors measured, among the monolingual and bilingual children.

Results revealed that among monolingual children, a significant association was found between most of the numeric tasks and the linguistic tasks, apart from the task of comparing quantities, which did not correlate with any of the linguistic tasks. Among the bilingual children, a significant correlation was found between number knowledge and simple calculations with all three linguistic tasks. The quantity comparison task correlated with the orthographic and phonological awareness tasks, but not with the linguistic knowledge and vocabulary tasks, and the verbal problems were related to phonological awareness and linguistic abilities but not to orthographic knowledge.

In order to compare the correlations between the monolingual and bilingual group, a Fisher analysis was conducted. It was found that the correlation between orthographic knowledge and number knowledge task was higher among the monolingual children ($Z = 1.95$, $p < 0.05$) as well as between the linguistic knowledge and number knowledge ($Z = 2.88$, $p < 0.01$). In addition, the correlation between linguistic knowledge and simple calculation was also higher among the monolingual group ($Z = 2.27$, $p < 0.01$). Finally, the correlation between orthographic knowledge and verbal problem slowing was higher among the monolingual children ($Z = 2.35$, $p < 0.01$) as well as between the linguistic knowledge and verbal problem-solving ($Z = 1.99$, $p < 0.05$). All the correlations are detailed in **Table 5**.

# DISCUSSION

The current study examined whether there is a difference in the early literacy and numeracy abilities among monolingual children as compared to bilingual children, as well as examining the connections between these two abilities among the different groups of children. The findings are consistent with the research literature and lead to generalizations regarding all children who speak any two languages, who usually exhibit lower performance than monolingual children in linguistic and print dependent tasks.

**TABLE 3** | Means and SD of the different early literacy factors among the different groups of children.

| | Monolingual children | | | Bilingual children | | |
|---|---|---|---|---|---|---|
| | ***N*** | ***M*** | ***SD*** | ***N*** | ***M*** | ***SD*** |
| Orthographic Knowledge | 141 | 73.15 | 20.61 | 139 | 61.14 | 22.55 |
| Phonological awareness | 136 | 45.32 | 32.09 | 129 | 39.04 | 31.84 |
| Linguistic knowledge | 141 | 65.26 | 13.44 | 135 | 46.38 | 20.39 |

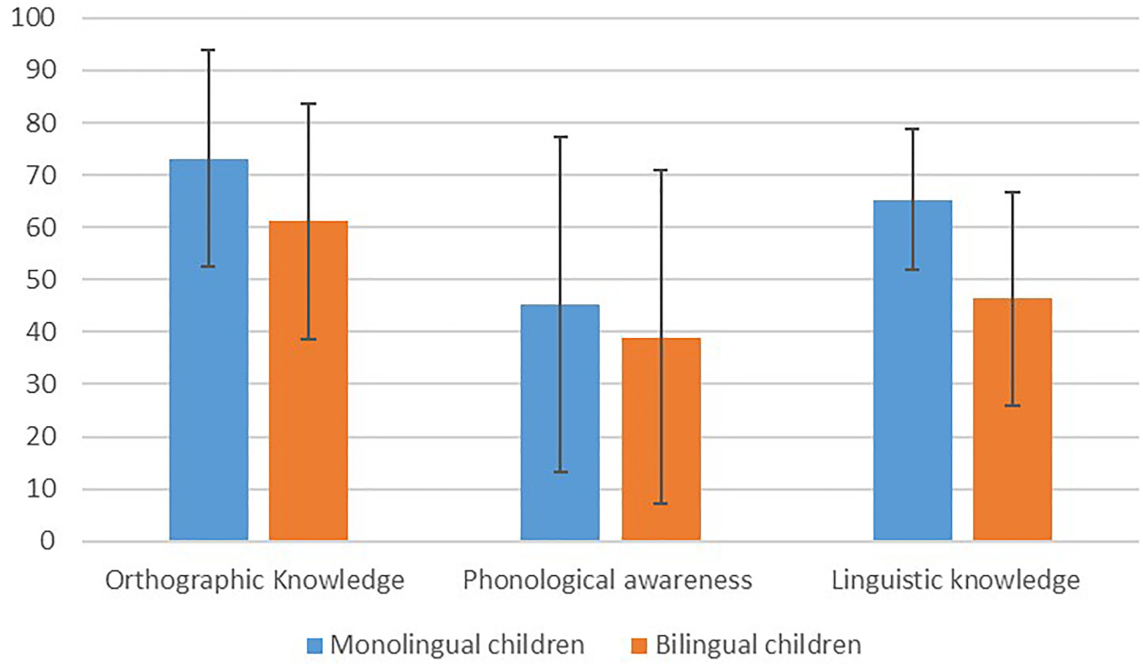


**FIGURE 1 |** The performance of monolingual and bilingual children on the different early literacy factors.

**TABLE 4 |** Means and SD of the different early numeracy factors among the different groups of children.

| | **Monolingual children** | | | **Bilingual children** | | |
|---|---|---|---|---|---|---|
| | ***N*** | ***M*** | ***SD*** | ***N*** | ***M*** | ***SD*** |
| Number knowledge | 145 | 85.49 | 22.79 | 143 | 77.13 | 25.95 |
| Quantity comparison | 148 | 20.22 | 5.47 | 145 | 20.68 | 7.13 |
| Simple calculations | 144 | 59.86 | 28.08 | 139 | 55.11 | 28.85 |
| Verbal problems | 145 | 77.03 | 28.51 | 144 | 68.40 | 28.36 |

## Differences in Early Literacy Abilities

The first research question examined whether there were differences in early literacy abilities between monolingual and bilingual children. Consistent with our hypothesis, significant differences were found in the measures of orthography and linguistic knowledge, in which the performance of monolingual children was better than the performance of bilingual children. These results support the findings in the literature that bilinguals are known to master one language more than the other and that similar proficiency in both languages is considered rare (Misdraji-Hammond et al., 2014). In addition, these children, who speak two languages, sometimes have to suppress one of their languages while speaking the other language (Volmer et al., 2018). This may explain the differences found between the groups in the literacy tasks.

It can be assumed that knowledge of the Hebrew language among bilingual children was lower, probably due to less exposure to Hebrew. Most of the children in the study came from homes where other languages are spoken and they were exposed to Hebrew mainly in kindergarten, so they had fewer opportunities to learn Hebrew vocabulary as compared to children who were exposed only to Hebrew. In addition, their print knowledge was less developed, since their print environment at home likely consisted of books in other languages.

Regarding phonological awareness, no differences were found between the two groups. Phonological abilities are based mainly on auditory ability, or sensitivity to the sounds of the language, which develops in the same way among all children whether or not they are bilingual. The literature provides support for the notion that the development of phonological processing – the ability to analyze and process auditory information – does not depend on the specific language to which you are exposed (Leikin et al., 2010). Hence, it can be concluded that when there is significant exposure to any oral language at home, no matter which one, then children can perform the phonological awareness task.

In conclusion, it can be seen that there are significant differences between monolingual children and bilingual children in most early linguistic literacy abilities, which form the basis for formal learning in school. In the phonological awareness task, one of the significant abilities predicting reading in school, no differences were found. In contrast, in the orthography

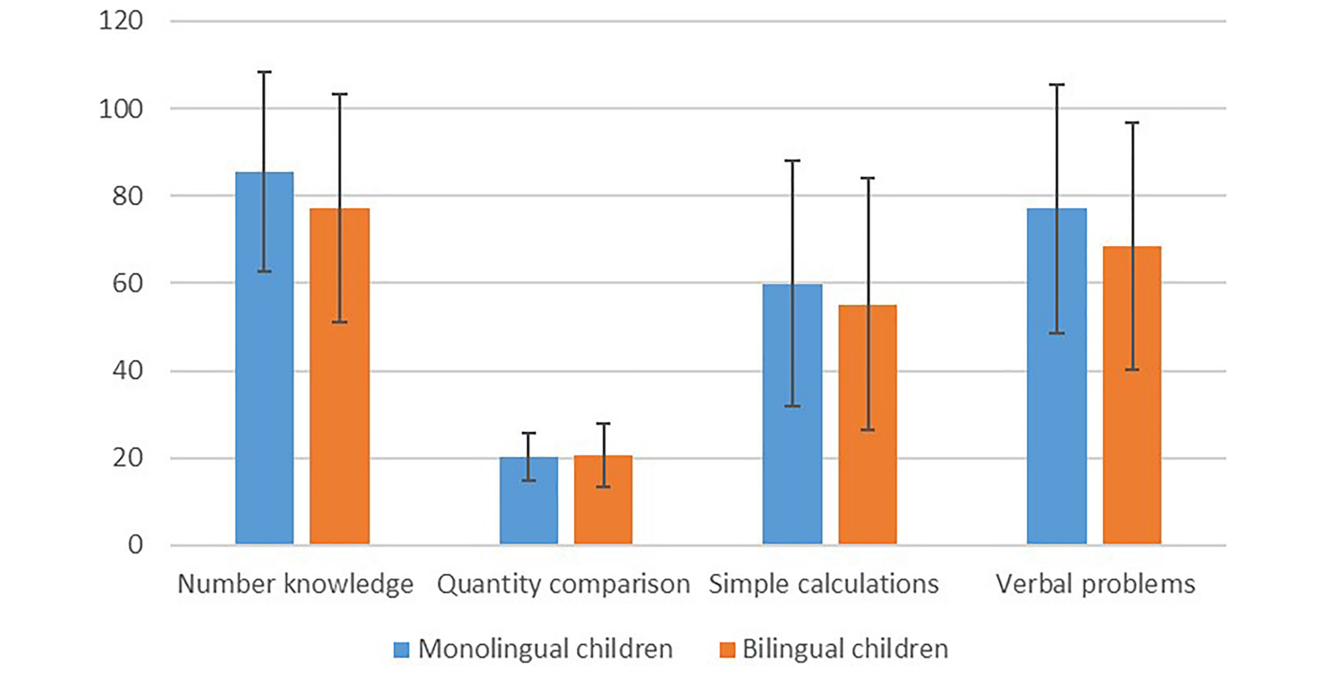


**FIGURE 2 |** The performance of monolingual and bilingual children on the different early numeracy factors.

**TABLE 5 |** Correlation between linguistic and numeric factors among monolingual and bilingual children.

| Task | Monolingual children | | | Bilingual children | | |
|---|---|---|---|---|---|---|
| | Orthographic Knowledge | Phonological awareness | Linguistic knowledge | Orthographic Knowledge | Phonological awareness | Linguistic knowledge |
| Number knowledge | **^0.514**** | 0.455** | **^0.566**** | 0.321** | 0.331** | 0.285* |
| Quantity comparison | 0.138 | 0.141 | 0.149 | 0.213* | 0.182* | 0.103 |
| Simple calculations | 0.422** | 0.492** | **^0.476**** | 0.373** | 0.372** | 0.238** |
| Verbal problems | **^0.422**** | 0.260** | **^0.458**** | 0.164 | 0.176* | 0.249** |

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

^The correlations that were significantly higher among the monolingual as compared to the bilingual children are in bold.

and linguistic knowledge tasks, major differences were found. Similar findings were found in other studies in which bilingual children have lower early literacy skills than monolingual children (Hur et al., 2020). These findings suggest that some abilities probably develop in same way in all children (phonological awareness), whether bilingual or monolingual. In contrast, in orthographic knowledge and linguistic and vocabulary knowledge, significant differences were observed between the groups, in favor of the monolingual children. It is evident that these tasks are based on verbal abilities and require knowledge and mastery of a specific language in order to be performed optimally.

Therefore, in their work with bilingual children, educators should emphasize tasks that involve language knowledge, such as vocabulary expansion and orthographic tasks. It is possible that with the help of fieldwork following these findings, bilingual children will be able to bridge the gap with the monolingual group and even reach a level similar to theirs.

## Differences in Early Numeracy Abilities

The second research question examined whether there are differences in early numeracy abilities between monolingual children and bilingual children. The results of the study were in line with the previous research and found that only in the number knowledge task, which involves verbal and vocabulary abilities, is there a very clear difference between the two groups. That is, it is evident that main differences in verbal and numeracy abilities between the two groups of children were in naming and vocabulary. In contrast, in the three additional numeracy tasks – comparing quantities, solving simple calculations, and verbal problems – no differences were found between the two groups of children. It can be assumed that these three tasks are pure numeracy skills and are not based on language knowledge or that the language knowledge they require is less significant, at least at the level of kindergarten tasks, and therefore, no differences were observed.

With respect to the task of comparing quantities, since the literature shows that this task does not involve verbal abilities, we assumed that no difference would be found between the groups in performing the task, as found by Bonifacci et al. (2016). Comparing quantities of dots or numbers is a task that requires visual-spatial ability and relies on mechanisms of pure number processing, so if children understand the meaning of the number and their perception of quantity is intact, they can perform the task regardless of the language they speak.

According to the literature, there are also verbal aspects to solving simple sums through calculation (Harvey and Miller, 2017). Even so, in a study examining the differences between bilingual and monolingual kindergarten-age groups, no significant differences were found between the two, and numerical abilities were not found to be related to language abilities at this age (Iglesias, 2012). Hence, it seems that there are different approaches regarding language involvement. Solving simple sums in kindergarten may rely more on numeracy meaning or memory since from a young age there is exposure to and repetition of counting to 10 and rehearsing simple sums in the range of these numbers. It may be that differences will be found between the two groups when they are required to calculate more complex exercises later in their development.

Regarding the task of solving verbal problems, we expected to find differences between the two groups, since this task involves language knowledge and vocabulary. No differences were found between the groups in this task, and this may be because the numeracy abilities required to perform this type of task in preschoolers are more significant than the verbal abilities, due to the very simple questions, which do not require sophisticated language abilities. In kindergarten, children are exposed to verbal problems in different areas, in different interactions, and in different places; therefore, it is likely that both monolingual and bilingual children were exposed to verbal problems in simple language, acquired tools to deal with them, and consequently were able to solve verbal problems.

In conclusion, it can be seen that in most of the early numeracy literacy abilities, no differences were observed between the groups of monolingual and bilingual children, except for the numeric knowledge task, which requires linguistic knowledge, such as counting and naming. These findings reinforce the understanding that the linguistic knowledge of bilingual children should also be strengthened in the numeracy field. Also, it is very likely that upon arrival at school, formal learning will include many components of linguistic numeracy knowledge, and if language skills linked to numeracy are stronger, children will be better able to deal with more complex exercises that require verbal knowledge.

## The Relationship Between Linguistic and Numeric Abilities

The third question examined whether there is a relationship between the different early numeracy and literacy abilities among monolingual and bilingual children in the study and whether the relationships differ in the different groups. Correlations were found among most factors, but weaker connections were found among the bilingual children as compared to monolingual children, only between the orthographic knowledge and the linguistic knowledge and several numeric abilities. In general, the relationships found between the different abilities are consistent with the hypothesis that early exposure to language is important and influences the development of mathematical abilities (Vukovic and Lesaux, 2013), but the types and levels of relationships differ. In addition, the strong association between language abilities and numeracy abilities is manifested early in development and has been previously observed among preschoolers (Purpura and Reid, 2016). Furthermore, the current results are also consistent with findings from a previous study, which found that the link between language and mathematics was stronger among native speakers than among second language speakers (Peng et al., 2020).

In addition, a different pattern of connections was found between the two groups of children in the quantity comparison task. Among the monolingual children, no connection was found with any of the literacy tasks, but the bilingual children's performance on this task was correlated with the phonological and orthographic factors. However, another study that examined the relationships between numeracy and verbal abilities among monolingual and bilingual children found no connections between the quantities comparison and the verbal tasks in either group of children (Bonifacci et al., 2016).

The most significant relationship was found between the simple calculation and number knowledge tasks and the three verbal factors in both groups of children. It seems that both counting and the process of calculating a simple sum involve literacy abilities in a significant manner. This finding can be strengthened by a study suggesting that basic mathematical skills, such as solving word problems, rely at least in part on verbal cognitive processing that may be difficult for those who have not yet mastered the language (Van Rinsveld et al., 2016). It is possible that the calculations are related to learning ability in general and not necessarily specifically to language.

These findings of the numeric knowledge factor are also consistent with our hypothesis. It is likely that if a numeracy task that involves linguistic knowledge of naming numbers and counting, a connection will be found with various verbal abilities. This is also the type of task in which the bilingual children performed worse than the monolingual children, which strengthens the involvement of linguistic abilities in this factor. Hence, when low abilities were observed in both literacy tasks and this type of numeracy task, it is likely that a strong association between these skills will be found.

In addition, in the verbal problems factor, a connection was found between phonological awareness tasks and verbal knowledge and vocabulary but not with orthographic knowledge among the bilingual children. This may be because understanding of the verbal story is required before you can perform the sum, and therefore, solving verbal problems is a cognitive task that relies heavily on language skills (Van Rinsveld et al., 2015).

Furthermore, the fact that comparing quantities was found to be connected with the phonological and orthographic factor is surprising and should be further investigated, in order to better understand this relationship. Previous studies found that the task of estimating quantities was not related to verbal abilities, but to intuition of numerical size, and it uses areas in the brain related to visual-spatial processing rather than language-related areas, which is contradiction to the current results (Dehaene et al., 1999). It may be that the visual scanning is required to perform this task and the orthographic tasks as well among the bilingual group.

It is important to note that only several of the correlations were found to be significantly higher among the monolingual children as compared to the bilingual children, and it was only between the linguistic and orthographic knowledge and numerical knowledge and the different calculation skills. No significant differences were found in the phonological factor and the comparison of quantities factor, and this may be because there was no difference between the two groups of children in these factors, and these abilities are more domain-specific and not connected to other factors, which share more abilities that are common (numeric and linguistic). These results strengthen the assumption that there is a strong connection between specific linguistic and numeric abilities and that the better performance of the monolingual children in the linguistic and orthographic knowledge strengthens their number knowledge and calculation abilities.

## LIMITATIONS AND CONCLUSION

There are a number of limitations in the present study. First, we did not classify the bilingual group according to the level of knowledge of the Hebrew language, although for all children, the level of Hebrew was good enough to perform the tasks. It is possible that if the bilingual group had been divided according to the level of exposure to Hebrew at home, the results would have been expressed in a different way. In addition, the level of control of the home language was not tested either. Finally, the bilingual group was not divided according to the additional language they speak. It may be that the different languages affect different abilities based on their similarity to the other language. Therefore, it may important to examine the bilingual children in both languages they speak in future studies in order to investigate the differences in their performance in L1 and L2. This point is especially important for the number knowledge factor, while counting was taught in Hebrew only at the kindergarten to all children; the bilingual children might have been exposed to counting in another language at home. It is a very interesting point, and future studies should check the bilingual children in counting in both languages.

It is also important to continue to monitor children at different ages in order to see the differences after entering school and formal learning that can reduce or neutralize any negative impact of the second language. Perhaps as children get older, knowledge of another language can actually contribute to better performance, as found in other studies.

This study has educational implications for fieldwork. This research added to our knowledge about the numeracy and linguistic abilities of bilingual children, as well as the significant skills that are important to strengthen, expose, encourage, and improve during the day in kindergarten. It is critical to emphasize these skills in order to promote school readiness among this group. As noted in the literature, identifying a different profile of bilingual children from monolingual children may help in tailoring their learning to help them succeed and in creating learning goals unique to them, such as developing literacy in both languages (McCardle and Hoff, 2006).

According to the findings of this study, insufficient linguistic knowledge and vocabulary in the language spoken at school is one of the main difficulties of bilingual children. Hence, during the kindergarten period, it is important to work on language knowledge and vocabulary expansion among populations that speak more than one language in order to strengthen the language skills and abilities that affect additional skills.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## ETHICS STATEMENT

The studies involving human participants were reviewed and approved by University of Haifa, Faculty of Education Ethics Committee. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

## AUTHOR CONTRIBUTIONS

LB and SS conceptualized this study and contributed to the writing and interpretation of the data. LB contributed to data collection and wrote the first draft. SS did all the revision and performed the statistical analysis. All authors contributed to the article and approved the submitted version.

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## REFERENCES

Abu-Rabia, S., Shakkour, W., and Siegel, L. (2013). Cognitive retroactive transfer (CRT) of language skills among bilingual arabic-english readers. *Biling. Res. J.* 36, 61–81. doi: 10.1080/15235882.2013.775975

Adesope, O. O., Lavin, T., Thompson, T., and Ungerleider, C. (2010). A systematic review and meta-analysis of the cognitive correlates of bilingualism. *Rev. Educ. Res.* 80, 207–245. doi: 10.3102/0034654310368803

Adi-Japha, E., Berberich-Artzi, J., and Libnawi, A. (2010). Cognitive flexibility in drawings of bilingual children. *Child Dev.* 81, 1356–1366. doi: 10.1111/j.1467-8624.2010.01477.x

Arafat, S. H., Korat, O., Aram, D., and Saiegh-Haddad, E. (2017). Continuity in literacy achievements from kindergarten to first grade: a longitudinal study of Arabic-speaking children. *Read. Writ.* 30, 989–1007. doi: 10.1007/s11145-016-9709-x

Bar-On, A., and Ravid, D. (2011). Morphological analysis in learning to read pseudowords in hebrew. *Appl. Psychol.* 32, 553–581. doi: 10.1017/S014271641100021X

Ben-Zeev, S. (1977). The influence of bilingualism on cognitive strategy and cognitive development. *Child Dev.* 48, 1009–1018. doi: 10.2307/1128353

Bialystok, E. (1987). Influences of bilingualism on metalinguistic development. *Interlang. Stud. Bull.* 3, 154–166. doi: 10.1177/026765838700300205

Bialystok, E. (2001). *Bilingualism in Development: Language, Literacy, and Cognition*. Cambridge, UK: Cambridge University Press.

Blom, E., Küntay, A. C., Messer, M., Verhagen, J., and Leseman, P. (2014). The benefits of being bilingual: working memory in bilingual Turkish–Dutch children. *J. Exp. Child Psychol.* 128, 105–119. doi: 10.1016/j.jecp.2014.06.007

Bonifacci, P., Tobia, V., Bernabini, L., and Marzocchi, G. M. (2016). Early literacy and numeracy skills in bilingual minority children: toward a relative independence of linguistic and numerical processing. *Front. Psychol.* 7:1020. doi: 10.3389/fpsyg.2016.01020

Chard, D. J., Clarke, B., Baker, S., Otterstedt, J., Braun, D., and Katz, R. (2005). Using measures of number sense to screen for difficulties in mathematics: preliminary findings. *Assess. Eff. Interv.* 30, 3–14. doi: 10.1177/073724770503000202

Clarke, B., and Shinn, M. R. (2004). A preliminary investigation into the identification and development of early mathematics curriculum-based measurement. *Sch. Psychol. Rev.* 33, 234–248. doi: 10.1080/02796015.2004.12086245

Clements, D. H., and Sarama, J. (2007). Effects of a preschool mathematics curriculum: summative research on the building blocks project. *J. Res. Math. Educ.* 38, 136–163. doi: 10.2307/30034954

Cui, J., Georgiou, G. K., Zhang, Y., Li, Y., Shu, H., and Zhou, X. (2017). Examining the relationship between rapid automatized naming and arithmetic fluency in Chinese kindergarten children. *J. Exp. Child Psychol.* 154, 146–163. doi: 10.1016/j.jecp.2016.10.008

Dehaene, S., Spelke, E., Pinel, P., Stanescu, R., and Tsivkin, S. (1999). Sources of mathematical thinking: behavioral and brain-imaging evidence. *Science* 284, 970–974. doi: 10.1126/science.284.5416.970

De Houwer, A. (2007). Parental language input patterns and children's bilingual use. *Appl. Psychol.* 28, 411–424. doi: 10.1017/S0142716407070221

Duncan, G. J., Dowsett, C. J., Claessens, A., Magnuson, K., Huston, A. C., Klebanov, P., et al. (2007). School readiness and later achievement. *Dev. Psychol.* 43, 1428–1446. doi: 10.1037/0012-1649.43.6.1428

Ehri, L. C. (2005). Learning to read words: theory, findings, and issues. *Sci. Stud. Read.* 9, 167–188. doi: 10.1207/s1532799xssr0902_4

Fennell, C. T., Byers-Heinlein, K., and Werker, J. F. (2007). Using speech sounds to guide word learning: the case of bilingual infants. *Child Dev.* 78, 1510–1525. doi: 10.1111/j.1467-8624.2007.01080.x

Foster, M. E., Sevcik, R. A., Romski, M., and Morris, R. D. (2015). Effects of phonological awareness and naming speed on mathematics skills in children with mild intellectual disabilities. *Dev. Neurorehabil.* 18, 304–316. doi: 10.3109/17518423.2013.843603

Giovannoli, J., Martella, D., Federico, F., Pirchio, S., and Casagrande, M. (2020). The impact of bilingualism on executive functions in children and adolescents: a systematic review based on the PRISMA method. *Front. Psychol.* 11:574789. doi: 10.3389/fpsyg.2020.574789

Gombert, J. E., and Fayol, M. (1992). Writing in preliterate children. *Learn. Instr.* 2, 23–41. doi: 10.1016/0959-4752(92)90003-5

Hartanto, A., Yang, H., and Yang, S. (2018). Bilingualism positively predicts mathematical competence: evidence from two large-scale studies. *Learn. Individ. Differ.* 61, 216–227. doi: 10.1016/j.lindif.2017.12.007

Harvey, H. A., and Miller, G. E. (2017). Executive function skills, early mathematics, and vocabulary in head start preschool children. *Early Educ. Dev.* 28, 290–307. doi: 10.1080/10409289.2016.1218728

Hornburg, C. B., Schmitt, S. A., and Purpura, D. J. (2018). Relations between preschoolers' mathematical language understanding and specific numeracy skills. *J. Exp. Child Psychol.* 176, 84–100. doi: 10.1016/j.jecp.2018.07.005

Hur, J. H., Snyder, P., and Reichow, B. (2020). Systematic review of english early literacy interventions for children who are dual language learners. *Top. Early Child. Spec. Educ.* 40, 6–23. doi: 10.1177/0271121419894623

Iglesias, C. L. (2012). Investigating the status of early numeracy skills in bilingual dual language learner Latino children attending Head Start and the association with parent demographic characteristics. Dissertation, University of South Florida.

Jordan, N. C., Kaplan, D., Ramineni, C., and Locuniak, M. N. (2009). Early math matters: kindergarten number competence and later mathematics outcomes. *Dev. Psychol.* 45, 850–867. doi: 10.1037/a0014939

Kaushanskaya, M., and Marian, V. (2009). The bilingual advantage in novel word learning. *Psychon. Bull. Rev.* 16, 705–710. doi: 10.3758/PBR.16.4.705

Kuhl, P. K., and Ramirez, N. F. (2016). *Bilingual Language Learning in Children*. University of Washington, USA: Institute of Learning.

Lee, J. (2011). Size matters: early vocabulary as a predictor of language and literacy competence. *Appl. Psychol.* 32:69. doi: 10.1017/S0142716410000299

Leikin, M., Schwartz, M., and Share, D. L. (2010). General and specific benefits of bi-literate bilingualism: a Russian–Hebrew study of beginning literacy. *Read. Writ.* 23, 269–292. doi: 10.1007/s11145-009-9210-x

Li, P., Legault, J., and Litcofsky, K. A. (2014). Neuroplasticity as a function of second language learning: anatomical changes in the human brain. *Cortex* 58, 301–324. doi: 10.1016/j.cortex.2014.05.001

Lukie, I. K., Skwarchuk, S. L., LeFevre, J. A., and Sowinski, C. (2014). The role of child interests and collaborative parent–child interactions in fostering numeracy and literacy development in Canadian homes. *Early Childhood Educ. J.* 42, 251–259. doi: 10.1007/s10643-013-0604-7

McCardle, P., and Hoff, E. (eds.) (2006). "An agenda for research on childhood bilingualism," in *Childhood Bilingualism: Research on Infancy Through School Age*. Clevedon: Multilingual Matters, 157–165.

Méndez, L. I., Crais, E. R., and Kainz, K. (2018). The impact of individual differences on a bilingual vocabulary approach for Latino preschoolers. *J. Speech Lang. Hear. Res.* 61, 897–909. doi: 10.1044/2018_JSLHR-L-17-0186

Misdraji-Hammond, E., Lim, N. K., Fernandez, M., and Burke, M. E. (2014). Object familiarity and acculturation do not explain performance difference between Spanish–English bilinguals and english monolinguals on the Boston naming test. *Arch. Clin. Neuropsychol.* 30, 59–67. doi: 10.1093/arclin/acu065

Mix, K. S., Levine, S. C., and Huttenlocher, J. (1997). Numerical abstraction in infants: another look. *Dev. Psychol.* 33, 423–428. doi: 10.1037/0012-1649.33.3.423

Nagy, W. E. (1995). On the role of context in first-and second-language vocabulary learning. Champaign, Ill.: University of Illinois at Urbana-Champaign, Center for the Study of Reading.

Nosworthy, N., Bugden, S., Archibald, L., Evans, B., and Ansari, D. (2013). A two-minute paper-and-pencil test of symbolic and nonsymbolic numerical magnitude processing explains variability in primary school children's arithmetic competence. *PLoS One* 8:e67918. doi: 10.1371/journal.pone.0067918

Oller, D. K., Pearson, B. Z., and Cobo-Lewis, A. B. (2007). Profile effects in early bilingual language and literacy. *Appl. Psychol.* 28, 191–230. doi: 10.1017/S0142716407070117

Peng, P., Lin, X., Ünal, Z. E., Lee, K., Namkung, J., Chow, J., et al. (2020). Examining the mutual relations between language and mathematics: a meta-analysis. *Psychol. Bull.* 146, 595–634. doi: 10.1037/bul0000231

Poulin-Dubois, D., Blaye, A., Coutya, J., and Bialystok, E. (2011). The effects of bilingualism on toddlers' executive functioning. *J. Exp. Child Psychol.* 108, 567–579. doi: 10.1016/j.jecp.2010.10.009

Prevoo, M. J., Malda, M., Mesman, J., and van IJzendoorn, M. H. (2016). Within- and cross-language relations between oral language proficiency and school outcomes in bilingual children with an immigrant background: a meta-analytical study. *Rev. Educ. Res.* 86, 237–276. doi: 10.3102/0034654315584685

Purpura, D. J., and Ganley, C. M. (2014). Working memory and language: skill-specific or domain-general relations to mathematics? *J. Exp. Child Psychol.* 122, 104–121. doi: 10.1016/j.jecp.2013.12.009

Purpura, D. J., Hume, L. E., Sims, D. M., and Lonigan, C. J. (2011). Early literacy and early numeracy: the value of including early literacy skills in the prediction of numeracy development. *J. Exp. Child Psychol.* 110, 647–658. doi: 10.1016/j.jecp.2011.07.004

Purpura, D. J., Logan, J. A., Hassihger-Das, B., and Napoli, A. R. (2017). Why do early mathematics skills predict later reading? The role of mathematical language. *Dev. Psychol.* 53, 1633–1642. doi: 10.1037/dev0000375

Purpura, D. J., and Reid, E. E. (2016). Mathematics and language: individual and group differences in mathematical language skills in young children. *Early Child. Res. Q.* 36, 259–268. doi: 10.1016/j.ecresq.2015.12.020

Purpura, D. J., Reid, E. E., Eiland, M. D., and Baroody, A. J. (2015). Using a brief preschool early numeracy skills screener to identify young children with mathematics difficulties. *Educ. Psychol. Rev*. 44, 41–59.

Sarama, J., and Clements, D. H. (2009). *Early Childhood Mathematics Education Research: Learning Trajectories for Young Children*. UK: Routledge.

Schmitterer, A. M., and Schroeder, S. (2018). The recognition of letters in emergent literacy in German: evidence from a longitudinal study. *J. Res. Read.* 41, 423–437. doi: 10.1111/1467-9817.12116

Sénéchal, M., and LeFevre, J. A. (2014). Continuity and change in the home literacy environment as predictors of growth in vocabulary and reading. *Child Dev.* 85, 1552–1568. doi: 10.1111/cdev.12222

Starkey, P., Klein, A., and Wakeley, A. (2004). Enhancing young children's mathematical knowledge through a pre-kindergarten mathematics intervention. *Early Child. Res. Q.* 19, 99–120. doi: 10.1016/j.ecresq.2004.01.002

Swanson, H. L., Arizmendi, G. D., and Li, J. T. (2021). Working memory growth predicts mathematical problem-solving growth among emergent bilingual children. *J. Exp. Child Psychol.* 201:104988. doi: 10.1016/j.jecp.2020.104988

Van der Kooy-Hofland, V. A., Van der Kooy, J., Bus, A. G., van IJzendoorn, M. H., and Bonsel, G. J. (2012). Differential susceptibility to early literacy intervention in children with mild perinatal adversities: short-and long-term effects of a randomized control trial. *J. Educ. Psychol.* 104:337. doi: 10.1037/a0026984

Van Rinsveld, A., Brunner, M., Landerl, K., Schiltz, C., and Ugen, S. (2015). The relation between language and arithmetic in bilinguals: insights from different stages of language acquisition. *Front. Psychol.* 6:265. doi: 10.3389/fpsyg.2015.00265

Van Rinsveld, A., Schiltz, C., Brunner, M., Landerl, K., and Ugen, S. (2016). Solving arithmetic problems in first and second language: does the language context matter? *Learn. Instr.* 42, 72–82. doi: 10.1016/j.learninstruc.2016.01.003

Viesel-Nordmeyer, N., Schurig, M., Bos, W., and Ritterfeld, U. (2019). Effects of pre-school mathematical disparities on the development of mathematical and verbal skills in primary school children. *Learn. Disabil. Contemp. J.* 17, 149–164.

Volmer, E., Grabner, R. H., and Saalbach, H. (2018). Language switching costs in bilingual mathematics learning: transfer effects and individual differences. *Z. Erziehungswiss.* 21, 71–96. doi: 10.1007/s11618-017-0795-6

Vukovic, R. K., and Lesaux, N. K. (2013). The language of mathematics: investigating the ways language counts for children's mathematical development. *J. Exp. Child Psychol.* 115, 227–244. doi: 10.1016/j.jecp.2013.02.002

Whitehurst, G. J., and Lonigan, C. J. (1998). Child development and emergent literacy. *Child Dev.* 69, 848–872. doi: 10.1111/j.1467-8624.1998.tb06247.x

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# Children's Verbal, Visual and Spatial Processing and Storage Abilities: An Analysis of Verbal Comprehension, Reading, Counting and Mathematics

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The importance of working memory (WM) in reading and mathematics performance has been widely studied, with recent research examining the components of WM (i.e., storage and processing) and their roles in these educational outcomes. However, the differing relationships between these abilities and the foundational skills involved in the development of reading and mathematics have received less attention. Additionally, the separation of verbal, visual and spatial storage and processing and subsequent links with foundational skills and downstream reading and mathematics has not been widely examined. The current study investigated the separate contributions of processing and storage from verbal, visual and spatial tasks to reading and mathematics, whilst considering influences on the underlying skills of verbal comprehension and counting, respectively. Ninety-two children aged 7- to 8-years were assessed. It was found that verbal comprehension (with some caveats) was predicted by verbal storage and reading was predicted by verbal and spatial storage. Counting was predicted by visual processing and storage, whilst mathematics was related to verbal and spatial storage. We argue that resources for tasks relying on external representations of stimuli related mainly to storage, and were largely verbal and spatial in nature. When a task required internal representation, there was a draw on visual processing and storage abilities. Findings suggest a possible meaningful separability of types of processing. Further investigation of this could lead to the development of an enhanced WM model, which might better inform interventions and reasonable adjustments for children who struggle with reading and mathematics due to WM deficits.

**Keywords: working memory, education, visual processing, spatial storage, spatial processing, visual storage, verbal processing, verbal storage**

## INTRODUCTION

Working memory (WM) is commonly defined as the ability to process information and maintain it for short periods of time, in the pursuit of a known goal (Baddeley and Hitch, 1974; Cowan, 1999; Cowan et al., 2005; Henry et al., 2012). Often separated into verbal WM (i.e., information that can be verbally processed and maintained) and visuospatial WM (i.e., information that is processed and stored in terms of its location and/or visual characteristics), studies have shown that primary school-age children demonstrate marked increases in the quantity of and the length of time that information can be stored in WM. For example, there is evidence that visual WM capacity doubles between the ages of 5 years and 10 years (Riggs et al., 2006), and the ability to hold verbal information in WM for longer periods of time might be attributed to the emergence of verbal rehearsal in 7- to 8-year-olds (Henry and Millar, 1993; but see Jarrold and Citroën, 2013). Also, results from a study by Gathercole et al. (1994) suggest that the basic structure of WM is evident from 6 years of age. Thus, the early to mid-primary school years are an important time of development for this ability.

It is beneficial to briefly explain some key theories of WM, relating specifically to what WM is and what explains individual variation in this ability. First, it is important to consider the enduring multicomponent model of WM (Baddeley and Hitch, 1974). This model consists of a modality-free control system (i.e., the central executive) with two modality-specific subsystems which temporarily store phonological and visuospatial material. Increases in WM ability occur with the use of maintenance strategies which prolong the duration over which information can be maintained. These include verbal rehearsal of phonological information (Baddeley, 1996) and image generation for visuospatial information (Logie, 1995). Second, the time-based resource-sharing (TBRS) model (Barrouillet et al., 2004) argues that an ability to rapidly switch attention between items being processed and items being remembered is fundamental to WM. According to this model, increases in WM capacity are explained by faster processing speeds allowing for more opportunities to refresh items to be remembered. Thirdly, the embedded-process model of WM (Cowan, 1999, 2008; Cowan et al., 2015) sees the role of attention as fundamental to WM capacity. Cowan and colleagues argue that increased, effortful attentional abilities to process salient information is the fundamental component of efficient WM.

Many studies have measured verbal WM and visuospatial WM separately to understand the respective roles in educational outcomes related to mathematics and reading. For example, there is evidence that visuospatial WM is important for mathematics (e.g., Van der Ven et al., 2013; Giofrè et al., 2018; see Allen et al., 2019 for a review) and verbal WM for reading (e.g., Oakhill et al., 2011; Giofrè et al., 2018; see Peng et al., 2018 for a meta-analysis). Verbal WM also shows strong links with word-based mathematics abilities such as problem solving (Rasmussen and Bisanz, 2005; Andersson, 2007; see Peng et al., 2016 for a review) and can be important in the retrieval of mathematics facts from a knowledge base (Gordon et al., 2021). However, studies have also found visuospatial WM to predict reading comprehension in 9- to 12-year-olds (e.g., Pham and Hasson, 2014), suggesting that this type of WM may play a role in reading ability once reading skills have been established. Furthermore, a review by Peng et al. (2016) found mathematics to be related to verbal and visuospatial WM, and to WM tasks that were numerical in nature. Such variability in findings highlights the need for further investigation as to why this might be the case.

A consideration, when investigating relationships between WM and academic outcomes, is the examination of the underlying components of WM to better understand this link. For example, Gordon et al. (2020) examined processing speeds, recall times, processing accuracy and recall accuracy in numerical, verbal and visuospatial WM tasks and found that processing speed and storage in a Counting Span task separately predicted mathematics and reading in 7- and 8-year-olds. More specifically, as manipulations of processing time allowance did not affect storage in WM, faster processing speeds were interpreted as enabling downstream academic abilities rather than increasing WM ability itself. A meta-analysis by Swanson et al. (2009) looked at how storage and processing in short-term memory might explain reading disabilities. They found that poor readers showed deficits in verbal short-term memory tasks that required the recall of digit sequences and phonemes. In addition, it was found that measures combining both storage and processing of digits that were embedded within short sentences also predicted reading ability. Furthermore, a study with primary school children by Gordon et al. (2021) found that the components of WM (i.e., storage and processing) changed in their relationships with mathematics dependent on whether the tasks were verbal or visuospatial in nature. Such findings suggest a possible fractionation of storage and processing within WM in terms of their relationships with educational outcomes. Given this added dimension to the complex relationships between WM and the academic abilities, the current study separately measured storage and processing abilities to better understand how these WM underlying components related to educational outcomes in reading and mathematics.

The conclusions that can be drawn from the literature become more complex when considering the foundational abilities upon which downstream skills, such as reading and mathematics, might rely. Reading can be defined as single word reading of real words often described as 'word decoding' or simply 'decoding' (Gough and Tunmer, 1986; Hoover and Gough, 1990). It is important to note that this is separate to phonemic decoding which refers specifically to speech sounds and might be measured by the ability to read nonsense words (Van Norman et al., 2018). Verbal comprehension is the ability to understand spoken language, and is a strong predictor of reading ability in children (Reynolds and Turek, 2012). Mathematics can be defined as the "science of structure, order, and relation that has evolved from elemental practices of counting, measuring, and describing the shapes of objects." (Berggren et al., 2020, webpage). Counting is a method of identifying the number of items in a finite set of those items, and is a strong predictor of mathematics ability (Durand et al., 2005).

There is evidence for the importance of visuospatial WM in reading (Pham and Hasson, 2014) and verbal WM in verbal comprehension (Pham and Hasson, 2014; Schwering and MacDonald, 2020), which in turn predicts later reading ability (Reynolds and Turek, 2012). These findings suggest that verbal WM may better explain verbal comprehension, and visuospatial and verbal WM together explain reading ability, as reading also requires comprehension. Similarly, studies have found that verbal WM predicts broader mathematics ability (Van de

Weijer-Bergsma et al., 2015) whereas visuospatial WM predicts counting (Zhang et al., 2014; Georges et al., 2021), which in turn predicts mathematics ability (Durand et al., 2005; Johansson, 2005). These findings showing visuospatial WM to be important for counting, and visuospatial and verbal WM for later general mathematics, suggest that mathematics relies on basic number knowledge (e.g., counting), albeit in a somewhat automated manner. Given this evidence for possible separate roles for verbal and visuospatial WM dependant on whether foundational or downstream abilities are measured, there is a need to further examine the different relationships between these cognitive and educational skills in a single sample. The current study looked at the differing relationships between these four educational outcomes and performance on processing and storage tasks representative of these underlying components of different types of WM.

Whilst many studies have measured verbal and visuospatial WM as two separate abilities, it may be problematic to measure visuospatial WM as a single construct, when, ostensibly, it can be separated into visual and spatial components. This issue was investigated in a review by Allen et al. (2019), with a concluding recommendation that the relationship between mathematics and visuospatial WM could be better understood by examining the subcomponents of the construct. The idea of separating these subcomponents is not new (see Logie and Pearson, 1997; Vicari et al., 2003). In fact, Cornoldi and Vecchi (2003) have proposed a model of visuospatial WM with separate subcomponents specifically for the short-term storage of information related to shapes and colours (i.e., visual WM) and another for the position of objects (i.e., spatial WM). Further, Fanari et al. (2019) examined both visual and spatial WM abilities, finding that they separately predicted mathematics in 6- to 7-year-olds. Specifically, they found evidence suggesting that spatial WM is important in early numeracy, and that both visual and spatial WM predict mathematics as children grow older (but see Vergauwe et al., 2009, that found no dissociation between visual and spatial WM in adults). Finally, a study by Caviola et al. (2020) examined verbal and spatial WM as predictors of mathematics and reading achievement in 7-, 9- and 12-year-olds and found that both verbal and spatial abilities predicted mathematics, whereas only verbal ability predicted reading. Evidently, the separation of visual and spatial abilities may alter the interplay with educational outcomes.

There is value in further examining the separate roles of processing and storage within verbal, visual and spatial WM tasks to better understand which aspects of WM (i.e., processing and storage) enable acquisition of the complex skills of reading and mathematics. Examining how these separate abilities relate to the underlying foundational skills of verbal comprehension and counting can contribute to our understanding of how they, in turn, explain mathematics and reading ability. However, there is a paucity of research that has investigated these separate relationships in a single study. This consideration of the relationships between the components of WM and foundational skills (i.e., counting and verbal comprehension) and the broader abilities of mathematics and reading respectively, could also provide valuable insights into the effectiveness of interventions. These questions are particularly important in relation to the educational outcomes of children in mid-primary education as this is a time when abilities related to increases in WM begin to emerge.

The current study examined the relative contributions of verbal, visual and spatial storage and processing abilities to reading and mathematics in 7- to 8-year-olds, whilst also considering influences on verbal comprehension and counting, respectively. The following research questions were addressed.

1. What are the roles of verbal, visual and spatial storage and processing for reading and mathematics abilities in children aged 7 to 8 years?
2. What are the roles of verbal, visual and spatial storage and processing for verbal comprehension and counting in children aged 7 to 8 years?
3. Are these relationships different for the foundational skills of comprehension and counting compared the downstream skills of reading and mathematics?

Based on recent research (Gordon et al., 2020), it was predicted that processing abilities would explain individual variation in the downstream skills of reading and mathematics, while storage abilities would explain variance in the foundational skills of verbal comprehension and counting. Specifically, it was predicted that:

1. Spatial storage would explain counting (Zhang et al., 2014; Fanari et al., 2019; Gordon et al., 2020; Georges et al., 2021)
2. Verbal, visual and spatial processing would explain mathematics performance (Van de Weijer-Bergsma et al., 2015; Gordon et al., 2021)
3. Verbal storage would explain verbal comprehension skill (Pham and Hasson, 2014; Schwering and MacDonald, 2020)
4. Verbal processing would explain reading ability (Pham and Hasson, 2014)
5. In addition, although it was expected that visual and/or spatial ability would explain reading, due to a lack of preceding evidence, there were no specific predictions as to which of these abilities might be important for reading

## MATERIALS AND METHODS

### Participants

An initial sample of 99 7- to 8-year-old children was recruited. As the aim of this research was to assess a representative sample of children in the United Kingdom mainstream education system the only exclusion criterion applied was for children with known developmental delays and/or a Special Educational Needs statement. One child moved to another school before they could complete the third testing session and five more children left school before completing any of the testing sessions. In addition, one child was excluded during their second testing session as it was identified that they were colour-blind and, therefore, unable to complete the spatial processing task. The remaining 92 children (41 male,

**TABLE 1** | Mean age, standard deviation and range at first and last testing session.

| Variable ($n = 92$; 51 females, 41 males) | Mean | *SD* | Min | Max |
|---|---|---|---|---|
| Age at testing first session (in months) | 93.95 | 4.23 | 86 | 103 |
| Age at testing last session (in months) | 97.76 | 3.55 | 92 | 107 |

51 female) aged between 7 and 8 years participated in all testing sessions. All children were unfamiliar with the assessments prior to the commencement of testing. The mathematics curriculum for each school was assessed and it was found that content was marginally inconsistent between schools. This was addressed in the measurement stage and is described in the following Section "Materials." Mean age and standard deviations at start and end of testing are shown in **Table 1**.

# Materials

## Verbal Storage

Verbal storage (short-term memory) was measured using the digit recall task from the Working Memory Test Battery for Children (WMTB-C; Pickering and Gathercole, 2001). This task was used as it correlates well with word span tasks (Oakhill et al., 2011), yet does not depend on word reading ability. This is important because it avoids the possibility of task impurity in that the task itself overlaps with the core abilities it is attempting to predict (i.e., reading). For the digit span task, the participant was verbally presented with a sequence of digits to be recalled in correct serial order. Digit sequences were designed to appear in random, non-repetitive sequences and were spoken at a rate of one digit per second. With six trials per block, the trials initially consisted of two numbers and increased by one number in each block until the participant was unable to recall four correct trials in a block. Scores for each trial correct were recorded as a value of '1'. The sum of these scores denoted the total trials correct as the verbal storage performance index.

## Verbal Processing

Verbal processing was measured using a time score from one component of the Verbal Inhibition Motor Inhibition (VIMI) task (Henry et al., 2012). The researcher said the words either 'day' or 'night' out loud and the participant was required to copy by repeating the word. For example:

Researcher: "Day."
Participant: "Day."
Researcher: "Day."
Participant: "Day."
Researcher: "Night."
Participant: "Night."
Researcher: "Day."
Participant: "Day."

The time taken to complete the 20 trials was recorded by the researcher using a digital stopwatch. The purpose of this was to record the time taken by each child to process what the researcher had said and then repeat it. Due to the nature of the task, the utterances from the researcher were also included in the time recorded. However, the duration of the words spoken by the researcher were fixed across trials and participants (i.e., spoken immediately after the prior response from the child). Therefore, any delay was due to the hesitancy of the child rather than the researcher. There were twenty trials and the total time taken to complete the task represented verbal processing ability.

## Spatial Storage

Spatial storage (short-term memory) was measured using the WMTB-C block recall task (Pickering and Gathercole, 2001). For this task, the participant was presented with a plastic tray consisting of an array of nine fixed, three-dimensional cubes. The researcher then pointed to a number of cubes in a sequence and the participant was required to point to each of the cubes indicated by the researcher in the correct serial order. The locations of the cubes were designed to appear in random and non-repetitive sequences. Each block was indicated at a rate of one per second. Trials consisted initially of two items and increased by one number in each block until the participant was unable to recall four correct trials in a block. The scoring was similar to that used in the digit span task, wherein a value of '1' was awarded for each trial correctly recalled. The sum of these scores denoted the total trials correct as the spatial storage performance index.

## Spatial Processing

Spatial processing was measured by the Colour Number Switch (CNS; Gordon, 2016) task. This assesses each participant's ability to search for and connect a series of twelve red dots in an irregular pattern across the page. The dots were numbered 'one' to 'twelve'. The time taken on this task was recorded by the experimenter using a digital stopwatch. The time taken on this task denoted the participant's spatial processing ability.

## Visual Storage

Visual storage (short-term memory) was measured using the Visual Sequential Memory task from the Test of Memory and Learning (TOMAL; Reynolds and Voress, 2009). The participants were presented with abstract designs in a linear array. They were then required to indicate the order in which they were originally presented when given the same designs in a different order. They did this by pointing at each design and stating the order it appeared in the original presentation (i.e., 1st, 2nd, 3rd, etc.). Up to 12 sets of stimuli were presented, one per page. The first set consisted of two designs. This increased by one on progression to each following set, up to a maximum of 7 designs on the final page. Testing was discontinued if a participant failed to correctly recall the design order in two consecutive trials. The total number of correct positions recalled was recorded.

## Visual Processing

Visual processing was assessed using a time score from a component of the Odd One Out Span task (Henry, 2001). In this task, the participant was asked to identify, from a horizontal line of three shapes in three separate boxes, which shape was different to the other two (i.e., was the "odd one out"). Two of the shapes were always identical, whilst a third (in any of the three available positions) was the odd one out. The odd one out was always designed to be definitely identifiable without being immediately obvious. For example, two arrows pointing left and one arrow point right; or two squares tilted right and one square tilted left. The time taken on this task was recorded and denoted the participants visual processing ability.

### Verbal Comprehension

To assess verbal comprehension, a computerised task specifically developed for the study was presented on a Dell 5000 Series Inspiron laptop, and written in E-Prime Version 2.0 (Schneider et al., 2005). The task was driven by a push-button response box operated by the researcher. Children completed a series of twenty trials to calculate their verbal comprehension ability. The participants were requested to complete these trials "as quickly and as carefully as possible." In individual sessions, each child listened to a sentence (e.g., "Apples have noses"), deciding whether or not it made sense and informing the researcher of their decision by saying "yes" or "no" (in this case, "no"). The researcher recorded the response by pressing the corresponding button on the box. After the twenty trials, the program calculated each participant's mean verbal comprehension ability based on their time taken to engage in the processing tasks and provide a response. To ensure children were attending to the stimuli (and therefore comprehending it), an 85% accuracy rate with regard to the veracity of the sentences was required for inclusion in further assessment. This calculation of 85% accuracy was based on the automated OSPAN task developed by Unsworth et al. (2005) to assess WM capacity. It was designed to ensure that participants were attending sufficiently to the stimuli. However, no participant performed below this ability level.

### Reading Ability

Reading ability was measured using the Word Reading task from The British Ability Scales third edition (BAS III, Elliot and Smith, 2011). The participants were required to read single words that became progressively more difficult to decode. Testing was discontinued after 10 successive reading failures. A single point was awarded for each correctly articulated word.

### Counting

There was a need to ensure the counting task was sensitive enough to identify differences in ability between children aged 7 to 8 years, as they are already proficient in this skill (Simms et al., 2013). Therefore, counting ability was assessed using a component score from the Creature Counting task from the Test of Everyday Attention for Children (TEA-Ch; Manly et al., 2001). The task features nine pages presented in a stimulus booklet. On each page, a picture showed a variable number of "creatures" in a tunnel. Interposed at varying stages between the creatures were arrows either pointing up or down. The participant was asked to count the creatures from the start of the tunnel beginning with number one, and to use the arrows as a trigger to switch the direction of the count (e.g., from counting up to counting down, or vice versa). This requirement to switch from counting up to counting down (and vice versa) introduces a level of difficulty that can identify individual differences in counting ability in this age group (Thompson, 1995). Two practice pages were completed prior to commencing the task in order to establish the participant's ability to count up and down. Each subsequent page was timed. This task was originally designed to assess the executive skill of task-switching. For that ability, a time and error cost were calculated for each child, to represent an attentional capacity to switch between two rules. Therefore, errors would indicate attentional lapses by 'losing track' of counting. As the purpose of the current study was to assess counting only, there was a need to minimise the possibility of confounding measurement with this executive aspect. Therefore, only sets that were counted correctly by the child were included. This was done to isolate the speed with which each child could count up and down, without introducing an index of their ability to switch between rules. A calculation of each child's time score on correct sets was used to measure counting ability.

### Mathematical Ability

A review of the mathematics curriculum across the schools involved in the study indicated that learning was not consistent across the schools in terms of curriculum content (e.g., one school included teaching percentages, another school did not). This is because Year 3 was not a mandatory testing year in the United Kingdom at the time of data collection. Therefore, the schools were not required to include specific content in their mathematics curriculum for that year. As this would almost certainly induce performance differences due to variations in exposure to certain topics, it was decided that a standardised mathematics test would not provide the correct insight into ability. However, each school had assessed the children's mathematics ability using the United Kingdom's Standard Assessment Tasks (SATs; Kirkup et al., 2005), tailored within each school in consideration of the taught topics for that academic year. Hence it was decided that the SATs scores provided by the school would be the best indication of mathematics ability (for a similar approach see Gathercole and Pickering, 2000; Lépine et al., 2005; St Clair-Thompson and Gathercole, 2006). An equivalency measure of ability between schools is included in the Section "Results."

## Procedure

Each participant was tested individually in a quiet room at school, during class times in the school day. Due to the number of tests, assessment was carried out over three sessions. Each session lasted between 30 and 45 min. Occasionally, it was necessary to break a session into two parts due to interruptions such as break-time, lunch, or non-curriculum-related demands (e.g., school play rehearsal, school photograph). However, on such occasions, the testing session was always completed within a single school day. The tasks were presented in the order shown in **Table 2**. Counter-balancing was not used as this is not

**TABLE 2** | Sequence of tasks within each testing session.

| Session | Ability |
|---|---|
| One | Counting |
| | Verbal storage |
| | Spatial storage |
| Two | Reading |
| | Spatial processing |
| | Visual processing |
| | Verbal comprehension |
| Three | Verbal processing |
| | Visual storage |

appropriate for studies investigating individual differences (Tolmie et al., 2011). This is due to the fact that counter-balancing creates a confound between order and individual differences as the source of variation. With the exception of the SATs mathematics grades, which were collected from the class teachers at the end of Year Three, the remaining nine tasks were administered throughout the Year Three academic year. There was a mean duration of 4 months between first and last session.

## RESULTS

Exploratory analysis identified some skewed distributions for some of the variables. For these variables, the values were converted to z-scores to identify any values more than 2.5 standard deviations from the mean. The corresponding true values were winsorized and substituted with the closest criterion value that fell within 2.5 standard deviations from the mean. This process was undertaken to remove the influence of any extreme responses as recommended by Ratcliff (1993; for a similar approach, see Bayliss et al., 2003, 2005, and Gordon et al., 2020). Means and standard deviations for all measures of storage, processing, verbal comprehension, counting, reading, and mathematics, including the number of values winsorized for each measure are included in **Table 3**.

To understand the relationships between each of the cognitive measures and the academic measures, a parametric correlation was run. With regard to the inter-correlations between the academic measures, mathematics and reading were significantly correlated ($r = 0.522$, $p < 0.001$) and counting speed (lower scores indicating faster counting) correlated significantly with both reading ($r = -0.415$, $p < 0.001$) and mathematics ($r = -0.423$, $p < 0.001$). Verbal comprehension was not significantly associated with reading, counting or mathematics. All correlations between academic and cognitive measures can be seen in **Table 4**. Verbal comprehension was related to verbal storage only, with slower response times in the verbal comprehension task linked to lower storage scores (indicated by a negative relationship). Reading correlated with both verbal and spatial storage, as did mathematics ability. Counting was negatively correlated with visual and spatial storage, with slower response times in the counting task times linked to lower storage scores. Counting was also correlated with verbal and visual processing. There were no other significant relationships.

Given the difference in curriculum between the two schools that participated in this study, there was a need to ensure equivalency in terms of the relationships between mathematics and the individual cognitive measures. A comparison of values of $r$ from the two schools is shown in **Table 5**. For all but one of the measures, there were no significant differences in the correlations between mathematics grade and each of the cognitive measures. There was a significant difference in the relationship between mathematics ability and verbal storage ($p = 0.047$). Therefore, a further correlational analysis was conducted to examine the links between mathematics ability and verbal storage for each school. For one school there was a significant relationship ($r = 0.358$, $p < 0.01$, $n = 70$); whereas, for the other, there was not ($r = -0.079$, $p = 739$, $n = 20$). Although this non-equivalence is acknowledged, it is possible that the smaller sample (i.e., $n = 20$) was too small to detect the effect. As there was a significant correlation in the larger sample (i.e., $n = 70$), and the comparison of values of $r$ showed borderline significance (i.e., $p = 0.047$) it was decided that the two schools could be considered comparable in terms of the relationships between mathematics and the cognitive measures used in this study.

To identify the roles of verbal, visual and spatial storage and processing in verbal comprehension, reading, counting and mathematics, a series of multiple regressions were run to understand the overall relationships between performance on the cognitive and academic measures. The processing and storage measures for verbal, visual and spatial abilities were entered together as predictors and assessed in terms of the variance explained in reading, verbal comprehension, mathematics and counting in turn. Squared semi-partial correlations are included to show the unique contributions from each predictor to the academic outcomes. These are shown in **Table 6**. For ease of reading, significant values are shown in bold. The models for reading, mathematics and counting were all significant. In terms of individual relationships with the cognitive measures, counting was predicted by visual storage and processing. Mathematics was predicted by verbal and spatial storage. Verbal comprehension was predicted by verbal storage; however, as the overall model was not significant, this is treated with some caution in the discussion. Reading was predicted by verbal and spatial storage. None of the academic skills were predicted by verbal and spatial processing.

## DISCUSSION

This study examined the relative contributions of verbal, visual and spatial storage and processing abilities to reading and mathematics, whilst also considering their influences on the underlying skills of verbal comprehension and counting, respectively. The findings are now discussed in the context of the predictions.

The first prediction was that spatial storage would explain variance in counting skill. However, this was not found to be the case, as visual storage and processing were the only measures that predicted counting. Although this finding does not support the suggestion of Fanari et al. (2019) that spatial

**TABLE 3 |** Mean and standard deviations for all cognitive and academic measures.

| Task | Mean | *SD* | Min | Max | Values winsorized |
|---|---|---|---|---|---|
| Mathematics[1] | 8.26 | 1.34 | 6 | 11 | 1[a] |
| Reading[2] | 67.37 | 8.1 | 47 | 80 | 2[b] |
| Verbal comprehension (s) | 3.04 | 1.6 | 0.89 | 7.07 | 2[a] |
| Counting ability (s) | 123.85 | 37.33 | 45 | 202 | 1[a] |
| Verbal storage (TTC) | 28.98 | 3.53 | 22 | 37 | 3[a] |
| Verbal processing (s) | 33.65 | 3.77 | 24 | 43 | 1[a] |
| Visual storage (TTC) | 18.54 | 4.3 | 8 | 28 | 0 |
| Visual processing (s) | 3.32 | 2.07 | 0.89 | 12.9 | 1[a] |
| Spatial storage (TTC) | 24.26 | 3.02 | 17 | 31 | 0 |
| Spatial processing (s) | 21.23 | 6.43 | 12 | 36 | 4[a] |

*[1]school grade converted; [2]total words correct; [a]above the mean; [b]below the mean. s, seconds; TTC, total trials correct.*

**TABLE 4 |** Correlation between all cognitive and academic measures.

| | Reading | Verbal comprehension | Counting | Verbal storage | Verbal processing | Visual storage | Visual processing | Spatial storage | Spatial processing |
|---|---|---|---|---|---|---|---|---|---|
| Mathematics | **0.522**** | 0.085 | **−0.423**** | **0.284**** | −0.002 | 0.173 | −0.188 | **0.326**** | −0.186 |
| Reading | – | −0.143 | **−0.415**** | **0.320**** | −0.127 | 0.034 | −0.193 | **0.293**** | −0.010 |
| Verbal comprehension | | – | −0.118 | **−0.216*** | −0.155 | 0.038 | 0.052 | 0.056 | −0.046 |
| Counting | | | – | −0.009 | **0.312**** | **−0.365**** | **0.313**** | **−0.290**** | 0.093 |
| Verbal storage | | | | – | −0.046 | 0.057 | 0.065 | −0.049 | −0.026 |
| Verbal processing | | | | | – | **−0.249*** | 0.019 | **−0.359**** | 0.158 |
| Visual storage | | | | | | – | −0.094 | **0.338**** | 0.047 |
| Visual processing | | | | | | | – | **−0.211*** | 0.060 |
| Spatial storage | | | | | | | | – | −0.196 |

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

WM is important in early numeracy, it could explain why studies have found visuospatial abilities to predict counting (Zhang et al., 2014; Georges et al., 2021). The current study separated visual and spatial abilities and storage and processing WM sub-components, which permitted identification of a specific relationship between visual processing and storage and counting in this age group. This approach supports a recommendation by Allen et al. (2019) that the relationship between WM and numeracy could be better understood by separating visual and spatial abilities.

The second prediction was that verbal, visual and spatial processing would be related to mathematics performance. However, contrary to this prediction, it was found that verbal and spatial *storage* were related to mathematics performance. This finding does not support the results of Gordon et al. (2021). They found stronger links between processing times (within WM tasks) and mathematics than between storage measures and mathematics. Gordon et al. concluded that processing abilities explained downstream mathematics outcomes, although, importantly, they used measures of WM that required concurrent processing and storage, and extracted these measures separately from task performance. The findings from the current study suggest that, without the executive load created by the need to process and store information concurrently, the links between processing and academic abilities are lost. There is a view that WM and short-term storage of information simply represent varying grades of executive attentional abilities (see Unsworth and Engle, 2007). Therefore, the current finding that storage, but not processing, abilities explain mathematics outcomes may be due to there being very little executive load in the processing tasks. This suggests that it is the executive element of the processing tasks that relates to mathematics (see Bayliss et al., 2003, for a supporting argument).

The third, fourth and fifth predictions are best discussed together. It was predicted that verbal storage would explain variance in verbal comprehension. This was found to be the case, although the overall model was not significant so this finding should be treated with caution. It suggests that any effect of verbal storage as a predictor was diluted by the presence of the other predictors. However, there is value in further investigation to understand the role verbal storage plays in verbal comprehension. It was also predicted that verbal processing would predict reading, and this relationship was not found. Finally, it was expected that some form of visual/spatial ability would also explain reading and, indeed, it was found that spatial storage predicted reading. These findings, in part, support the supposition that the early ability to store information verbally is a precursor to later reading ability, when the information is presented non-verbally. As stated in the introduction, there is no preceding evidence to direct a detailed prediction here as to whether visual or spatial processing or storage would be important for reading. Although speculative, the current study provides some early evidence for the role of spatial storage in reading.

**TABLE 5** | Comparison of correlations (*r*'s) between school maths grades and cognitive measures in each of the two schools.

| Verbal storage | Verbal processing | Visual storage | Visual processing | Spatial storage | Spatial processing |
|---|---|---|---|---|---|
| $Z = -1.673$<br>$p = 0.047$ | $Z = 0.730$<br>$p = 0.233$ | $Z = 0.084$<br>$p = 0.467$ | $Z = -0.528$<br>$p = 0.299$ | $Z = -1.024$<br>$p = 0.153$ | $Z = -1.139$<br>$p = 0.127$ |

**TABLE 6** | Multiple regressions showing combined predictors of performance on academic measures.

| | Overall model | Verbal storage | Verbal processing | Visual storage | Visual processing | Spatial storage | Spatial processing |
|---|---|---|---|---|---|---|---|
| Mathematics | **$F(6,83) = 4.12^{**}$** | **$t = 3.091^{**}$** | $t = -0.475$ | $t = 0.427$ | $t = -1.392$ | **$t = 0.2.271^{*}$** | $t = -1.119$ |
| | **Adjusted R2 = 0.17** | **$\beta = 0.300$** | $\beta = -0.050$ | $\beta = 0.045$ | $\beta = -0.138$ | **$\beta = 0.253$** | $\beta = -0.112$ |
| $sr^2$ | | **0.089** | 0.002 | 0.002 | 0.018 | **0.048** | 0.012 |
| Reading | **$F(6,83) = 4.35^{**}$** | **$t = 3.660^{***}$** | $t = -0.406$ | $t = -1.161$ | $t = -1.1689$ | **$t = 2.872^{**}$** | $t = 0.825$ |
| | **Adjusted R2 = 0.18** | **$\beta = 0.353$** | $\beta = -0.042$ | $\beta = -0.121$ | $\beta = -0.166$ | **$\beta = 0.318$** | $\beta = 0.082$ |
| $sr^2$ | | **0.123** | 0.002 | 0.012 | 0.026 | **0.076** | 0.006 |
| Verbal comprehension | $F(6,81) = 1.11$ | **$t = -2.139^{*}$** | $t = -1.240$ | $t = 0.169$ | $t = 0.673$ | $t = -0.060$ | $t = -0.320$ |
| | Adjusted $R^2 = 0.01$ | **$\beta = -0.231$** | $\beta = -0.145$ | $\beta = 0.020$ | $\beta = 0.074$ | $\beta = -0.007$ | $\beta = -0.035$ |
| $sr^2$ | | **0.052** | 0.017 | <0.001 | 0.005 | <0.001 | 0.001 |
| Counting | **$F(6,83) = 4.86^{***}$** | $t = -0.042$ | $t = 1.877$ | **$t = -2.652^{*}$** | **$t = 2.759^{**}$** | $t = -0.539$ | $t = 0.443$ |
| | **Adjusted R2 = 0.21** | $\beta = -0.004$ | $\beta = 0.194$ | **$\beta = -0.272$** | **$\beta = 0.267$** | $\beta = -0.059$ | $\beta = 0.043$ |
| $sr^2$ | | <0.001 | 0.031 | **0.063** | **0.068** | 0.003 | 0.002 |

*$^*p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$; $sr^2$ = squared semi-partial correlations for each predictor against each outcome.*

Explanations for these findings are now discussed in more detail, in the context of the different abilities. Though interpreted with caution, the finding that verbal storage predicted performance on the verbal comprehension measure supports the idea that verbal comprehension requires the online processing of continuous language input. Diamond (2013) notes that storage in WM may underpin comprehension as it is fundamental for understanding input that unfolds over time. As auditory information is the only stimulus provided (i.e., there is no written text), the participant must hold continuous verbal input in mind for long enough to process and understand it.

For reading, the key material is provided in written and spatial form on a page but reading nevertheless requires the continuous processing of meaning from continuous input, as well as keeping track of spatial position on the page. Therefore, the links between reading and both verbal and spatial storage could reflect the need to hold in mind and process key verbal and spatial information during the reading process (Pham and Hasson, 2014). Although the reading task required single word reading, it was developed based on its robust validity in reflecting reading comprehension (Elliot and Smith, 2011); therefore, the extension here to reading comprehension was not considered unreasonable. A further possibility is that there is a specific spatial demand in single word reading, especially for younger readers, as there is a requirement to accurately map the letters to create the correct word. The absence of a relationship with either visual measure is plausible as the visual information is stored externally (i.e., in written form), reducing demands on resources in this domain. This latter finding also suggests that the separation of visual and spatial WM may provide further insights into the importance of these abilities in reading. The finding of relationships between mathematics and verbal and spatial storage supports previous research that has shown both these abilities might be important in mathematics generally (see Andersson, 2007; Peng et al., 2016). However, the absence of any relationships with visual task performance again highlights the value in separating visual and spatial abilities when examining WM.

It was surprising, however, that for verbal comprehension, reading and mathematics, only the storage variables were found to be important, with no relationships found for the processing variables (verbal storage related to verbal comprehension; and verbal *and* spatial storage related to reading and mathematics). Conversely, counting was the only skill that showed any relationship with processing, showing links to visual processing (as well as to visual storage). There are a few possible explanations for this finding. Firstly, the counting task requires an additional visual processing stage prior to task commencement, in contrast to the other skills measures. Words (reading task), sentences (comprehension) and sums (mathematics) are all provided (either verbally or visually) for the child to use in order to complete the task. However, for the counting task, the child is required to translate the creatures into meaningful information (i.e., numbers). Therefore, there is a need for internal visual storage of the count objects along with continual processing (for the purpose of updating) as children progress through the task. Secondly, links between counting and visual storage and processing may indicate that children who were able to use a visual strategy such as a number line, were better at this counting task (see Schneider et al., 2005, for a review). Thirdly, the visual nature of the task (i.e., counting pictures of creatures and using arrows to indicate the task rule) could simply reflect a visual processing ability. Fourthly, and more speculatively, there is a need for conversion to symbolic numbers in counting objects that requires a visual representation (i.e., of the Arabic symbol). For children with established number knowledge, number symbols are automatically brought to mind when saying the number word (Mundy and Gilmore, 2009). This may assist storage, in the same way as spoken and written words have been argued to automatically trigger each other (*cf.* the visual word form area; Dehaene and Cohen, 2011).

One of the important features about these findings, overall, is that the storage and processing tasks for the measures of verbal, visual and spatial abilities all held separate relationships with reading, verbal comprehension, mathematics and counting. These findings will now be considered in the context of the key WM models.

Only one variable, verbal storage, was related to verbal comprehension, suggesting that the embedded process model (Cowan, 1999, 2008; Cowan et al., 2015) might best represent WM in this instance. This model proposes that WM is the use of attention to activate and hold in mind information from long-term memory. This attentional capacity is argued to be capacity-limited and consciously controlled, whilst supported by unconscious automatic processes. Verbal comprehension demands the activation of information from long-term memory (i.e., word meaning) and continuous attention that is updated as new information (i.e., subsequent words in the sentence) is presented. For the task used in the current study, there was also an additional requirement for the child to draw on their knowledge of the world from long-term memory (as well as accessing word meaning), in order to determine the veracity of the sentence and respond accordingly. This proposal is in line with Cowan's (1999) argument that WM relies on long-term memory to allow new episodic representations to be available for recall.

Similarly, the role of verbal and spatial storage found here in reading ability is best explained by the embedded-process model (e.g., Cowan, 1999), as verbal and spatial storage could reflect an attentional capacity which activates the relevant information (i.e., phonological and graphic word knowledge respectively) from long-term memory in pursuit of the known goal of reading the word out loud correctly. For both reading and verbal comprehension, the absence of a role for processing in contributing to these academic abilities has been explained previously in this section as being the result of a reduced demand on the need to internalise representations.

Links between verbal and spatial storage and the written mathematics task again suggest the embedded-process model (e.g., Cowan, 1999) as the preferred explanation for the role of WM in this ability. In such a task, the processing of information is external (i.e., in written and numerical text). The child must draw on knowledge from long-term memory, even at the most basic level such as recognising the Arabic numeral '2' as representative of a quantity of two. Attention must be focused on the relevant information in order to complete the task in written form and this information can be verbal (e.g., reciting a number) or spatial such as a reliance on a workspace to support a transition from concrete informal knowledge to formal operation (see Holmes et al., 2008).

Counting ability was related to visual storage and processing, and this might be best explained by the TBRS model of WM (Camos and Barrouillet, 2011). It is noted that the combined abilities of processing and storing information reflect the multicomponent model (Baddeley and Hitch, 1974), but a negative relationship between storage and processing in WM tasks would suggest that the greater a child's capacity for storing visual information, the faster they are at processing numbers. This trade-off between processing and storage is in line with the TBRS model that posits there is a need to rapidly switch attention from processing to storage in order to maintain relevant information when pursuing a known goal. The faster a child's processing ability, the better able they are to switch attention and thus maintain information for longer periods before it decays. Although it is noted that the processing and storage tasks in the current study were not integrated (i.e., they were not part of the same task, which does place limits on the conclusions), the links between counting and visual processing and storage could imply a greater role for processing beyond that covered by Cowan's (1999) embedded-process model. Also, no variance in performance on any academic measures was explained by any of the other processing tasks. This suggests there may be some meaningful separability of types of processing, a finding which does not wholly support other studies (e.g., Bayliss et al., 2003) which have argued for domain-general processing in children, as opposed to domain-specific storage. There are presently no models of WM that argue for discrete types of processing (i.e., verbal, visual, spatial). However, findings from a recent study by Alghamdi et al. (2021) suggest that visual processing ability relates only to the development of visual WM and not verbal WM in 5- to 7-year-olds, supporting the suggestion here that types of processing within WM might be discrete. As the Alghamdi et al. study only examined visual processing ability, there is value in further investigating visual, spatial and verbal processing to understand links with the development of the respective storage abilities in WM. This possible enhanced structure of WM could better inform the links between WM and academic outcomes.

The current study provides some insights as to why the literature continues to be so varied, with differing relationships between WM and reading and mathematics found, depending on the different cognitive tasks used. This may reflect a phenomenon similar to that related to the Miyake et al. (2000; Miyake and Friedman, 2012) model of executive function. That is, when different measures are used for (supposedly) the same executive abilities, disparate relationships with academic abilities are found (see Gordon et al., 2018, for a review). This is referred to as the task impurity problem (Burgess, 1997). That is, when participants complete tasks aimed at measuring a specific ability, other cognitive mechanisms are called into play (e.g., verbal ability in a spatial task). This can make it challenging when trying to isolate what aspect of cognitive task performance relates to a specific outcome (e.g., reading or mathematics). The Miyake model does become more stable as its application moves up the age range (Friedman et al., 2016; see Karr et al., 2018, for a review). In terms of child development this makes sense as, early in childhood, children make use of a mass of processes that are, to a large degree, not directed toward specific tasks or contexts. As they become more familiar with external tasks (e.g., reading and mathematics), these processes become more stable and fractionate out to specific types of function as the tasks demand (Best and Miller, 2010).

At present, for young children, it does not seem to be the case that one model can explain how the development of certain academic abilities is supported by WM. Although the embedded-process model (e.g., Cowan, 1999) goes a long way in explaining the four academic abilities included in this study, it is limited in how it might explain the role of processing. Given what we know about neural processes, it is plausible that brain mechanisms differentiate according to different underlying task demands. This, in part, is in line with the findings of Gordon et al. (2020), who found that time-based demands within WM tasks altered relationships with academic measures, whereby links with storage became weaker and links with processing were strengthened. Although the limitations of some of the tasks used in the current study are acknowledged below, there is value in further pursuing the roles of verbal, visual and spatial processing in WM, and how their influence on educational outcomes might change when task demands are manipulated (e.g., time allowed for processing).

It is acknowledged that the choice of mathematics measure in the current study limits findings to very broad ability. There would be benefit in examining these relationships with mathematical subcomponents, such as those used by Gordon et al. (2021; see also Allen et al., 2019) in their developmental investigation into the WM-mathematics relationship. Similarly, it would be informative to apply the method employed in the current study to different age groups to better understand how the relationships examined here change in younger and older children. It must also be noted that the mathematics measure used in the current study was not consistent across the two schools involved. The end of year mathematics grades awarded by the form teachers were used to minimise a risk of findings being confounded by differences in the curriculum between schools. A comparison of the correlations between each of the cognitive measures and the mathematics measure revealed a possible significant difference between the schools with regard to the link with verbal storage. Further analysis indicated that this difference may be negligible. However, it is acknowledged that a consistent mathematics measure for all participants would be preferable. In addition, it is possible that some of the cognitive tasks used could explain some of the links with academic abilities. For example, the fact that the verbal storage task used numbers might explain the link with mathematics. However, set against this, a study by Oakhill et al. (2011) found that the predictive nature of WM tasks did not depend on the processing stimuli being either word- or number-based. This is in line with other studies that have found different processing stimuli in WM do not affect relationships with academic abilities; rather it is the separability of processing and storage skills that explain this link (Bayliss et al., 2003, 2005).

In summary, the current study found that verbal storage was important for verbal comprehension and reading, and spatial storage was additionally important for reading. However, for counting, visual processing and storage both played a role, but only verbal and spatial storage were relevant for mathematics. We have argued that cognitive resources for tasks that did not require internal representations of the stimuli being monitored related mainly to storage, and were largely verbal and spatial in nature. However, when the tasks did not have externally presented representations (i.e., the numbers sequence in counting tasks), there was a draw on visual storage and processing abilities. Additional research could further examine whether there is indeed a difference in cognitive demands for these internalised tasks. Furthermore, investigation into the possible meaningful separability of types of processing could lead to the development of a new or enhanced WM model, which might better inform interventions and reasonable adjustments for children who struggle with reading and mathematics due to WM deficits.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## ETHICS STATEMENT

The studies involving human participants were reviewed and approved by London South Bank University, London. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

## AUTHOR CONTRIBUTIONS

RG: conception of article, data collection, analysis, and drafting of manuscript. All authors: critical revision of the text and approved the final version of the manuscript.

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## REFERENCES

Allen, K., Higgins, S., and Adams, J. (2019). The relationship between visuospatial working memory and mathematical performance in school-aged children: a systematic review. *Educ. Psychol. Rev.* 31, 509–531. doi: 10.1007/s10648-019-09470-8

Alghamdi, R. J., Murphy, M. J., and Crewther, S. G. (2021). The contribution of visual processing speed to visual and auditory working memory in early school years. *Psychol. Neurosci.* doi: 10.1037/pne0000274, [Epub ahead of print]

Andersson, U. (2007). The contribution of working memory to children's mathematical word problem solving. *Appl. Cogn. Psychol.* 21, 1201–1216. doi: 10.1002/acp.1317

Baddeley, A. (1996). The fractionation of working memory. *Proc. Natl. Acad. Sci. U. S. A.* 93, 13468–13472. doi: 10.1073/pnas.93.24.13468

Baddeley, A. D., and Hitch, G. J. (1974). "Working memory," in *The Psychology of Learning and Motivation, Vol. 8* (New York: Academic Press.)

Barrouillet, P., Bernardin, S., and Camos, V. (2004). Time constraints and resource sharing in adults' working memory spans. *J. Exp. Psychol. Gen.* 133, 83–100. doi: 10.1037/0096-3445.133.1.83

Bayliss, D. M., Jarrold, C., Baddeley, A. D., Gunn, D. M., and Leigh, E. (2005). Mapping the developmental constraints on working memory span performance. *Dev. Psychol.* 41, 579–597. doi: 10.1037/0012-1649.41.4.579

Bayliss, D. M., Jarrold, C., Gunn, D. M., and Baddeley, A. D. (2003). The complexities of complex span: explaining individual differences in working memory in children and adults. *J. Exp. Psychol. Gen.* 132, 71–92. doi: 10.1037/0096-3445.132.1.71

Berggren, J. L., Folkerts, M., Gray, J. J., Fraser, C. G., and Knorr, W. R. (2020). Mathematics. *Encyclopedia Britannica*. Available at: https://www.britannica.com/science/mathematics (Accessed November 9, 2020).

Best, J. R., and Miller, P. H. (2010). A developmental perspective on executive function. *Child Dev.* 81, 1641–1660. doi: 10.1111/j.1467-8624.2010.01499.x

Burgess, P. W. (1997). "Theory and methodology in executive function research," in *Methodology of Frontal and Executive Function*. ed. P. Rabbitt (Hove, UK: Psychology Press), 81–116.

Camos, V., and Barrouillet, P. (2011). Developmental change in working memory strategies: from passive maintenance to active refreshing. *Dev. Psychol.* 47, 898–904. doi: 10.1037/a0023193

Caviola, S., Colling, L. J., Mammarella, I. C., and Szűcs, D. (2020). Predictors of mathematics in primary school: magnitude comparison, verbal and spatial working memory measures. *Dev. Sci.* 23:e12957. doi: 10.1111/desc.12957

Cornoldi, C., and Vecchi, T. (2003). "Congenitally blindness and spatial mental imagery," in *Touching for Knowing: Cognitive Psychology of Haptic Manual Perception*. eds. Y. Hatwell, A. Streri and E. Gentaz (Philadelphia: John Benjamins Publishing), 173–187.

Cowan, N. (1999). *An Embedded-Processes Model of Working Memory*. New York: Cambridge University Press.

Cowan, N. (2008). What are the differences between long-term, short-term, and working memory? *Prog. Brain Res.* 169, 323–338. doi: 10.1016/S0079-6123(07)00020-9

Cowan, N., Elliott, E. M., Saults, J. S., Morey, C. C., Mattox, S., Hismjatullina, A., et al. (2005). On the capacity of attention: its estimation and its role in working memory and cognitive aptitudes. *Cogn. Psychol.* 51, 42–100. doi: 10.1016/j.cogpsych.2004.12.001

Cowan, N., Ricker, T. J., Clark, K. M., Hinrichs, G. A., and Glass, B. A. (2015). Knowledge cannot explain the developmental growth of working memory capacity. *Dev. Sci.* 18, 132–145. doi: 10.1111/desc.12197

Dehaene, S., and Cohen, L. (2011). The unique role of the visual word form area in reading. *Trends Cogn. Sci.* 15, 254–262. doi: 10.1016/j.tics.2011.04.003

Diamond, A. (2013). Executive functions. *Annu. Rev. Psychol.* 64, 135–168. doi: 10.1146/annurev-psych-113011-143750

Durand, M., Hulme, C., Larkin, R., and Snowling, M. (2005). The cognitive foundations of reading and arithmetic skills in 7-to 10-year-olds. *J. Exp. Child Psychol.* 91, 113–136. doi: 10.1016/j.jecp.2005.01.003

Elliot, C., and Smith, P. (2011). *British Ability Scales. Technical Manual. 3rd Edn*. London: Elliott.

Fanari, R., Meloni, C., and Massidda, D. (2019). Visual and spatial working memory abilities predict early math skills: a longitudinal study. *Front. Psychol.* 10:2460. doi: 10.3389/fpsyg.2019.02460

Friedman, N. P., Miyake, A., Altamirano, L. J., Corley, R. P., Young, S. E., Rhea, S. A., et al. (2016). Stability and change in executive function abilities from late adolescence to early adulthood: a longitudinal twin study. *Dev. Psychol.* 52, 326–340. doi: 10.1037/dev0000075

Gathercole, S. E., Adams, A. M., and Hitch, G. J. (1994). Do young children rehearse? An individual-differences analysis. *Mem. Cogn.* 22, 201–207. doi: 10.3758/BF03208891

Gathercole, S. E., and Pickering, S. J. (2000). Working memory deficits in children with low achievements in the national curriculum at 7 years of age. *Br. J. Educ. Psychol.* 70, 177–194. doi: 10.1348/000709900158047

Georges, C., Cornu, V., and Schiltz, C. (2021). The importance of visuospatial abilities for verbal number skills in preschool: adding spatial language to the equation. *J. Exp. Child Psychol.* 201:104971. doi: 10.1016/j.jecp.2020.104971

Giofrè, D., Mammarella, I. C., Ronconi, L., and Cornoldi, C. (2013). Visuospatial working memory in intuitive geometry, and in academic achievement in geometry. *Learn. Individ. Differ.* 23, 114–122. doi: 10.1016/j.lindif.2012.09.012

Gordon, R. (2016). Measuring children's working memory: the influence of titrated time constraints on complex span tasks and the relationship with higher order cognitive abilities. doctoral dissertation. London: London South Bank University.

Gordon, R., Santana De Morais, D., Whitelock, E., and Mukarram, A. (2021). Mapping components of verbal and visuospatial working memory to mathematical topics in seven-to fifteen-year-olds. *Br. J. Educ. Psychol.* doi: 10.1111/bjep.12440 [Epub ahead of print].

Gordon, R., Smith-Spark, J. H., Newton, E. J., and Henry, L. A. (2018). Executive function and academic achievement in primary school children: the use of task-related processing speed. *Front. Psychol.* 9:582. doi: 10.3389/fpsyg.2018.00582

Gordon, R., Smith-Spark, J. H., Newton, E. J., and Henry, L. A. (2020). Working memory and high-level cognition in children: an analysis of timing and accuracy in complex span tasks. *J. Exp. Child Psychol.* 191:104736. doi: 10.1016/j.jecp.2019.104736

Gough, P. B., and Tunmer, W. E. (1986). Decoding, reading, and reading disability. *Remedial Spec. Educ.* 7, 6–10. doi: 10.1177/074193258600700104

Henry, L. A. (2001). How does the severity of a learning disability affect working memory performance? *Memory* 9, 233–247. doi: 10.1080/09658210042000085

Henry, L. A., Messer, D. J., and Nash, G. (2012). Executive functioning in children with specific language impairment. *J. Child Psychol. Psychiatry* 53, 37–45. doi: 10.1111/j.1469-7610.2011.02430.x

Henry, L. A., and Millar, S. (1993). Why does memory span improve with age? A review of the evidence for two current hypotheses. *Eur. J. Cogn. Psychol.* 5, 241–287. doi: 10.1080/09541449308520119

Holmes, E. A., Geddes, J. R., Colom, F., and Goodwin, G. M. (2008). Mental imagery as an emotional amplifier: application to bipolar disorder. *Behav. Res. Ther.* 46, 1251–1258. doi: 10.1016/j.brat.2008.09.005

Hoover, W. A., and Gough, P. B. (1990). The simple view of reading. *Read. Writ.* 2, 127–160. doi: 10.1007/BF00401799

Jarrold, C., and Citroën, R. (2013). Reevaluating key evidence for the development of rehearsal: phonological similarity effects in children are subject to proportional scaling artifacts. *Dev. Psychol.* 49, 837–847. doi: 10.1037/a0028771

Johansson, B. S. (2005). Number-word sequence skill and arithmetic performance. *Scand. J. Psychol.* 46, 157–167. doi: 10.1111/j.1467-9450.2005.00445.x

Karr, J. E., Areshenkoff, C. N., Rast, P., Hofer, S. M., Iverson, G. L., and Garcia-Barrera, M. A. (2018). The unity and diversity of executive functions: a systematic review and re-analysis of latent variable studies. *Psychol. Bull.* 144, 1147–1185. doi: 10.1037/bul0000160

Kirkup, C., Sizmur, J., Sturman, L., and Lewis, K. (2005). *Schools' Use of Data in Teaching and Learning*. England: National Foundation for Educational Research.

Lépine, R., Parrouillet, P., and Camos, V. (2005). What makes working memory spans so predictive of high-level cognition? *Psychon. Bull. Rev.* 12, 165–170. doi: 10.3758/BF03196363

Logie, R. H. (1995). *Visuo-Spatial Working Memory*. New York: Psychology Press.

Logie, R., and Pearson, D. G. (1997). The inner eye and the inner scribe of visuo-spatial working memory: evidence from developmental fractionation. *Eur. J. Cogn. Psychol.* 9, 241–257. doi: 10.1080/713752559

Manly, T., Anderson, V., Nimmo-Smith, I., Turner, A., Watson, P., and Robertson, I. H. (2001). The differential assessment of children's attention: the test of everyday attention for children (TEA-Ch), normative sample and ADHD performance. *J. Child Psychol. Psychiatry* 42, 1065–1081. doi: 10.1111/1469-7610.00806

Miyake, A., and Friedman, N. P. (2012). The nature and organization of individual differences in executive functions: four general conclusions. *Curr. Dir. Psychol. Sci.* 21, 8–14. doi: 10.1177/0963721411429458

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., and Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: a latent variable analysis. *Cogn. Psychol.* 41, 49–100. doi: 10.1006/cogp.1999.0734

Mundy, E., and Gilmore, C. K. (2009). Children's mapping between symbolic and nonsymbolic representations of number. *J. Exp. Child Psychol.* 103, 490–502. doi: 10.1016/j.jecp.2009.02.003

Oakhill, J., Yuill, N., and Garnham, A. (2011). The differential relations between verbal, numerical and spatial working memory abilities and children's reading comprehension. *Int. Electron. J. Elem. Educ.* 4, 83–106.

Peng, P., Barnes, M., Wang, C., Wang, W., Li, S., Swanson, H. L., et al. (2018). A meta-analysis on the relation between reading and working memory. *Psychol. Bull.* 144, 48–76. doi: 10.1037/bul0000124

Peng, P., Namkung, J., Barnes, M., and Sun, C. (2016). A meta-analysis of mathematics and working memory: moderating effects of working memory domain, type of mathematics skill, and sample characteristics. *J. Educ. Psychol.* 108, 455–473. doi: 10.1037/edu0000079

Pham, A. V., and Hasson, R. M. (2014). Verbal and visuospatial working memory as predictors of children's reading ability. *Arch. Clin. Neuropsychol.* 29, 467–477. doi: 10.1093/arclin/acu024

Pickering, S. J., and Gathercole, S. E. (2001). *Working Memory Test Battery for Children*. London: Psychological Corporation.

Rasmussen, C., and Bisanz, J. (2005). Representation and working memory in early arithmetic. *J. Exp. Child Psychol.* 91, 137–157. doi: 10.1016/j.jecp.2005.01.004

Ratcliff, R. (1993). Methods for dealing with reaction time outliers. *Psychol. Bull.* 114, 510–532. doi: 10.1037/0033-2909.114.3.510

Reynolds, M. R., and Turek, J. J. (2012). A dynamic developmental link between verbal comprehension-knowledge (Gc) and reading comprehension: verbal comprehension-knowledge drives positive change in reading comprehension. *J. Sch. Psychol.* 50, 841–863. doi: 10.1016/j.jsp.2012.07.002

Reynolds, C. R., and Voress, J. K. (2009). "Clinical neuropsychological assessment with the test of memory and learning," in *Handbook of Clinical Child Neuropsychology* (Springer: Boston, MA), 297–319.

Riggs, K. J., McTaggart, J., Simpson, A., and Freeman, R. P. (2006). Changes in the capacity of visual working memory in 5-to 10-year-olds. *J. Exp. Child Psychol.* 95, 18–26. doi: 10.1016/j.jecp.2006.03.009

Schneider, W., Bolger, D. J., Eschman, A., Neff, C., and Zuccolotto, A. P. (2005). Psychology Experiment Authoring Kit (PEAK): formal usability testing of an easy-to-use method for creating computerized experiments. *Behav. Res. Methods* 37, 312–323. doi: 10.3758/BF03192699

Schwering, S. C., and MacDonald, M. C. (2020). Verbal working memory as emergent from language comprehension and production. *Front. Hum. Neurosci.* 14:68. doi: 10.3389/fnhum.2020.00068

Simms, V., Muldoon, K., and Towse, J. (2013). Plane thinking: mental representations in number line estimation as a function of orientation, scale, and counting proficiency. *J. Exp. Child Psychol.* 115, 468–480. doi: 10.1016/j.jecp.2013.03.011

St Clair-Thompson, H. L., and Gathercole, S. E. (2006). Executive functions and achievements in school: shifting, updating, inhibition, and working memory. *Q. J. Exp. Psychol.* 59, 745–759. doi: 10.1080/17470210500162854

Swanson, H. L., Zheng, X., and Jerman, O. (2009). Working memory, short-term memory, and reading disabilities: a selective meta-analysis of the literature. *J. Learn. Disabil.* 42, 260–287. doi: 10.1177/0022219409331958

Thompson, I. (1995). The role of counting in the idiosyncratic mental calculation algorithms of young children. *Eur. Early Child. Educ. Res. J.* 3, 5–16. doi: 10.1080/13502939585207651

Tolmie, A., Muijs, D., and McAteer, E. (2011). Quantitative Methods in Educational and Social Research Using SPSS. UK: McGraw-Hill Education.

Unsworth, N., and Engle, R. W. (2007). On the division of short-term and working memory: an examination of simple and complex span and their relation to higher order abilities. *Psychol. Bull.* 133, 1038–1066. doi: 10.1037/0033-2909.133.6.1038

Unsworth, N., Heitz, R. P., Schrock, J. C., and Engle, R. W. (2005). An automated version of the operation span task. *Behav. Res. Methods* 37, 498–505. doi: 10.3758/BF03192720

Van de Weijer-Bergsma, E., Kroesbergen, E. H., and Van Luit, J. E. (2015). Verbal and visual-spatial working memory and mathematical ability in different domains throughout primary school. *Mem. Cogn.* 43, 367–378. doi: 10.3758/s13421-014-0480-4

Van der Ven, S. H., van der Maas, H. L., Straatemeier, M., and Jansen, B. R. (2013). Visuospatial working memory and mathematical ability at different ages throughout primary school. *Learn. Individ. Differ.* 27, 182–192. doi: 10.1016/j.lindif.2013.09.003

Van Norman, E. R., Nelson, P. M., and Parker, D. C. (2018). A comparison of nonsense-word fluency and curriculum-based measurement of reading to measure response to phonics instruction. *Sch. Psychol. Q.* 33, 573–581. doi: 10.1037/spq0000237

Vergauwe, E., Barrouillet, P., and Camos, V. (2009). Visual and spatial working memory are not that dissociated after all: a time-based resource-sharing account. *J. Exp. Psychol. Learn. Mem. Cogn.* 35, 1012–1028. doi: 10.1037/a0015859

Vicari, S., Bellucci, S., and Carlesimo, G. A. (2003). Visual and spatial working memory dissociation: evidence from Williams syndrome. *Dev. Med. Child Neurol.* 45, 269–273. doi: 10.1017/s0012162203000513

Zhang, X., Koponen, T., Räsänen, P., Aunola, K., Lerkkanen, M. K., and Nurmi, J. E. (2014). Linguistic and spatial skills predict early arithmetic development via counting sequence knowledge. *Child Dev.* 85, 1091–1107. doi: 10.1111/cdev.12173

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# Tracking Familial History of Reading and Math Difficulties in Children's Academic Outcomes

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The current study aimed to investigate the extent to which familial history of reading and math difficulties have an impact on children's academic outcomes within a 3-year longitudinal study, which evaluated their core reading and math skills after first ($N$ = 198; 53% girls) and second grades ($N$ = 166), as well as performance on complex academic tasks after second and third grades ($N$ = 148). At baseline, parents were asked to complete the *Adult Reading History Questionnaire* (ARHQ) and its adaption, *Adult Math History Questionnaire* (AMHQ), to index familial history of reading and math difficulties, respectively. Preliminary findings established the psychometric properties of the AMHQ, suggesting that it is a reliable and valid scale. Correlation analyses indicated that the ARHQ was negatively associated with children's reading skills, whereas the AMHQ was negatively related to math outcomes. Path results revealed that the ARHQ predicted children's performance on complex reading tasks indirectly via their core reading skills, and the AMHQ was linked to complex math outcomes indirectly via core math abilities. The ARHQ was also found to be negatively correlated with measures of children's math performance, with path findings suggesting that these relations were indirectly explained by differences in their core reading skills. These results suggest that assessing familial risk for academic difficulties may be crucial to understanding comorbid etiological and developmental associations between reading and math differences.

**Keywords: familial history, academic, reading, math, intergenerational transmission, reading difficulties, math difficulties**

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## INTRODUCTION

Parents' self-report of academic difficulties, often referred to as familial history, has been shown as a significant predictor of children's academic outcomes. For example, familial history of reading difficulties has been found to be negatively associated with children's reading skills and, to some extent, math abilities (Scarborough, 1989; Pennington and Lefly, 2001). However, much remains to be understood regarding the impact of familial math history on academic outcomes, particularly as related to the subcomponents of reading and math, as well as math more generally. As such, the first aim of this study was to build on existing findings by asking whether parents' self-report of math difficulties, in parallel with familial reading history, negatively predicts differences in children's academic outcomes. Leveraging a longitudinal design, the second aim was to demarcate the direct and indirect effects of familial history on children's core reading and math skills versus their performance on complex academic tasks. Results from these research aims could offer diagnostic and intervention implications for children at heightened familial history for academic difficulties, as well as add to the understanding of the comorbid etiological and developmental associations between reading and math differences. (For the list of abbreviations used throughout this study, see **Table 1**).

## Parents' Self-Report of Academic Difficulties

One way to capture familial history of academic difficulties is by parents' self-report, which has been shown to be reliable (e.g., Lefly and Pennington, 2000). Some studies have utilized a dichotomous, or yes-versus-no, indicator for familial history of reading and/or math difficulties (Landerl and Moll, 2010; Erbeli et al., 2019; Khanolainen et al., 2020). Parents' self-report of academic difficulties, operationalized as a dichotomous variable, has indeed been shown to negatively predict children's reading and math outcomes. These findings have revealed that children with parents who self-report childhood difficulties when learning to read words or performing arithmetic computation in elementary school as compared to children whose parents report no such difficulties are more likely to exhibit differences in their academic skills when they start their formal education (e.g., Landerl and Moll, 2010; Erbeli et al., 2019; Khanolainen et al., 2020). Nevertheless, the strategy in treating familial history of academic difficulties as a dichotomous variable has been caveated to be somewhat arbitrary because "the liability distribution for a given disease is often continuous and quantitative" (Snowling et al., 2003; Pennington, 2006). To this end, some studies have used more in-depth questionnaires, such as the *Adult Reading History Questionnaire* (ARHQ), to refine the specificity, sensitivity, as well as severity in terms of reading-related differences in a dimensional manner (Lefly and Pennington, 2000; see also Welcome and Meza, 2019). The ARHQ, a revision of an earlier self-report designed by Finucci et al. (1982), includes items that query not only childhood reading difficulties, but also previous school experiences, attitude toward reading, as well as current literacy practices among adult responders or parents (Lefly and Pennington, 2000). Findings reveal substantial correlations among these items within the ARHQ (Lefly and Pennington, 2000; Welcome and Meza, 2019), thus supporting the approach of assessing familial history, at least within the reading domain, in a dimensional and continuous manner. For example, studies have reported that higher scores on the ARHQ are prospectively associated with worse performance across reading and, although evidence for this is limited, even math tasks (Pennington and Lefly, 2001). Such predictive effects of the ARHQ has further been implicated to be independent from some children's eventual status of reading disability (dyslexia) and parents' level of educational attainment (Pennington and Lefly, 2001), and have been replicated in a range of studies and designs (neurobiological: Black et al., 2012; twin: Rosenberg et al., 2012; and genotyping: Stefansson et al., 2014), motivating the utility of this scale in underscoring the continuous nature and predictive effect of familial reading history in reading and perhaps math outcomes.

While the ARHQ has fairly robust empirical support at this time, findings with regard to familial history of math difficulties measured in a dimensional, continuous manner have not yet been reported, as there is currently no validated scale that captures familial history of math difficulties that mirrors the ARHQ[1]. To address this gap in the literature, the *Adult Math History Questionnaire* was designed and implemented when the current longitudinal study commenced in 2015 in order to track the role of familial math history in children's academic outcomes over time.

**TABLE 1 |** List of abbreviations used throughout the current study.

| Acronym | Term |
|---|---|
| **Familial history** | |
| ARHQ | Adult Reading History Questionnaire |
| AMHQ | Adult Math History Questionnaire |
| **Core academic skills** | |
| WR | Word recognition |
| AR | Arithmetic calculation |
| **Complex academic tasks** | |
| RC | Reading comprehension |
| PS | Problem solving |

## Familial History of Reading Difficulties

The predictive effect of familial reading history has been characterized in terms of children's emergent literacy processes and later reading outcomes. Evidence has revealed that presence of familial reading difficulties is negatively associated with children's letter-word knowledge and phonological awareness (Pennington and Lefly, 2001; Carroll and Snowling, 2004; Giménez et al., 2017). These are important emergent literacy processes that provide children with the linguistic foundation prior to formal education and prepare for when they learn how to read (Storch and Whitehurst, 2002). Familial history of reading difficulties has indeed been shown to negatively predict word recognition (WR) differences in children starting elementary school – i.e., where and when they receive explicit reading instruction (Ehri, 2005; Common Core State Standards Initiative, 2010a). Furthermore, results from path analyses have highlighted the indirect impact of familial reading history on children's WR skills through their emergent literacy processes (Solari et al., 2018; Esmaeeli et al., 2019). These reports are consistent with various reading frameworks, including the core versus multiple deficit hypotheses (Pennington, 2006; Melby-Lervåg et al., 2012; van Bergen et al., 2014) that speculate for the distinguishable effects of familial history on developmental predictors and subskills in reading.

Later in school, children's WR proficiency is a critical predictor of their performance on complex academic tasks such as reading comprehension (RC) (García and Cain, 2014); given that RC is key to children's future educational and vocational

[1]Validated with current parental academic functioning (see **Supplementary Table 8**).

outcomes (Ritchie and Bates, 2013), understanding the extent to which familial history of reading difficulties over the course of development plays a role in the endpoint of reading – RC – is of substantial importance. While some studies have shown that familial history of reading difficulties negatively predicts children's performance on RC tasks (Pennington and Lefly, 2001; van Viersen et al., 2018), such predictive effect of familial history in children's RC outcomes appeared to be substantially reduced when measures of their core reading abilities, including WR, are included (Conlon et al., 2006; Solari et al., 2018). Results from longitudinal path analyses have indeed shown that familial history of reading difficulties relates to children's RC performance indirectly via their WR skills (Hulme et al., 2015). Much less is known about the influence of familial reading history on math outcomes, and most centrally whether familial history of math difficulties is linked to children's math performance. Such an approach that distinguishes differential effects on various academic domains (reading versus math) as well as levels of academic outcomes (core versus complex; Cirino et al., 2018; Child et al., 2019) could highlight the extent to which aspects of familial history of specific academic difficulties explains the etiological differences in children's learning and cognitive profiles.

## Familial History of Math Difficulties

Some evidence, although much more limited than in the reading domain, has implicated a link between familial history of math difficulties and children's math outcomes. Just as complex reading tasks are known to rely on children's WR proficiency, a core skill to math performance is arithmetic calculation (AR), or the ability to solve single- and often multi-digit addition and subtraction tasks (Fuchs et al., 2006; Cirino et al., 2018). Similar to WR, children are introduced to AR and the procedural aspect of math performance in the first years of formal education (Common Core State Standards Initiative, 2010b). Studies using a performance-based operationalization of math difficulties from family members have observed comparable differences in AR skills between children with math difficulties (dyscalculia) and their family members, i.e., parents and siblings (Shalev et al., 2001). While not with self-report, these findings nonetheless suggest initial yet compelling evidence for a role of familial history in children's math outcomes (Shalev et al., 2001; Geary, 2011). In a recent study, a dichotomous measure of parents' self-report of math, but not reading, difficulties was demonstrated to negatively predict children's performance on timed AR tasks (Khanolainen et al., 2020). As they advance in school, children continue to build on their AR proficiency when working on complex math tasks, namely problem solving (PS), which generally includes linguistically presented arithmetic prompts (Fuchs et al., 2006; Common Core State Standards Initiative, 2010b). However, insufficient data are available to determine whether familial history of math difficulties might play a role in children's performance on PS tasks.

In sum, scarce but compelling evidence prompts a need for the *Adult Math History Questionnaire* (AMHQ). The AMHQ would be expected to capture the continuous nature as well as predictive effect of familial history of math difficulties. By referencing and adapting the ARHQ (Lefly and Pennington, 2000), items in the AMHQ were designed to tap childhood math difficulties, school experiences with math-related materials, attitude toward math, and current numeracy practices. Specifically, *Items 1*, *2*, *3*, and *4* survey the respondents' experiences with math learning and related contents in elementary school, whereas *Items 5* and *6* with materials in post-primary education (high school and college). *Items 7*, *8*, and *10* target the respondents' (current) attitude toward math and related contents, while *Items 14*, *15*, *16*, and *17* also place an emphasis on confidence and interest in math. *Items 9*, *11*, *12*, and *13* inquire about the respondents' current numeracy practices and math exposure. Using the ARHQ and AMHQ in parallel enables mapping the overlapping versus unique impacts that familial history of reading versus math difficulties might have on children's academic outcomes. This is critical, as previous studies suggest an indirect predictive effect via WR skills of the ARHQ on children's RC performance. Therefore, it is plausible that familial history of math difficulties, indexed by the AMHQ in this study, could have an indirect association with children's PS performance via AR skills. Moreover, in view of the multiple deficit hypothesis (Pennington, 2006; van Bergen et al., 2014), along with prior findings on the impact of familial history of reading difficulties on children's math performance (Pennington and Lefly, 2001), the ARHQ and AMHQ could have cross-domain effects.

## Comorbid Reading and Math Differences

Difficulties in reading and math co-occur more often than differences in either domain alone (e.g., Dirks et al., 2008; Landerl and Moll, 2010); yet, the etiological basis of their comorbid association, especially in terms of familial history, remains unclear. As aforementioned, studies have observed the negative associations between scores on the ARHQ and both reading and math outcomes in children (Pennington and Lefly, 2001). Other studies that have tracked parents' self-report of math difficulties, though as a dichotomous indicator, have found differences in children's performance on math and, to a lesser extent, on reading (Landerl and Moll, 2010). These findings are consistent with previous suggestions that difficulties in one academic domain could exacerbate concerns in another (Jordan, 2007). It bears noting that while the rates of comorbid academic differences differ between population-based twin studies, what is fairly consistent is the percentage of children with math difficulties showing reading challenges is relatively higher than that of those with reading problems exhibiting math struggles (e.g., Dirks et al., 2008; Landerl and Moll, 2010). This may be because children with familial history of reading difficulties may not adequately meet the verbal demands in math tasks (Amland et al., 2021; also see Moll et al., 2015).

Differentiating various levels of academic outcomes, as previously remarked, could be crucial to understanding the etiological differences in children's learning and cognitive profiles. Comorbid differences in core academic skills, i.e., WR and AR, have been thought by some to stem from familial transmission of procedural learning difficulties (Light and DeFries, 1995; Niemi et al., 2011). With respect to the reported rates of comorbidity in math versus reading outcomes, it could be that differences in WR abilities mediate the relation between familial history of academic difficulties and AR skills (see Pennington and Lefly, 2001; Landerl and Moll, 2010; Moll et al., 2015). Studies have observed some genetic overlapping between children's WR abilities and their performance on PS tasks (Hart et al., 2009). RC and PS outcomes are also substantially associated (Compton et al., 2012; Fuchs et al., 2018). Emerging evidence asserts that RC performance is a better predictor of PS outcome, than vice versa, largely due to both verbal (linguistic) and non-verbal (reasoning) demands in applied math tasks (Fuchs et al., 2018; Spencer et al., 2020). What remains elusive is the knowledge about whether and, if so, to what extent familial history of academic difficulties contributes to the comorbid differences in children's performance on complex tasks. Based on comorbidity and prediction findings, we hypothesized that familial history of reading difficulties would have an indirect impact on children's math outcomes through their reading abilities.

## Current Study and Specific Aims

Broadly, the present study focused on understanding the extent to which familial history of academic difficulties have an impact on children's reading and math outcomes by using data from a 3-year longitudinal study that collected parental self-report of academic difficulties at baseline and assessed children's core academic skills (WR and AR) after first and second grades, as well as performance on complex academic tasks (RC and PS) after second and third grades. The first aim was to replicate and extend previous findings by examining the relations between parents' self-reports of academic difficulties (ARHQ and AMHQ) and children's reading and math outcomes, including establishing psychometric properties of the AMHQ. With correlation analyses, scores on the ARHQ were expected to be associated with children's reading abilities, whereas the AMHQ were hypothesized to be linked to their math skills.

The second aim examined the extent to which familial history of reading versus math difficulties would predict differences in children's performance on complex tasks directly or indirectly via their core skills (see **Supplementary Figure 1**). Path analyses were used in order to take into account the developmental associations within and between academic skills, i.e., their autoregressions and covariances, respectively (Erbeli et al., 2019). At the same time, the current longitudinal design allowed for evaluating the cross-lagged effects that core academic skills (collected after first and second grades) would predict performance on complex tasks (evaluated after second and third grades). The ARHQ was hypothesized to indirectly predict children's RC performance via differences in WR skills, while the AMHQ was hypothesized to predict PS outcomes via AR abilities. Particular attention was paid toward observing whether there might be overlapping versus unique impacts from familial history of reading versus math difficulties on children's reading and/or math outcomes, with the hypothesis that familial history of reading difficulties would impact math skills; however, we were agnostic as to whether the same cross-domain effects would be present for familial history of math difficulties.

# MATERIALS AND METHODS

## Participants and Procedure Overview

The current study and related procedures were carried out in accordance with the Institutional Review Board at (DBPR). Participants were recruited from local schools, clinics, and pediatrician's officers as well as the greater (DBPR). All participants were native English speakers, with normal or correctable visual or auditory differences, and did not demonstrate history or presence of a pervasive development disorder or known neurological disorder. Participants with ADHD were not excluded, provided that they could sustain attention for assessments. Upon enrollment, children provided informed assent, and their parents completed written consent. [Additional information on this longitudinal sample can be found in (DBPR); (DBPR)].

Data were drawn from $N = 198$ children after their successful completion of first grade ($m_{age} = 7.47$, $sd = 0.36$, *range* = 6.42–8.33). 105 (53%) were girls. 5 (3%) were Asian, 23 (12%) Black, 150 (76%) White, 16 (8%) more than one race, and 4 (2%) reported as others. 10 (5%) reported as Hispanic/Latino. Information about the school that children attended was collected by identifying whether or not it receives Title 1 Federal Supplement (i.e., with more than 40% of students receiving free or reduced-price lunch, living below the poverty line) to accommodate educational activities, based on publicly available data [(DBPR); as done in, e.g., Del Tufo et al., 2019]. $N = 166$ (84% of 198) children returned after second grade, and $N = 148$ (89% of 166) after third grade, with approximately a year between visits. Children's IQ was measured once at baseline, using both Vocabulary and Matrix Reasoning subtests from the *Wechsler Abbreviated Scale for Intelligence* (Wechsler, 2011). Descriptive information for the current longitudinal sample can be found in **Table 2**.

## Parental Measures

Self-report data on familial history of reading and math difficulties as well as educational attainment were collected from parents once using questionnaires at the first visit (i.e., when children were enrolled in the study after first grade). Additionally, performance-based measures of academic skills were administered to parents in order to establish the psychometric properties of their self-report data in supplemental analyses.

### Familial History

For reading history, parents were asked to complete the *Adult Reading History Questionnaire* (ARHQ; Lefly and Pennington, 2000). The ARHQ contained 23 items (see **Supplementary Table 1**), where each used a five-point Likert scale and higher score would indicate increased likelihood of familial history of reading difficulties. For example, for (*Item 2*) "How much difficulty did you have learning to read in elementary school?", the responses would range from 0 = "None" to 4 = "A great deal." Partial credit was acknowledged with 0.5-point increment.

For math history, parents were asked to complete the *Adult Math History Questionnaire* (AMHQ), which was adapted from

**TABLE 2 |** Descriptive statistics for the current longitudinal sample, including information on parental measures [reading history (ARHQ), math history (AMHQ), and educational attainment] and children's demographic variables [age, IQ (at baseline), sex, and school information (Title 1 Status)], core academic skills [word recognition (WR) and arithmetic calculation (AR)], and performance on complex tasks [reading comprehension (RC) and problem solving (PS)].

| | | *M* | *Sd* | *Min* | *Max* |
|---|---|---|---|---|---|
| **Parental measures** | | | | | |
| (1) | Reading history (ARHQ) | 27.78 | 13.48 | 3 | 74 |
| (2) | Math history (AMHQ) | 31.04 | 18.57 | 0 | 80 |
| (3) | Educational attainment | 6.10 | 0.88 | 3 | 7 |
| **Child measures** | | | | | |
| **Demographic variables** | | | | | |
| (4) | Age (after 1st grade) | 7.47 | 0.36 | 6.42 | 8.33 |
| (5) | IQ | 104.66 | 13.82 | 60 | 136 |
| (6) | Sex | 105 (53%) girls | | | |
| (7) | School (Title 1 Status) | 35 (17%) attended | | | |
| **Core academic skills** | | | | | |
| (8) | WR (after 1st grade) | 477.39 | 19.42 | 413 | 519 |
| (9) | WR (after 2nd grade) | 490.99 | 16.21 | 443 | 530 |
| (10) | AR (after 1st grade) | 452.34 | 12.60 | 401 | 486 |
| (11) | AR (after 2nd grade) | 466.70 | 14.11 | 427 | 506 |
| **Complex academic tasks** | | | | | |
| (12) | RC (after 2nd grade) | 484.50 | 13.26 | 443 | 515 |
| (13) | RC (after 3rd grade) | 494.68 | 13.05 | 460 | 521 |
| (14) | PS (after 2nd grade) | 493.04 | 17.46 | 431 | 531 |
| (15) | PS (after 3rd grade) | 503.86 | 34.93 | 116 | 534 |

*Data were drawn from N = 198 children after first grade, N = 166 after second, and N = 148 after third. [W scores from Woodcock et al. (2001, 2007) on child measures were used].*

the ARHQ (Lefly and Pennington, 2000; see also Stefansson et al., 2014; Ulfarsson et al., 2017). The AMHQ contained 17 five-point items, with partial credit of 0.5-point increment (see **Supplementary Table 2**), where higher score would indicate increased likelihood of math difficulties. For example, for (*Item 4*) "Compared to others in your elementary classes, how much did you struggle to complete your math work?", the responses would range from 0 = "Not at all" to 4 = "Much more than most." (See also "**Supplementary Materials and Methods**" for the descriptive information on individual items from the AMHQ, what they were purported to capture, and how they might overlap with or differ from another scale of this kind).

### Academic Skills

For reading, the Letter-Word Identification, Word Attack, and Sentence Reading Fluency from the *Woodcock-Johnson III* (WJ-III; Woodcock et al., 2001, 2007) were administered to measure parents' ability to identify isolated real words and apply phonic skills to decode non-words (untimed), as well as read and comprehend simple sentences (timed), respectively, all of which were used to calculate the composite score (Basic Reading cluster from the WJ-III).

For math, the Calculation and Math Facts Fluency subtests also from the WJ-III (Woodcock et al., 2001, 2007) were administered to estimate parents' ability to perform basic mathematical operations (untimed) and apply calculation skills to single-digit numbers (timed), both of which were used to compute the composite score (Math Calculation cluster from the WJ-III).

### Educational Attainment

Parents were asked to report their highest level of educational attainment, which was then rated on a seven-point scale, where 1 = "*less than seventh grade,*" 2 = "*junior high school (ninth grade),*" 3 = "*partial high school (tenth or eleventh grade),*" 4 = "*high school graduate (whether private preparatory, parochial, trade, or public school),*" 5 = "*partial college (at least 1 year) or specialized training,*" 6 = "*standard college or university graduation,*" or 7 = "*graduate professional training (graduate degree).*"

## Child Measures

Performance data on core academic skills (word recognition and arithmetic calculation) were acquired from children after first and second grades using standardized measures, whereas complex academic tasks (text comprehension and word-problem solving) were administered after second and third grades. *W* scores from child measures were used in analyses. A *W* score is purported to represent both person-level ability and item-level difficulty on the same equal-interval scale and thought to be suitable for longitudinal modeling strategies (Woodcock et al., 2001, 2007).

### Core Academic Skills

For word recognition (WR), the Letter-Word Identification and Word Attack subtests from the WJ-III (Woodcock et al., 2001, 2007) were administered to assess children's ability to recognize real words and decode non-words, respectively, both of which were used to calculate the composite score (Basic Reading cluster from the WJ-III) for analyses.

For arithmetic calculation (AR), the Calculation subtest also from the WJ-III (Woodcock et al., 2001, 2007) was administered to evaluate children's number knowledge and ability to perform basic algebraic computation.

### Complex Academic Tasks

For reading comprehension (RC), the Passage Comprehension subtest from the WJ-III (Woodcock et al., 2001, 2007) was administrated to measure children's ability to read, relate ideas, and fill in missing words (modified cloze).

For problem solving (PS), the Applied Problems subtest from the WJ-III (Woodcock et al., 2001, 2007) was administered to capture children's quantitative reasoning and ability to solve orally presented problems.

## Statistical Strategies

Analyses were performed in *R* (with publicly available packages indicated where appropriate).

### Psychometric Analyses

Self-report data from parents (on the ARHQ and AMHQ, separately) were subjected to three sets of preliminary analyses to (1) establish the reliability of each scale as a whole and at the level of individual items, (2) explore the factor structure of each scale, and (3) evaluate the correlations between scores (total and factor) on each scale and performance-based measures of academic skills. Analyses were conducted using the *psych* and *scale* packages (Revelle, 2018).

- First, for reliability analyses, after reporting their descriptive statistics, questionnaire items were individually correlated with the total score (i.e., item-total correlation) and corrected for scale reliability. Each item was reported with item-rest correlation and Cronbach's α if it were to be dropped. Pairwise correlations were examined among items within and between the ARHQ and AMHQ, along with their corresponding total scores.
- Second, to explore their factor structure, the ARHQ and AMHQ were each analyzed following steps previously taken in Welcome and Meza (2019; particularly for the ARHQ and the naming convention for its derived factors), which include: establishing the *KMO* (Kaiser–Meyer–Olkin) value of sampling adequacy, conducting the *BTS* (Bartlett's Test of Sphericity) for suitability in capturing sample variance, visualizing scree plot to estimate the number of factors to extract, and performing maximum likelihood method with oblique rotation (direct oblimin) to derive the respective components, which were rendered through a regression-based approach to calculate factor scores (Tabachnick and Fidell, 2007; DiStefano et al., 2009). Note that the directionality for the computed factor scores remain consistent with the directionality of the questions on each scale – that is, higher scores on any factors extracted from the ARHQ or AMHQ indicate, e.g., increased difficulties with learning to read or do simple arithmetic.
- Third, total scores on the ARHQ and AMHQ, as well as their factor scores to be derived from these scales, were subjected to correlation analyses with performance-based measures of parents' reading and math skills as supplemental findings. Total scores on the ARHQ and AMHQ were used in the following formal correlation and path analyses to index familial history of reading and math difficulties, respectively.

### Correlational Analyses

Analyses were conducted to evaluate the pairwise associations among parental measures [reading history (ARHQ), math history (AMHQ), and educational attainment] and children's demographic variables [age, IQ (at baseline), sex, and school information (Title 1 Status)], core academic skills (WR and AR), and performance on complex tasks (RC and PS) across visits. At the same time, results from these correlational analyses would reveal the validity of the ARHQ and AMHQ in relation to performance-based measures of children's academic performance. Supplementary analyses were also performed to assess the correlations between scores on individual factors derived from the ARHQ and AMHQ and measures of children's academic performance.

### Path Analyses

Path models were constructed to determine the direct and indirect effects of familial history of reading and math difficulties on children's core academic skills and performance on complex academic tasks. Analyses were conducted in two ways: first, using the total scores on the ARHQ and the AMHQ; and second, with scores for individual factors to be derived from these scales. Consistent with previous literature, using total scores on the ARHQ to analyze with children's academic outcomes captures the continuous nature of familial reading history over time and across contexts (Lefly and Pennington, 2000; Welcome and Meza, 2019). Similar to this line of reasoning, findings from analyzing total scores on the AMHQ and children's academic outcomes would also illustrate the continuous nature of familial math history based on parents' self-reported experiences over time and across contexts that involve general math learning and numeracy practices. Subsequently, analyses with factor scores derived from the ARHQ and AMHQ then enable a more granular understanding of the impact of familial reading and/or math history by differentiating which specific components, such as difficulties with learning in childhood or current literacy/numeracy practices, could have driven the overall associations between familial reading and/or math history and children's academic outcomes.

Variables included in correlational analyses were submitted to path modeling using the *lavaan* package (Rosseel, 2012). Familial history of reading and math difficulties were directly mapped onto children's core academic skills measured after first and second grades, as well as onto their academic performance assessed after second and third grades. All variables were adjusted for parents' educational attainment and children's demographic variables [age, IQ (at baseline), sex, and school information (Title 1 Status)]. Then, longitudinal paths were represented for measures of children's academic profile across the three visits, where core skills were treated as the longitudinal mediators for the indirect effects of familial history of academic difficulties on complex tasks. Covariances were specified for pairs of predictors between reading and math domains – i.e., between familial reading and math history (ARHQ and AMHQ), between WR and AR, and between RC and PS. Finally, any non-significant paths were constrained to zero to yield the final model. Then, the standard errors, and thus levels of significance, were inferred using the bootstrapping approach (Fritz et al., 2012; Rosseel, 2012). For each model, fit was determined by non-significant $\chi^2$ (chi-square), *CFI* and *TLI* (Comparative Fit and Tucker–Lewis Indices) greater than or equal to 0.95, and *RSMEA* (Root Mean Square Error of Approximation) and *SRMR* (Standardized Root Mean Square Residual) values less than 0.05 (Hu and Bentler, 1999). Supplementary analyses were also conducted by repeating the outlined path modeling strategies to model the effects of individual factors derived from the ARHQ and AMHQ and measures of children's academic performance.

## RESULTS

Descriptive statistics on the current longitudinal sample can be found in **Table 2**, which includes information on parental measures [reading history (ARHQ), math history (AMHQ), and educational attainment] and children's demographic variables [age, IQ (at baseline), sex, and school information (Title 1 Status)], core academic skills [word recognition (WR) and arithmetic calculation (AR)], and performance on complex tasks [reading comprehension (RC) and problem solving (PS)]. [Additional findings (from intermediate steps or follow-up analyses) are available for viewing in conjunction with this Section "Results" and can be found in the **Supplementary Results**].

## Psychometric Findings

Reliability analyses were conducted on self-report data from parents on the ARHQ and AMHQ. Since there is not yet a scale capturing familial history of math difficulties, the AMHQ was adapted from the ARHQ (Lefly and Pennington, 2000) with the intention that the AMHQ would translate items in the ARHQ to estimate math- rather than reading-related contents. To this end, analyses on the AMHQ were conducted in parallel with data from the ARHQ to attest to their reliability as well as validity properties.

### Adult Reading History Questionnaire

- The ARHQ was reported with Cronbach's $\alpha = 0.87$, with 95% confidence interval of (0.85, 0.90), suggesting good internal consistency. Descriptive and reliability statistics on individual items can be found in **Supplementary Table 1**. Briefly, (*Item 2*) "How much difficulty did you have learning to read in elementary school?" and (*Item 6*) "How would you compare your reading skill to that of others in your elementary classes?" appeared to demonstrate the highest correlations with the total score on the ARHQ (item-total *r*'s = 0.727 and 0.701, respectively, after corrected for scale reliability). In contrast, (*Item 23*) "Do you read a newspaper on Sunday?" and (*Item 21*) "Do you read daily (Monday–Friday) newspapers?" appeared to have the lowest correlations with the total score (item-total *r*'s = 0.246 and 0.217, after corrected for scale reliability). Pairwise correlations among items in the ARHQ are reported in **Supplementary Table 3** and with those from the AMHQ in **Supplementary Table 4**.
- The KMO coefficient was reported with 0.81, and the BTS was significant ($\chi^2 = 2275.697$, $p < 0.01$), indicating adequate sampling as well as suitability to capture the sample's variability. The scree plot suggested a six-factor solution, wherein the oblique rotation yielded the following: (*Factor 1*) Childhood Ability, (*Factor 2*) Attitude/Exposure, (*Factor 3*) Memory, (*Factor 4*) Media Use, (*Factor 5*) Reversal, and (*Factor 6*) Spelling. [Findings from Welcome and Meza (2019) were used to guide the naming convention for factors derived in the current study]. Loading coefficients from individual items for these factors can be found in **Table 3** and **Supplementary Results**.
- Analyses with performance-based measures of parents' academic skills revealed that scores on the ARHQ were significantly and negatively correlated with reading scores (*r*'s = $-0.31$ – $-0.43$, $p < 0.05$) (see **Supplementary Table 7**). Additionally, scores on the ARHQ were significantly and negatively correlated with math scores (*r*'s = $-0.20$ – $-0.30$, $p < 0.05$). Detailed discussion on the correlations between factor scores derived from the ARHQ and performance-based measures of parents' academic skills can be found in **Supplementary Results**. Briefly, the Childhood Ability, Attitude/Exposure, Reversal, and Spelling factors derived from the ARHQ were associated with parents' reading skills, while the Childhood Ability, Reversal, and Spelling ones were correlated with their reading and math abilities.

### Adult Math History Questionnaire

- The AMHQ was reported with Cronbach's $\alpha = 0.93$, with 95% confidence interval of (0.91, 0.94), suggesting excellent internal consistency. Descriptive and reliability statistics on individual items from the AMHQ in **Supplementary Table 2**. Briefly, (*Item 8*) "Math makes me feel uncomfortable and nervous." and (*Item 4*) "Compared to others in your elementary classes, how much did you struggle to complete your math work?" had the highest correlations with the total score on the AMHQ (item-total *r*'s = 0.852 and 0.803, respectively, after corrected for scale reliability). In contrast, (*Item 11*) "My current work requires I use math." and (*Item 15*) "I would like to further develop my math skills." were reported with the lowest correlations with the total score (item-total *r*'s = 0.422 and 0.393, after corrected for scale reliability). Pairwise correlations among items in the AMHQ are reported in **Supplementary Table 5** and with those from the ARHQ in **Supplementary Table 6**.
- In the initial steps, the KMO coefficient was reported with 0.91, and the BTS was significant ($\chi^2 = 2333.652$, $p < 0.01$). The scree plot suggested a three-factor solution. Though, findings from the oblique rotation revealed that *Item 13* loaded poorly or out of range (i.e., absolute value > 1.000), thus prompting the decision to omit this item in subsequent steps for factor analyses. After omitting *Item 13*, the KMO coefficient was reported with 0.93, and the BTS was significant ($\chi^2 = 2165.691$, $p < 0.01$). The scree plot suggested a two-factor solution, wherein the oblique rotation yielded the following: (*Factor 1*) Attitude/Exposure and (*Factor 2*) Childhood Ability. Loading coefficients from individual items for these factors can be found in **Table 4** and **Supplementary Results**.
- Analyses with performance-based measures of parents' academic skills revealed that scores on the AMHQ were significantly and negatively correlated with math scores (*r*'s = $-0.41$ – $-0.53$, $p < 0.05$) (see **Supplementary Table 7**). There was a weak but significant and negative correlation between scores on the AMHQ and some reading scores (*r*'s = $-0.17$, $p < 0.05$). Discussion regarding the correlations between factor scores derived from the AMHQ and performance-based measures of parents' academic skills can be found in **Supplementary Results**. Briefly, the Attitude/Exposure factor derived from the AMHQ was only associated with parents' math abilities, whereas the Childhood Ability one was correlated with both their math and reading skills.

**TABLE 3 |** Factor loadings for individual items in the structure revealed from the ARHQ, wherein the solution was reported with (*Factor 1*) Childhood Ability, (*Factor 2*) Attitude and Exposure, (*Factor 3*) Memory, (*Factor 4*) Media Use, (*Factor 5*) Reversal, and (*Factor 6*) Spelling.

| Item | Description | Childhood ability | Attitude and exposure | Memory | Media Use | Reversal | Spelling |
|---|---|---|---|---|---|---|---|
| **Adult Reading History Questionnaire** | | | | | | | |
| 1 | Which of the following most nearly describes your attitude toward school when you were a child? | 0.398 | 0.118 | 0.156 | – | −0.133 | – |
| 2 | How much difficulty did you have learning to read in elementary school? | 0.822 | – | – | – | – | – |
| 3 | How much extra help did you need when learning to read in elementary school? | 0.832 | – | – | – | – | – |
| 4 | Did you ever reverse the order of letters or numbers when you were a child? | – | – | – | – | 0.995 | – |
| 5 | Did you have difficulty learning letter and/or color names when you were a child? | 0.518 | – | – | – | 0.382 | −0.146 |
| 6 | How would you compare your reading skill to that of others in your elementary classes? | 0.697 | – | – | – | – | – |
| 7 | All students struggle from time to time in school. In comparison to others in your classes, how much did you struggle to complete your work? | 0.638 | – | 0.173 | – | – | 0.116 |
| 8 | Did you experience difficulty in high school or college English classes? | 0.553 | 0.126 | – | – | – | – |
| 9 | What is your current attitude toward reading? | 0.209 | 0.561 | – | – | – | – |
| 10 | How much reading do you do for pleasure? | – | 0.952 | – | – | – | – |
| 11 | How would you compare your current reading speed to that of others of the same age and education? | 0.236 | 0.238 | – | 0.135 | – | 0.220 |
| 12 | How much reading do you do in conjunction with your work? (If retired or not working, how much did you read when you were working?) | – | 0.159 | 0.135 | 0.215 | – | 0.183 |
| 13 | How much difficulty did you have learning to spell in elementary school? | 0.249 | – | 0.108 | – | 0.189 | 0.591 |
| 14 | How would you compare your current spelling to that of others of the same age and education? | – | – | – | – | – | 0.913 |
| 15 | Did your parents ever consider having you repeat any grades in school due to academic failure (not illness)? | 0.718 | – | – | – | −0.157 | – |
| 16 | Do you ever have difficulty remembering people's names or names of places? | – | – | 0.901 | – | – | – |
| 17 | Do you ever have difficulty remembering addresses, phone numbers, or dates? | – | – | 0.717 | – | – | – |
| 18 | Do you have difficulty remembering complex verbal instructions? | 0.131 | – | 0.649 | – | – | – |
| 19 | Do you currently reverse the other of letters or numbers when you read or write? | 0.120 | – | 0.122 | – | 0.491 | – |
| 20 | How many books do you read for pleasure each year? | – | 0.849 | – | – | – | – |
| 21 | How many magazines do you read for pleasure each month? | – | – | – | 0.456 | – | 0.117 |
| 22 | Do you read daily (Monday–Friday) newspapers? | – | – | – | 0.725 | – | 0.117 |
| 23 | Do you read a newspaper on Sunday? | – | – | – | 0.918 | – | – |
| | SS loadings | 3.723 | 2.095 | 1.854 | 1.681 | 1.496 | 1.375 |
| | Proportion variance | 0.162 | 0.091 | 0.081 | 0.073 | 0.065 | 0.060 |
| | Cumulative variance | 0.162 | 0.253 | 0.334 | 0.407 | 0.472 | 0.531 |

*[Findings from Welcome and Meza (2019) were used to guide the naming convention for factors derived in the current study].*

## Correlational Findings

Pairwise correlations among parental measures [reading history (ARHQ), math history (AMHQ), and educational attainment] and children's demographic variables [age, IQ (at baseline), sex, and school information (Title 1 Status)], core academic skills (WR and AR), and performance on complex tasks (RC and PS) can be found in **Table 5**. Total scores on the ARHQ and AMHQ (reading history versus math history, respectively) were significantly and positively correlated ($r = 0.33$, $p < 0.05$), implicating an association between familial history of reading

**TABLE 4 |** Factor loadings for individual items in the structure revealed from the AMHQ, wherein the solution was reported with (*Factor 1*) attitude and exposure and (*Factor 2*) childhood ability.

| Item | Description | Attitude and exposure | Childhood ability |
|---|---|---|---|
| **Adult Math History Questionnaire** | | | |
| 1 | When in elementary school, I struggled with learning new concepts in math. | – | 0.914 |
| 2 | When in elementary school, I needed extra help in math from a teacher or tutor. | −0.113 | 0.965 |
| 3 | How would you compare your math skills to those of others in your elementary classes? | 0.190 | 0.678 |
| 4 | Compared to others in your elementary classes, how much did you struggle to complete your math work? | 0.151 | 0.803 |
| 5 | During high school or college, I struggled in math courses. | 0.508 | 0.385 |
| 6 | I took math classes in high school or college that were not required because I enjoyed them. | 0.544 | – |
| 7 | What is your current attitude toward math? | 0.896 | −0.114 |
| 8 | Math makes me feel uncomfortable and nervous. | 0.814 | 0.116 |
| 9 | As an adult, I struggle to complete math-related tasks, such as calculating tips. | 0.499 | 0.281 |
| 10 | Math is important in everyday life. | 0.402 | – |
| 11 | My current work requires I use math. | 0.456 | −0.104 |
| 12 | I enjoy completing math and logic puzzles for fun. | 0.736 | – |
| 13 | I use math in my everyday life. | (Omitted) | (Omitted) |
| 14 | How would you compare your current math skills compared to those of others of the same age and education? | 0.755 | – |
| 15 | I would like to further develop my math skills. | 0.523 | −0.174 |
| 16 | I feel confident in helping my child with their math and homework. | 0.667 | – |
| 17 | New math content has usually been easy and enjoyable for me to understand. | 0.709 | 0.163 |
| | SS loadings | 5.042 | 3.205 |
| | Proportion variance | 0.315 | 0.200 |
| | Cumulative variance | 0.315 | 0.515 |

and math difficulties, respectively. Pairwise correlations between scores on individual factors derived from the ARHQ and AMHQ and measures of children's academic performance can be found in **Supplementary Table 8** and are discussed in **Supplementary Results**. As noted in Section "Materials and Methods," when interpreting findings that pertain to the computed factor scores, their directionality remain consistent with the that of the questions on each scale – that is, higher scores on any factors extracted from the ARHQ or AMHQ indicate, e.g., increased difficulties with learning to read or do simple arithmetic.

## Familial History of Reading Difficulties

### *Total Scores*

Familial history of reading difficulties, as indexed by total scores on the ARHQ, was significantly correlated negatively with parents' educational attainment ($r = -0.23$), and negatively with children's IQ ($r = -0.20$) and positively with school information (Title-1 Status; $r = 0.15$) (all $p < 0.05$). The ARHQ was significantly and negatively correlated with children's WR skills measured after first ($r = -0.19$) and second grades ($r = -0.17$), as well as with AR abilities captured after first ($r = -0.14$) and second grades ($r = -0.20$) (all $p < 0.05$). The ARHQ was also significantly and negatively correlated with children's performance on RC tasks administered after second ($r = -0.18$) and third grades ($r = -0.17$), as well as on PS assessment collected after second grade ($r = -0.26$) (all $p < 0.05$).

### *Factor Scores*

When unpacking these correlations using factor scores, findings revealed that the Childhood Ability was significantly and negatively associated with children's WR ($r = -0.24$ and $-0.20$) and AR skills ($r = -0.15$ and $-0.15$), as well as performance on RC ($r = -0.16$) and PS tasks ($r = -0.26$) (all $p < 0.05$). The Attitude/Exposure factor was significantly and negatively correlated with children's performance on RC ($r = -0.16$ and $-0.24$) and PS performance ($r = -0.27$ and $-0.25$) (all $p < 0.05$). The Media Use factor was significantly and negatively related to children's AR skill ($r = -0.19$), as well as performance on RC ($r = -0.22$) and PS tasks ($r = -0.19$) (all $p < 0.05$). The Spelling factor was significantly and negatively linked to children's WR skill ($r = -0.16$, $p < 0.05$).

## Familial History of Reading Difficulties

### *Total Scores*

Familial history of math difficulties, as indexed by total scores on the AMHQ, was significantly correlated negatively with parents' educational attainment ($r = -0.21$) and positively with children's school information (Title-1 Status; $r = 0.24$) (both $p < 0.05$). AMHQ total scores were also significantly and negatively correlated with children's AR skills measured after first ($r = -0.17$) and second grades ($r = -0.29$) (both $p < 0.05$). These results highlight the criterion validity of the AMHQ in relation to the ARHQ and parents' educational attainment. Findings also reflect on the construct validity in that the AMHQ is preferentially linked to children's math- but not reading-related measures (i.e., AR outcomes).

### *Factor Scores*

When unpacking these correlations using factor scores, findings revealed that the Childhood Ability factor was significantly ad

**TABLE 5 |** Pairwise correlations among parental measures [reading history (ARHQ), math history (AMHQ), and educational attainment] and children's demographic variables [age, IQ (at baseline), sex, and school information (Title 1 Status)], core academic skills [word recognition (WR) and arithmetic calculation (AR)], and performance on complex tasks [reading comprehension (RC) and problem solving (PS)].

| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Parental measures** | | | | | | | | | | | | | | | | |
| (1) | Reading history (ARHQ) | – | | | | | | | | | | | | | | |
| (2) | Math history (AMHQ) | **0.33** | – | | | | | | | | | | | | | |
| (3) | Educational attainment | **−0.23** | **−0.21** | – | | | | | | | | | | | | |
| **Child measures** | | | | | | | | | | | | | | | | |
| **Demographic variables** | | | | | | | | | | | | | | | | |
| (4) | Age (after 1st grade) | 0.01 | **0.15** | −0.04 | – | | | | | | | | | | | |
| (5) | IQ | **−0.20** | −0.02 | **0.28** | **−0.23** | – | | | | | | | | | | |
| (6) | Sex | −0.08 | −0.01 | 0.06 | 0.09 | −0.12 | – | | | | | | | | | |
| (7) | School (title 1 status) | **0.15** | **0.24** | **−0.28** | −0.02 | **−0.23** | 0.04 | – | | | | | | | | |
| **Core academic skills** | | | | | | | | | | | | | | | | |
| (8) | WR (after 1st grade) | **−0.19** | −0.08 | **0.22** | 0.06 | **0.43** | 0.00 | **−0.21** | – | | | | | | | |
| (9) | WR (after 2nd grade) | **−0.17** | −0.04 | **0.25** | 0.02 | **0.39** | 0.05 | **−0.25** | **0.89** | – | | | | | | |
| (10) | AR (after 1st grade) | **−0.14** | **−0.17** | **0.25** | 0.07 | **0.41** | 0.06 | **−0.17** | **0.57** | **0.50** | – | | | | | |
| (11) | AR (after 2nd grade) | **−0.20** | **−0.29** | **0.31** | **0.16** | **0.30** | 0.10 | −0.15 | **0.46** | **0.42** | **0.72** | – | | | | |
| **Complex academic tasks** | | | | | | | | | | | | | | | | |
| (12) | RC (after 2nd grade) | **−0.18** | 0.00 | **0.23** | 0.01 | **0.46** | −0.03 | **−0.17** | **0.68** | **0.71** | **0.46** | **0.37** | – | | | |
| (13) | RC (after 3rd grade) | **−0.17** | −0.06 | **0.23** | 0.00 | **0.50** | 0.01 | **−0.27** | **0.57** | **0.61** | **0.37** | **0.38** | **0.77** | – | | |
| (14) | PS (after 2nd grade) | **−0.26** | −0.13 | **0.39** | 0.13 | **0.53** | 0.09 | **−0.27** | **0.57** | **0.54** | **0.60** | **0.61** | **0.62** | **0.56** | – | |
| (15) | PS (after 3rd grade) | −0.13 | 0.00 | 0.14 | −0.09 | **0.17** | −0.04 | −0.06 | 0.12 | 0.15 | **0.28** | **0.25** | **0.19** | **0.55** | **0.32** | – |

*(Correlation coefficients in bold met $p < 0.05$).*

negatively correlated with children's WR ($r = -0.20$) and AR skills ($r = -0.23$ and $-0.31$), as well a performance on PS task ($r = -0.31$) (all $p < 0.05$). The Attitude/Exposure factor was significantly and negatively associated with children's AR skill ($r = -0.27$, $p < 0.05$).

## Path Findings

Path modeling strategies were employed to evaluate the direct and indirect effects of familial history of reading and math difficulties on children's core academic skills and performance on complex academic tasks. Variables for familial reading and math history (ARHQ and AMHQ), core academic skills (WR and AR), and performance on complex tasks (RC and PS) reported in correlational findings were subjected to path modeling, with parents' educational attainment and children's demographic variables [age, IQ (at baseline), sex, and school information (Title 1 Status)] included as covariates. The initial model (see section "Materials and Methods" and **Supplementary Figure 1**) was reported with $\chi^2 = 58.472$ ($p = 0.000$), $CFI = 0.974$, $TLI = 0.832$, $RMSEA = 0.115$ ($p = 0.002$), and $SRMR = 0.068$, indicating a fair fit. To improve model fit, non-significant paths were constrained to zero. The final model was reported with $\chi^2 = 82.513$ ($p = 0.002$), $CFI = 0.977$, $TLI = 0.963$, $RMSEA = 0.046$ ($p = 0.369$), and $SRMR = 0.043$, indicating a good fit. This step in constraining non-significant paths to zero did not significantly improve the fit ($\Delta\chi^2 = 24.041$, $p = 0.674$) when comparing the initial (full) and final models, though the latter was more parsimonious and thus reported here (see **Figure 1**). Summary findings from the final model can be found in **Table 6**. Findings from follow-up analyses to distinguish the effects of individual factors derived from the ARHQ and AMHQ on measures of children's academic performance can be found in **Figure 2** and **Table 7** and are discussed in **Supplementary Results**.

### Direct and Indirect Effects of Familial Reading History on Core Academic Skills

#### *Total Scores*

Familial history of reading difficulties, indexed by total scores on the ARHQ, was shown to have a direct and negative effect on children's WR skill captured after first grade ($b = -0.108$), which in turn had an indirect effect on WR outcome assessed after second grade ($b = -0.094$) ($p < 0.05$). Interestingly, it appeared that familial history of reading difficulties had an indirect effect on children's AR outcome measured after second grade via WR skill evaluated after first grade ($b = -0.016$, $p < 0.05$).

#### *Factor Scores*

Briefly, when unpacking these with factor scores on the ARHQ, findings suggested that the Childhood Ability factor significantly explained the extent to which familial reading history is negatively related to children's core academic skills.

### Direct and Indirect Effects of Familial Math History on Core Academic Skills

#### *Total Scores*

Familial history of math difficulties, indexed by total scores on the AMHQ, was revealed to have direct and negative effects on children's AR abilities captured after first ($b = -0.211$) as well as second grades ($b = -0.261$), uniquely from autoregressive

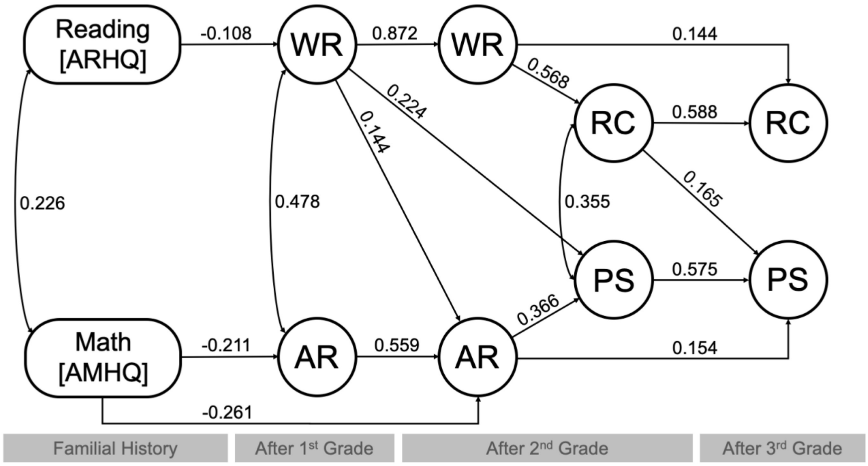


**FIGURE 1 |** Final path model for the direct and indirect effects of familial history of reading and math difficulties (i.e., indexed by ARHQ and AMHQ, respectively) on measures for children's core academic skills [word reading (WR) and arithmetic calculation (AR)] after first and second grades, and performance on complex tasks [reading comprehension (RC) and problem solving (PS)] after second and third grades. Parents' level of educational attainment and children's demographic information [age, IQ (at baseline), sex, and school information (Title 1 Status)] were included as covariates. (All paths with coefficients shown met $p < 0.05$).

**TABLE 6 |** Direct and indirect effects of familial history of reading and math difficulties on children's core academic skills [word reading (WR) and arithmetic calculation (AR)] after first and second grades, and performance on complex academic tasks [reading comprehension (RC) and problem solving (PS)] after second and third grades.

| Path | *b* | *se* | *p* |
|---|---|---|---|
| **Direct and indirect effects on core academic skills** | | | |
| **Familial reading history (ARHQ)** | | | |
| → WR (1st grade) | **−0.108** | **0.040** | **0.006** |
| → WR (1st grade) → WR (2nd grade) | **−0.094** | **0.035** | **0.007** |
| → WR (1st grade) → AR (2nd grade) | **−0.016** | **0.006** | **0.000** |
| **Familial math history (AMHQ)** | | | |
| → AR (1st grade) | **−0.211** | **0.037** | **0.000** |
| → AR (2nd grade) | **−0.261** | **0.079** | **0.001** |
| → AR (1st grade) → AR (2nd grade) | **−0.118** | **0.019** | **0.000** |
| **Indirect effects on performance on complex academic tasks** | | | |
| **Familial reading history (ARHQ)** | | | |
| → WR (1st grade) → WR (2nd grade) → RC (2nd grade) | **−0.054** | **0.022** | **0.014** |
| → WR (1st grade) → WR (2nd grade) → RC (3rd grade) | −0.014 | 0.010 | 0.183 |
| → WR (1st grade) → WR (2nd grade) → RC (2nd grade) → RC (3rd grade) | **−0.032** | **0.013** | **0.013** |
| → WR (1st grade) → WR (2nd grade) → RC (2nd grade) → PS (3rd grade) | −0.009 | 0.003 | 0.160 |
| → WR (1st grade) → PS (2nd grade) | −0.024 | 0.018 | 0.192 |
| → WR (1st grade) → PS (2nd grade) → PS (3rd grade) | −0.014 | 0.003 | 0.075 |
| → WR (1st grade) → AR (2nd grade) → PS (2nd grade) | **−0.006** | **0.002** | **0.014** |
| → WR (1st grade) → AR (2nd grade) → PS (3rd grade) | −0.002 | 0.001 | 0.112 |
| → WR (1st grade) → AR (2nd grade) → PS (2nd grade) → PS (3rd grade) | **−0.003** | **0.000** | **0.001** |
| **Familial math history (AMHQ)** | | | |
| → AR (1st grade) → AR (2nd grade) → PS (2nd grade) | **−0.043** | **0.008** | **0.000** |
| → AR (1st grade) → AR (2nd grade) → PS (3rd grade) | −0.018 | 0.004 | 0.123 |
| → AR (1st grade) → AR (2nd grade) → PS (2nd grade) → PS (3rd grade) | **−0.025** | **0.003** | **0.003** |
| → AR (2nd grade) → PS (2nd grade) | **−0.096** | **0.029** | **0.003** |
| → AR (2nd grade) → PS (3rd grade) | −0.040 | 0.012 | 0.198 |
| → AR (2nd grade) → PS (2nd grade) → PS (3rd grade) | **−0.055** | **0.003** | **0.000** |

*(Coefficients in bold met $p < 0.05$).*

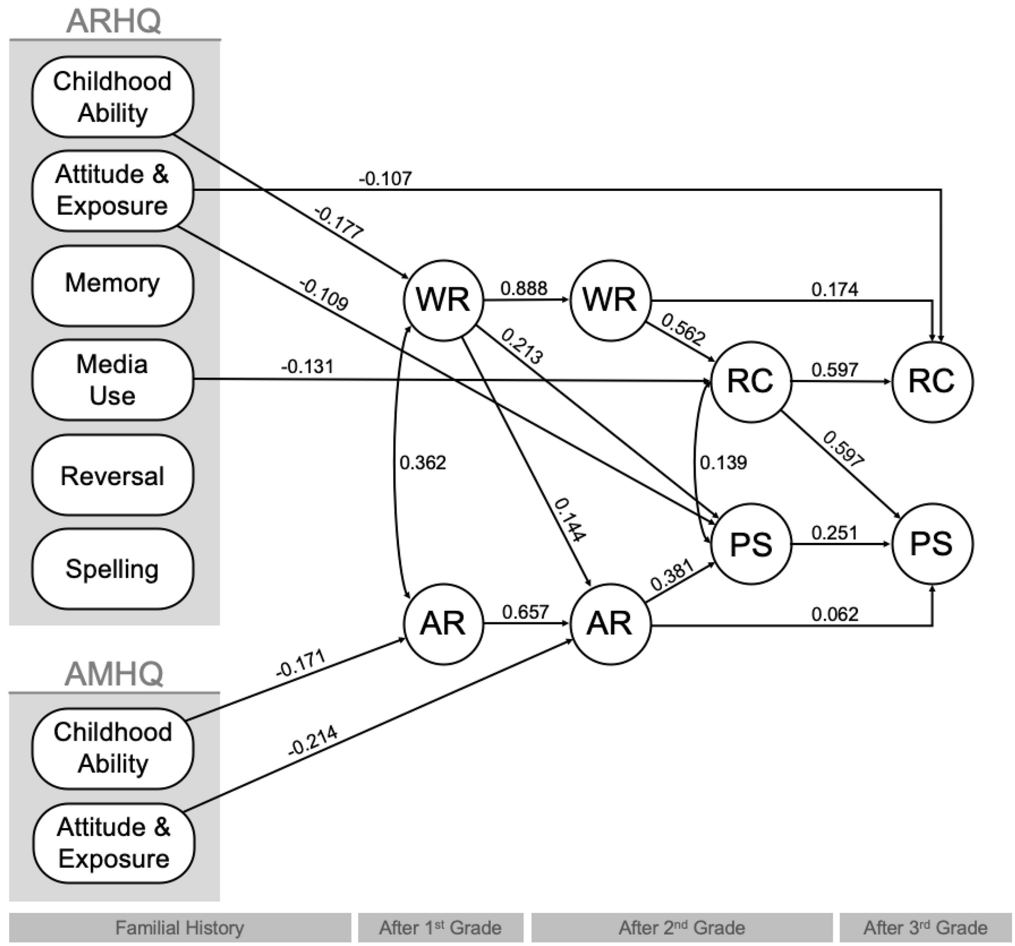


**FIGURE 2 |** Final path model for the effects of individual factors derived from the ARHQ and AMH on measures of children's core academic skills [word reading (WR) and arithmetic calculation (AR)] after first and second grades, and performance on complex tasks [reading comprehension (RC) and problem solving (PS)] after second and third grades. Parents' level of education attainment and children's demographic information [age, IQ (at baseline), sex, and school information (Title 1 Status)] were included as covariates. (All paths with coefficients shown met $p < 0.05$. Covariances among factors from the ARHQ and AMHQ can be found in **Supplementary Table 10**. The directionality of the computed factor scores remain consistent with the that of the questions on each scale – that is, higher scores on any factors extracted from the ARHQ or AMHQ indicate, e.g., increased difficulties with learning to read or do simple arithmetic).

effects ($p < 0.05$). Familial history of math difficulties was also demonstrated to have an indirect effect on children's AR outcomes at second via first grades ($b = -0.118$, $p < 0.05$).

#### *Factor Scores*

When unpacking these effects with factor scores on the AMHQ, the Childhood Ability and Attitude/Exposure factors were both found to explain the extent to which familial math history is negatively related to children's core math abilities.

### Indirect Effects on Familial Reading History on Complex Academic Tasks

#### *Total Scores*

Familial history of reading difficulties, indexed by total scores on the ARHQ, was shown to have an indirect effect on children's performance on RC task evaluated after second grade via the serial effects of WR skills measured after first and second grades ($b = -0.054$, $p < 0.05$). Such indirect effect of familial history on RC performance captured after second grade in turn had an impact on children's RC outcome assessed after third grade ($b = -0.032$, $p < 0.05$). Interestingly, familial history of reading difficulties was demonstrated to have an indirect effect on children's performance on PS task measured after second grade via the serial effects of WR skill captured after first grade on AR ability after second grade ($b = -0.006$, $p < 0.05$). Such indirect effect of familial history on PS performance assessed after second grade thereby had an impact on children's PS outcome evaluated after third grade ($b = -0.003$, $p < 0.05$).

#### *Factor Scores*

When unpacking these effects with factor scores on the ARHQ, the Childhood Ability factor was suggested to explain the extent to which familial reading history is indirectly related to children's performance on complex academic tasks via their core reading skills. The Media Use factor appeared to explain the extent to

**TABLE 7 |** Direct and indirect effects of individual factors derived from the ARHQ (centrally, the childhood ability, attitude and exposure, and media use ones) and AMHQ (the childhood ability and attitude and exposure ones) on children's core academic skills (WR and AR), and performance on complex tasks (RC and PS).

| Path | *b* | *se* | *p* |
|---|---|---|---|
| **Direct and indirect effects on core academic skills** | | | |
| **Familial reading history (ARHQ)** | | | |
| Childhood ability | | | |
| → WR (1st grade) | **−0.177** | **0.052** | **0.001** |
| → WR (1st grade) → WR (2nd grade) | **−0.158** | **0.053** | **0.003** |
| → WR (1st grade) → AR (2nd grade) | **−0.026** | **0.008** | **0.002** |
| **Familial math history (AMHQ)** | | | |
| Childhood ability | | | |
| → AR (1st grade) | **−0.171** | **0.042** | **0.000** |
| → AR (1st grade) → AR (2nd grade) | **−0.112** | **0.025** | **0.000** |
| Attitude and exposure | | | |
| → AR (2nd grade) | **−0.214** | **0.026** | **0.000** |
| **Direct and indirect effects on performance on complex academic tasks** | | | |
| **Familial reading history (ARHQ)** | | | |
| Childhood ability | | | |
| → WR (1st grade) → WR (2nd grade) → RC (2nd grade) | **−0.089** | **0.042** | **0.034** |
| → WR (1st grade) → WR (2nd grade) → RC (3rd grade) | −0.027 | 0.017 | 0.101 |
| → WR (1st grade) → WR (2nd grade) → RC (2nd grade) → RC (3rd grade) | **−0.053** | **0.026** | **0.041** |
| → WR (1st grade) → WR (2nd grade) → RC (2nd grade) → PS (3rd grade) | −0.007 | 0.004 | 0.081 |
| → WR (1st grade) → PS (2nd grade) | −0.038 | 0.021 | 0.069 |
| → WR (1st grade) → PS (2nd grade) → PS (3rd grade) | −0.009 | 0.005 | 0.075 |
| → WR (1st grade) → AR (2nd grade) → PS (2nd grade) | **−0.010** | **0.003** | **0.001** |
| → WR (1st grade) → AR (2nd grade) → PS (3rd grade) | −0.002 | 0.001 | 0.064 |
| → WR (1st grade) → AR (2nd grade) → PS (2nd grade) → PS (3rd grade) | **−0.002** | **0.001** | **0.000** |
| Media use | | | |
| → RC (2nd grade) | **−0.131** | **0.052** | **0.013** |
| → RC (2nd grade) → RC (3rd grade) | **−0.078** | **0.033** | **0.018** |
| → RC (2nd grade) → PS (3rd grade) | **−0.010** | **0.005** | **0.045** |
| Attitude and exposure | | | |
| → RC (3rd grade) | **−0.107** | **0.054** | **0.047** |
| → PS (2nd grade) | **−0.109** | **0.052** | **0.036** |
| → PS (2nd grade) → PS (3rd grade) | **−0.027** | **0.013** | **0.041** |
| **Familial math history (AMHQ)** | | | |
| Childhood ability | | | |
| → AR (1st grade) → AR (2nd grade) → PS (2nd grade) | **−0.043** | **0.010** | **0.000** |
| → AR (1st grade) → AR (2nd grade) → PS (3rd grade) | −0.007 | 0.003 | 0.017 |
| → AR (1st grade) → AR (2nd grade) → PS (2nd grade) → PS (3rd grade) | **−0.011** | **0.003** | **0.000** |
| Attitude and exposure | | | |
| → AR (2nd grade) → PS (2nd grade) | **−0.081** | **0.008** | **0.000** |
| → AR (2nd grade) → PS (3rd grade) | −0.013 | 0.007 | 0.068 |
| → AR (2nd grade) → PS (2nd grade) → PS (3rd grade) | **−0.020** | **0.003** | **0.000** |

*(Correlation coefficients in bold met $p < 0.05$. The directionality of the computed factor scores remain consistent with the that of the questions on each scale – that is, higher scores on any factors extracted from the ARHQ or AMHQ indicate, e.g., increased difficulties with learning to read or do simple arithmetic).*

which familial reading history is directly associated children's performance on complex academic tasks. The Attitude/Exposure factor was similarly shown to explain the extent to which familial reading history is directly linked to children's performance on complex academic tasks.

## Indirect Effects on Familial Math History on Complex Academic Tasks

### *Total Scores*

Familial history of reading difficulties, indexed by total scores on the ARHQ, was revealed to have an indirect effect on children's performance on PS task evaluated after second grade via the serial effects of AR skills measured after first and second grades ($b = -0.043$, $p < 0.05$). This indirect effect of familial history on PS performance captured after second grade in turn had an impact on children's PS outcome assessed after third grade ($b = -0.025$, $p < 0.05$). Familial history of math difficulties was also demonstrated to have an indirect effect on children's performance on PS task measured after second grade via AR skill captured also after second grade ($b = -0.096$, $p < 0.05$). The indirect effect of familial history then had an impact on children's PS outcome evaluated after third grade ($b = -0.055$, $p < 0.05$).

#### *Factor Scores*

When unpacking these effects with factor scores on the AMHQ, the Childhood Ability factor explained the extent to which familial math history is indirectly associated with children's performance on complex math tasks via their core math skills. The Attitude/Exposure factor was similar, in that it explained the extent to which familial math history is indirectly associated with children's performance on complex math tasks via their core math skills.

# DISCUSSION

The current study aimed to characterize the extent to which familial history of academic difficulties was related to children's reading and math outcomes. Preliminary findings confirmed the psychometric properties of the ARHQ and established the reliability and validity of the AMHQ. Results replicated the negative correlations between scores on the ARHQ and measures of children's reading outcomes (WR and RC), indicating that heightened familial history of reading difficulties is linked to worse reading performance. Similarly, higher scores on the AMHQ were linked to children's difficulties in math tasks (AR), thus corroborating the association between familial math history and math outcomes. In terms of the core versus complex pairings of academic outcomes in path analyses, familial history of reading difficulties indirectly explained differences in children's RC performance via their WR skills, and familial history of math difficulties was indirectly linked to children's PS outcomes via their AR abilities. Interestingly, scores on the ARHQ were also found to be negatively correlated with measures of children's math performance (AR and PS), with analyses revealing that these relations were indirectly influenced by differences in their WR skills. The AMHQ had distinctively direct and indirect effects on children's math performance, but not reading outcomes. Below we further unpack these findings, followed by limitations, potential directions, and implications for this line of research.

## Parents' Self-Report of Academic Difficulties

### Adult Reading History Questionnaire

#### *Total Scores*

Preliminary findings confirmed the psychometric properties for the ARHQ. The ARHQ was reported here with good internal consistency, which is in line with previous studies (Lefly and Pennington, 2000; Pennington and Lefly, 2001). Item-level analyses indicated that questions describing difficulties with learning to read were highly correlated with total scores on the ARHQ. Questions on difficulties with learning to read have been previously reported to be the driving component of the ARHQ as it could flag symptoms of dyslexia, whereas other items in this scale illustrate behavioral features linked to childhood reading differences, including current reading attitude and literacy exposure, that could persist into adulthood (Welcome and Meza, 2019; Feng et al., 2020). Moreover, scores on the ARHQ were shown to be negatively correlated with parents' reading performance. Interestingly, scores on the ARHQ were also revealed to be negatively associated with parents' math abilities.

#### *Factor Scores*

In keeping with past work (Welcome and Meza, 2019), our results supported a six-factor structure for the ARHQ, including Childhood Ability, Attitude/Exposure, Memory, Media Use, Reversal, and Spelling. Childhood Ability factor consisted of items concerning parents' experiences with learning to read in elementary school, which was shown to be associated with their reading and math skills. Items loading to Attitude/Exposure factor referenced current literacy practices, such as reading for leisure, and attitude toward reading in parents, as well as appeared to be linked with their reading but not math skills. Items making up Memory and Reversal factors contained details about, e.g., "names of places" and "phone numbers," as well as "letters or numbers," respectively, so could pertain to both reading and math domains. The Reversal factor, but not Memory, was shown to be correlated with both academic skills among parents from our sample, which is consistent with previous findings on reading (Welcome and Meza, 2019). Items in Media Use factor inquired about parents' usage of print and media, such as newspapers. Previous studies have suggested that print and media exposure is related to differences in general knowledge and information acquisition (Stanovich and Cunningham, 1993). In our results, the Media factor was not linked to parents' reading or math skills, which overlaps with prior evidence in reading (Welcome and Meza, 2019). One item loaded into Spelling factor asked parents to contrast their spelling ability to peers of similar age and education, which was demonstrated to be related to parents' both reading and math skills. This aligns with previous literature as spelling is reliant on phonological processes and linked to comorbid differences in academic abilities (Landerl and Moll, 2010; Slot et al., 2016).

### Adult Math History Questionnaire

#### *Total Scores*

The reliability and validity of the AMHQ were also established. Parents' self-report data on the AMHQ were analyzed with good internal consistency. Similar to findings on the ARHQ, item-level analyses revealed that questions linked to difficulties with completing math work were highly correlated with total scores on the AMHQ. Other items in this scale tapping respondents' current practices or numeracy exposure were demonstrated with lower correlations with the total scores. Total scores on the AMHQ were shown to be negatively correlated with parents' math and, to a lesser extent, reading performance. These results confirm the construct validity of the AMHQ by showing its correspondence with parents' math differences. Additionally, the criterion validity of the AMHQ was supported based on the positive correlation between scores on this scale and the ARHQ. The link between familial history of reading and math difficulties, particularly the Childhood Ability factors from the ARHQ and AMHQ, may also implicate a common feature or underlying cognitive mechanism in learning and academic achievement (Light and DeFries, 1995; Niemi et al., 2011; Costa et al., 2013; Fletcher et al., 2019).

### *Factor Scores*

Further exploratory analyses suggested a two-factor structure for the AMHQ, which reflected Childhood Ability and Attitude/Exposure. Consistent with first two factors in the ARHQ that query about the respondents' childhood and current reading experiences, Childhood Ability factor in the AMHQ included items about parents' self-reported difficulties with learning math contents in elementary education, and Attitude/Exposure factor surveyed current numeracy practices and attitude toward math. The Childhood Ability factor from each scale was shown to be correlated with parents' both reading and math skills. Whereas Attitude/Exposure factor from the ARHQ appeared to be uniquely associated with reading abilities in parents, this factor from the AMHQ was linked to their math proficiency. On the other hand, not only were a couple of remaining factors from the ARHQ were limited to one item, particularly Reversal and Spelling, these and others, including Memory and Media Use, did not appear to have an analogous AMHQ factor. Scores on the Reversal and Spelling dimensions from ARHQ, as aforementioned, were correlated with differences in parents' both reading and math skills. Despite differences in the numbers of factors found for each scale (six for ARHQ versus two for AMHQ), the patterns of associations between parents' academic functioning and these factors implicate overlapping or cross-domain effects (Childhood Ability, Reversal, and Spelling), as well as unique roles in either reading or math (Attitude/Exposure).

## Familial History of Reading Difficulties

### *Total Scores*

Correlational analyses were consistent with previous reports that have shown that familial history of reading difficulties negatively predicts differences in children's reading outcomes. Higher scores on the ARHQ were indeed associated with children's decreased ability to read individual words (WR skills), as well as worse performance on tasks that asked them to read, connect, and comprehend text using a cloze format (RC). Using samples of preschool children or those starting formal education, previous studies have reported the negative relations between familial history of reading difficulties and differences in children's emergent literacy skills, basic reading abilities (i.e., WR), and text reading fluency outcomes (e.g., Carroll and Snowling, 2004; Giménez et al., 2017). Some prior studies have observed a link between familial reading history and children's RC (Pennington and Lefly, 2001). Altogether, parents' self-report of increased reading difficulties could signal differences and degree of difficulty and severity in children's reading achievement. Some reports have further unpacked how familial history of reading difficulties is linked to reading over development, e.g., indirectly to RC via WR (Hulme et al., 2015).

The negative association between familial history of reading difficulties and children's performance on complex reading tasks (RC) was shown to be indirectly predicted by differences in core reading skills. These findings are not altogether surprising as previous reports have shown that familial history of reading difficulties has a negative impact on children's emergent literacy skills, and that this association in turn has an effect on their WR abilities that are measured when they start receiving explicit reading instruction (e.g., Esmaeeli et al., 2019). The current study built on these prior results by showing that familial history of reading difficulties has an indirect effect on children's RC performance by tapping their core reading skills (WR), which is consistent with other results also using a longitudinal design and path analyses (Hulme et al., 2015).

### *Factor Scores*

When unpacking which factors within the ARHQ were driving the path findings in our study, two following patterns emerged: Childhood Ability was correlated with core reading skills, whereas Attitude/Exposure and Media Use were associated with differences in complex reading performance. The Childhood Ability dimension appeared to explain the direct effect of familial reading history on children's WR skills, which in turn had an impact on their RC performance. These findings hold true even after adjusting for children's IQ (a combination of both verbal and non-verbal subscales). This in part supports the hypothesis for the familial influence on basic reading skills, which prior literature suggests would be at least driven by phonological abilities, in children's reading development (Pennington, 2006; van Bergen et al., 2014). Notably, the Attitude/Exposure and Media Use factors from the ARHQ were shown to have unique effects on children's RC performance, which was independent from and not indirectly through their WR skills. These findings are congruent with previous findings (Welcome and Meza, 2019) and suggest a link between parents' own attitude toward reading and literacy practices and children's performance on complex reading tasks.

## Familial History of Math Difficulties

### Total Scores

Findings showed that the familial history of math difficulties was negatively correlated with children's math outcomes. Higher scores on the AMHQ were found to be associated with children's lower performance in solving simple arithmetic tasks (addition/subtraction; AR). This is consistent with previous findings that used either the dichotomous self-report questionnaire as well as those that used performance-based measures collected from parents to operationalize their difficulties with arithmetic and computing skills (Shalev et al., 2001; Khanolainen et al., 2020; see also Wijsman et al., 2004). These findings also substantiate the construct validity of the AMHQ by tracking its link with children's math outcomes. Notably, using path analyses, the direct predictive effects of the AMHQ were shown in children's levels of AR performance assessed after both first and second grades, where the stability of individual differences in such math skills between these two occasions (or autoregressive effect) was represented. These findings suggest that familial history of math difficulties not only impacts initial AR abilities, but also predicts AR growth. Moreover, scores on the AMHQ were not directly related to children's performance on applied math problems. Instead, familial history of math difficulties was shown to have an indirect effect on children's performance on complex math tasks (PS) entirely via their core math skills (AR).

### *Factor Scores*

Supplementary analyses revealed that the Childhood Ability and Attitude/Exposure features of familial math history, as derived from the AMHQ, explained the extent to which parents' self-report of math difficulties indirectly related to children's PS performance through their AR skills. Previous literature has indicated the links between parents' dichotomous self-report of math difficulties and children's arithmetic and computing skills (Khanolainen et al., 2020), as well as between these core math abilities and performance on complex problem-solving tasks in children (Fuchs et al., 2006). These prior findings are consistent with our findings for an indirect prediction of familial math history in children's PS outcome via their AR skills (Bauer et al., 2006). Furthermore, some reports examining the intergenerational transmission of math difficulties have observed substantial correspondence in pre-numeracy abilities (e.g., approximate number system) between parents and children (Braham and Libertus, 2017; Bernabini et al., 2021). Familial history of math difficulties likely plays a role in children's pre-numeracy abilities before formal education, as well as their arithmetic skills that are introduced through explicit classroom instruction. On the other hand, the non-significant direct effect of familial history of math difficulties on children's performance on complex math tasks (PS) may be less surprising than expected because of additional cognitive processes involved and/or the use of specific language to teach math concepts and assess the respective understanding (e.g., Fuchs et al., 2006, 2021). Complex math tasks have been shown to place demands on not just AR skills but also non-verbal reasoning, concept formation, executive function, oral language, and WR abilities (Fuchs et al., 2006; Spencer et al., 2020). Some reports have conjectured that difficulties in children's performance on complex math tasks at the arithmetic level might be offset or compensated by some of these cognitive processes, such as oral language (Fuchs et al., 2018).

## Comorbid Reading and Math Difficulties

### Total Scores

Consistent with previous findings, familial history of reading difficulties was found to be negatively associated with children's math outcomes, while familial history of math difficulties was not linked to their reading performance. For example, Pennington and Lefly (2001) found evidence for the relations between scores on the ARHQ and children's AR skills as well as performance on PS tasks (Pennington and Lefly, 2001). Children with familial history of reading difficulties are thought to in part face challenges in meeting the verbal demands in math tasks (Khanolainen et al., 2020), given that previous theoretical accounts have posited a unique role for linguistic processes in math performance (e.g., Triple Code Model, see Dehaene and Cohen, 1995; Abstract-Code Model, see McCloskey, 1992). As aforementioned, phonological awareness is a known predictor in reading development (Storch and Whitehurst, 2002; Cirino et al., 2018), and has been shown to be linked to scores on the ARHQ (Pennington and Lefly, 2001). Studies suggested that phonological awareness is also a predictor of children's math performance (e.g., Slot et al., 2016; Child et al., 2019; Amland et al., 2021), perhaps more so in AR skills than PS outcomes (see Fuchs et al., 2006). Together these findings could be taken to mean that familial history of reading difficulties plays a role in children's reading and math outcomes via phonological or verbal processes. It is worthy to note, however, that math performance also draws on unique skills that are not necessarily tied to processes in reading; one skill that distinguishes math from reading is the approximate number system (Slot et al., 2016; Cirino et al., 2018), which some have previously reported as being linked to familial history of math difficulties (Braham and Libertus, 2017; Bernabini et al., 2021). The relation between familial history of math difficulties and children's math outcomes could thus be distinctly tapping skills, such as the approximate number system, that are not predictors of reading outcomes. This premise could explain the current results of the non-significant link between the AMHQ and measures of children's reading performance.

The relation between familial history of reading difficulties and children's math performance was shown to be facilitated by differences in children's core reading skills, as scores on the ARHQ were indirectly linked to children's AR abilities via their WR skills. Although not within the framework of familial history, recent longitudinal studies on comorbid academic differences have demonstrated that early reading skills are predictive of later math outcomes, but not vice versa, as their associations unfold over the first years of formal education (Erbeli et al., 2019). The current study builds on these findings by suggesting that the impact of familial reading history on children's reading performance could have downstream effect on their math abilities. Some reports have interpreted that the relation between familial history of academic difficulties and comorbid reading and math differences in children could signal a procedural learning problem or an inadequate response to instruction (Light and DeFries, 1995; Niemi et al., 2011). Furthermore, the extent to which familial history of reading difficulties had a negative impact on children's WR and in turn AR skills appeared to subsequently relate to their performance on PS tasks. These findings are in line with those that have shown that compared to peers with inadequate math skills, children with comorbid reading problems are more likely struggle with PS tasks of varying complexity (Fuchs and Fuchs, 2002). Findings from the current study suggest that familial history of reading difficulties could exacerbate the comorbid differences in children's reading and math skills, which could then result in poor performance on complex math tasks.

### *Factor Scores*

Follow-up findings indicate that specific factors in familial reading history, as derived from the ARHQ, were differentially related to levels of children's academic outcomes: Childhood Ability predicted core reading skills and in turn permeated math outcomes, whereas Attitude/Exposure and Media Use were linked to performance on complex reading and math tasks. Association between parents' difficulties with learning to read in elementary school and children's abilities in core academic skills

(WR and AR) could indicate some common phonological and verbal processes, as well as differences with procedural learning performance (e.g., Light and DeFries, 1995; Niemi et al., 2011; Child et al., 2019; Amland et al., 2021). What is particularly interesting were the direct effects of the Attitude/Exposure factor from the ARHQ on children's performance on both complex reading and math tasks (RC and PS). And, the Media Use factor was demonstrated to directly have an impact children's RC performance and in turn indirectly on PS outcomes. Together these findings could be taken to mean that parents' literacy practices (reading newspapers and/or books for leisure) are related to some core cognitive components, other than WR skills, that are key to performance on both complex reading and math tasks. In contrast, familial history of math difficulties was not shown to have any substantial effects on children's reading outcomes directly, or indirectly via their math skills. These findings implicate that there is a unique role for familial math history in children's math outcomes, versus the more ubiquitous impact of familial reading history on both reading and math performance in children.

## Limitations and Alternative Considerations

While the current findings offer novel insights into the role of familial history of reading and math difficulties, it is not without limitations. Parents' self-report was used as a way to survey familial history of academic difficulties. Within the past decades, studies have found the ARHQ useful in characterizing whether a child is at risk for difficulties with reading development (or dyslexia; e.g., Black et al., 2012; Rosenberg et al., 2012); the current report showed that both the ARHQ and AMHQ were related to parents' reading and math performance, respectively. As with any self-report measures, concerns remain in regard to the credibility of parents' endorsement on a questionnaire about their retrospective learning experiences in school, interpretation of "difficulty" when learning to read versus math concepts, and perception of own versus peers' performance (e.g., "... skill compared to others") across academic domains.

The psychometric findings on the ARHQ and AMHQ prompted a consideration for their dimensionality. While total scores on the ARHQ were previously used to capture the continuous nature of familial reading history, the wide range of correlation coefficients among items within this survey denotes presence of more than one dimension (as reported here, $r$'s = between −0.115 and 0.809). Findings from previous and our work indeed discern specific dimensions in the ARHQ, notably Childhood Ability and Attitude/Exposure (Welcome and Meza, 2019). In terms of the AMHQ, its items included different phrasing – i.e., in the forms of a question or statement – and also displayed a wide range of inter-item correlation coefficients ($r$'s = between 0.127 and 0.857). It should be noted, however, that items within the AMHQ loaded highly into corresponding constructs, Childhood Ability versus Attitude/Exposure, derived from this scale. These results not only suggest that the factor findings were not driven by the different phrasing, but also familial math history could be distinguished into specific dimensions. Future studies may take into account the continuous *and* dimensional nature of familial academic history by utilizing total and factor scores on the ARHQ and AMHQ.

Follow-up work should consider further examining the psychometric and predictive properties of the ARHQ and AMHQ, where the latter scale queries the respondents' experiences with math content generally, alongside with other academic history questionnaires, such as the *Adult Arithmetic Questionnaire* (AAHQ; Sury and Gaab, 2020). While the AAHQ has yet to be validated, it should be noted that this survey delves into the more granular components of math than the AMHQ (e.g., math facts, counting and estimation, memory for numbers, problem solving, simple and complex arithmetic); inclusion of such items may prove to have additional predictive power in children's outcomes. Notably, items in the ARHQ asked about the respondents' overall experience with reading rather than its specific components (e.g., rapid naming, phonological awareness, single word versus passage reading efficiency, and reading comprehension), which prompted our decision for the AMHQ to ask broad questions about math in a parallel format and not assess subcomponents. Further investigations of parents' reading experiences may consider emulating the nuanced strategies adopted in the AAHQ to tackle these various levels of reading performance, as well as to look at the familial learning history in terms of academic subcomponents.

Given the focus on investigating familial academic history, outcomes measures of interest were children's core versus complex reading and math skills. While the current findings offer some insights for the role of familial academic history in comorbid academic difficulties, future studies should consider nuanced genetic or twin design, along with the ARHQ and AMHQ, and in large-scale samples to create adequate grouping of children with single or combined deficits in reading and/or math (as executive in, e.g., Erbeli et al., 2019). It should be noted that children's performance on complex reading and math tasks is known to draw on cognitive processes other than core academic skills, including oral language and executive function. Proficiency in oral language is key to both RC and PS outcomes because of the verbal and linguistic demands in performance on these complex tasks (Child et al., 2019). Meta-analytic findings have revealed that familial history of reading difficulties is negatively associated with children's oral language proficiency, which could undermine their reading development (Snowling and Melby-Lervåg, 2016). Other reports have posited that intact oral language processes could play a compensatory role in RC among children with heightened familial history of reading difficulties (Torppa et al., 2007). Executive function, e.g., working memory, is another cognitive predictor of children's performance on complex reading and math tasks (Fuchs et al., 2006; Cutting et al., 2009; Cirino et al., 2018). Furthermore, intergenerational transmission of math anxiety could be linked to differences in children's executive function and performance on math tasks (Chang and Beilock, 2016). Therefore, to fully unpack the nature of the association between familial history and academic outcomes, future studies could consider examining cognitive predictors of children's reading and math outcomes, as well as math anxiety, in relation to familial history of academic difficulties (and factors derived from the ARHQ and AMHQ).

## SUMMARY AND IMPLICATIONS

The current study provides results that are promising both theoretically and practically, with implications for children at heightened familial history for academic difficulties. First, the novel simultaneous integration of the ARHQ and AMHQ suggests that assessing familial risk for academic difficulties may be important for understanding comorbid etiological and developmental associations among children's academic outcomes. In particular, findings on the roles of familial reading history and children's reading abilities in their math outcomes supply evidence for the phonological pathway in these academic domains (Geary, 1993; Child et al., 2019; Amland et al., 2021). This hypothesis on the phonological pathway may elicit the consideration of incorporating literacy contents in classroom instruction and interventions focusing on numeracy materials. Some reports have suggested that children with single or comorbid difficulties in reading and/or math could benefit from some forms of combined reading and math remediations (e.g., Fuchs et al., 2012; Glenberg et al., 2012; Powell et al., 2020).

Second, utility of parents' self-report information on the ARHQ and AMHQ as additional diagnostic metrics could facilitate early identification of children who are at heightened risk for reading and/or math difficulties and identify prevention strategies, which could be more effective than to implement later remediation (for intervention findings with known status of familial reading risk, see Muter and Snowling, 2009; Zijlstra et al., 2021). This is also because learning differences are commonly diagnosed not until after children have well entered formal education and exhibited substantial performance difficulties in the classroom – with concerns among many individuals often overlooked or recognized with delay (Fletcher et al., 2019). Some studies have utilized a dichotomous, or yes-versus-no, measure on parents' general self-report of reading or math difficulties to operationalize familial academic history (Landerl and Moll, 2010; Erbeli et al., 2019; Khanolainen et al., 2020). Using such approach, some have found that this indicator of familial reading history does not contribute substantially beyond performance-based assessment to screening children for reading difficulties (Ferrer et al., 2021). Others have used the ARHQ to capture the continuous nature in familial history of reading difficulties based on related clinical and additive features observed across the lifespan, such as learning to read in elementary school, current reading behaviors and print exposure, and attitude toward literacy (e.g., Lefly and Pennington, 2000). Previous and our work suggests that dimensions within the ARHQ on Childhood Ability, or learning in early education, and Attitude/Exposure, or current practices and interest, map onto the respondents' academic functioning (for samples of college-aged individuals, see Parilla et al., 2007; Welcome and Meza, 2019; see also Kirby et al., 2008) as well as their children's outcomes (shown among elementary students here in parallel with findings from the AMHQ; for a sample of adolescents, see also Conlon et al., 2006). Future prediction and preventive studies may want to consider the early learning and current behavioral features in familial reading and math history. For example, parents could be queried about own experiences to gage at their children's learning potentials; these children as they advance in post-secondary education may be asked about their attitude, interest, and perception toward reading; or individuals in adulthood could be surveyed to identify ways to target specific academic abilities (core skills versus performance on complex tasks; e.g., leisure reading and print exposure).

Third, results regarding the intergenerational effects of familial academic history on children's academic outcomes point to the contribution of parents' educational circumstances, literacy and numeracy practices, and role in the home cognitive environment (van Bergen et al., 2014). For example, parents who experienced more difficulties with learning to read in elementary school tend to read less in adulthood (Muter and Snowling, 2009; Snowling and Melby-Lervåg, 2016), and may in turn deliver a less sufficient home literacy environment or promote less reading opportunities for their children (Hamilton et al., 2016). One may also speculate that parents who struggled more with learning math contents in elementary could face more challenges with math materials in adulthood, and perhaps would offer less numeracy practices for their children (Bernabini et al., 2020). Findings for the respective effects of the Childhood Ability factors from the ARHQ and AMHQ on children's core reading versus math outcomes could implicate some underlying degree of intergenerational mediation or heritability in difficulties when learning to read words or do simple arithmetic (Pennington, 2006). On the other hand, what was shown to be independent from the effects between the Childhood Ability factors from these scales and children's core academic skills is the unique role of the Attitude/Exposure factor, as well as the Media Use one to some extent, from the ARHQ in their performance on both complex reading and math tasks. These results highlight the distinguishable impacts between parents' current literacy practices versus their retrospective difficulties with procedural learning (e.g., to read or do simple arithmetic) children's academic outcomes. Insights from the hypothesis on the intergenerational pathway could encourage future research and intervention efforts to place additional focus on adults' academic backgrounds and practices, which may confer downstream effects on their offsprings' educational needs and classroom performance.

## DATA AVAILABILITY STATEMENT

Data in the current study are not publicly available due to not all participants providing consent for their data to be shared outside of Vanderbilt University and Vanderbilt University Medical School. A subset of this data, from those participants who did provide consent for their data to be shared outside of the aforementioned institutions, are available from the corresponding author on reasonable request.

## ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Vanderbilt University's Institutional Review Board. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

## AUTHOR CONTRIBUTIONS

TN and AM-L conducted analyses and prepared manuscript draft. LC contributed to funding acquisition, data curation, and supervision. All authors contributed to experimental design, discussing results, revision, and approval of the manuscript.

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## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2021.710380/full#supplementary-material

## REFERENCES

Amland, T., Lervag, A., and Melby-Lervag, M. (2021). Comorbidity between math and reading problems: Is phonological processing a mutual factor? [Original Research]. *Front. Hum. Neurosci.* 14:592. doi: 10.3389/fnhum.2020.577304

Bauer, D. J., Preacher, K. J., and Gil, K. M. (2006). Conceptualizing and testing random indirect effects and moderated mediation in multilevel models: New procedures and recommendations. *Psycholog. Methods* 11, 142–163.

Bernabini, L., Tobia, V., and Bonifacci, P. (2021). Intergenerational Features of Math Skills: Symbolic and Non-Symbolic Magnitude Comparison and Written Calculation in Mothers and Children. *J. Cogn. Dev.* 2020, 1–19. doi: 10.1080/15248372.2020.1844711

Bernabini, L., Tobia, V., Guarini, A., and Bonifacci, P. (2020). Predictors of children's early numeracy: Environmental variables, intergenerational pathways, and children's cognitive, linguistic, and non-symbolic number skills. *Front. Psychol.* 11:505065–505065. doi: 10.3389/fpsyg.2020.505065

Black, J. M., Tanaka, H., Stanley, L., Nagamine, M., Zakerani, N., Thurston, A., et al. (2012). Maternal history of reading difficulty is associated with reduced language-related gray matter in beginning readers. *Neuroimage* 59, 3021–3032. doi: 10.1016/j.neuroimage.2011.10.024

Braham, E. J., and Libertus, M. E. (2017). Intergenerational associations in numerical approximation and mathematical abilities. *Dev. Sci.* 20:e12436. doi: 10.1111/desc.12436

Carroll, J. M., and Snowling, M. J. (2004). Language and phonological skills in children at high risk of reading difficulties. *J. Child Psychol. Psychiatry* 45, 631–640. doi: 10.1111/j.1469-7610.2004.00252.x

Chang, H., and Beilock, S. L. (2016). The math anxiety-math performance link and its relation to individual and environmental factors: a review of current behavioral and psychophysiological research. *Curr. Opin. Behav. Sci.* 10, 33–38. doi: 10.1016/j.cobeha.2016.04.011

Child, A. E., Cirino, P. T., Fletcher, J. M., Willcutt, E. G., and Fuchs, L. S. (2019). A cognitive dimensional approach to understanding shared and unique contributions to reading, math, and attention skills. *J. Learn. Disab.* 52, 15–30. doi: 10.1177/0022219418775115

Cirino, P. T., Child, A. E., and Macdonald, K. T. (2018). Longitudinal predictors of the overlap between reading and math skills. *Contemp. Educ. Psychol.* 54, 99–111. doi: 10.1016/j.cedpsych.2018.06.002

Common Core State Standards Initiative (2010b). *Common Core State Standards for mathematics*. Washington: Common Core State Standards Initiative.

Common Core State Standards Initiative (2010a). *Common Core State Standards for English Language arts & literacy in history/social studies, science, and technical subjects*. Retrieved from http://www.corestandards.org/assets/CCSSI_ELA%20Standards.pdf. (Retrieved April 15, 2012)

Compton, D. L., Fuchs, L. S., Fuchs, D., Lambert, W., and Hamlett, C. L. (2012). The cognitive and academic profiles of reading and mathematics learning disabilities. *J. Learn. Disab.* 45, 79–95. doi: 10.1177/0022219410393012

Conlon, E. G., Zimmer-Gembeck, M. J., Creed, P. A., and Tucker, M. (2006). Family history, self-perceptions, attitudes and cognitive abilities are associated with early adolescent reading skills. *J. Res. Read.* 29, 11–32. doi: 10.1111/j.1467-9817.2006.00290.x

Costa, H. C., Perdry, H., Soria, C., Pulgar, S., Cusin, F., and Dellatolas, G. (2013). Emergent literacy skills, behavior problems and familial antecedents of reading difficulties: A follow-up study of reading achievement from kindergarten to fifth grade. *Res. Dev. Disab.* 34, 1018–1035. doi: 10.1016/j.ridd.2012.11.029

Cutting, L. E., Materek, A., Cole, C. A. S., Levine, T. M., and Mahone, E. M. (2009). Effects of fluency, oral language, and executive function on reading comprehension performance. *Ann. Dysl.* 59, 34–54. doi: 10.1007/s11881-009-0022-0

Dehaene, S., and Cohen, L. (1995). Toward an anatomical and functional model of number processing. *Mathem. Cogn.* 1, 83–120.

Del Tufo, S. N., Earle, S., and Cutting, L. E. (2019). The impact of expressive language development and the left inferior longitudinal fasciculus on listening and reading comprehension. *J. Neurodev. Dis.* 11:37. doi: 10.1186/s11689-019-9296-7

Dirks, E., Spyer, G., van Lieshout, E. C. D. M., and de Sonneville, L. (2008). Prevalence of combined reading and arithmetic disabilities. *J. Learn. Disab.* 41, 460–473.

DiStefano, C., Zhu, M., and Mindrila, D. (2009). Understanding and using factor scores: Considerations for the applied researcher. *Pract. Assess. Res. Eval.* 14:20. doi: 10.7275/da8t-4g52

Ehri, L. C. (2005). Learning to read words: Theory, findings, and issues. *Sci. Stud. Read.* 9, 167–188. doi: 10.1207/s1532799xssr0902_4

Erbeli, F., Hart, S. A., and Taylor, J. (2019). Genetic and environmental influences on achievement outcomes based on family history of learning disabilities status. *J. Learn. Disab.* 52, 135–145. doi: 10.1177/0022219418775116

Esmaeeli, Z., Kyle, F. E., and Lundetræ, K. (2019). Contribution of family risk, emergent literacy and environmental protective factors in children's reading difficulties at the end of second-grade. *Read. Writ.* 32, 2375–2399. doi: 10.1007/s11145-019-09948-5

Feng, L., Hancock, R., Watson, C., Bogley, R., Miller, Z., Luisa, G. T. M., et al. (2020). Development of an abbreviated adult reading history questionnaire (ARHQ-Brief) using a machine learning approach. *PsyArXiv* 2020:5. doi: 10.31234/osf.io/8u5fe

Ferrer, E., Shaywitz, B. A., Holahan, J. M., and Shaywitz, S. E. (2021). Family history is not useful is screening children for dyslexia. *J. Pediat. Neuropsychol.* 2021:110. doi: 10.1007/s40817-021-00110-0

Finucci, J. M., Isaacs, S. D., Whitehouse, C. C., and Childs, B. (1982). Empirical validation of reading and spelling quotients. *Dev. Med. Child Neurol.* 24, 733–744. doi: 10.1111/j.1469-8749.1982.tb13695.x

Fletcher, J. M., Lyon, G., Fuchs, L. S., and Barnes, M. A. (2019). *Learning disabilities: From identification to intervention*. buenos aires: The Guilford Express.

Fritz, M. S., Taylor, A. B., and MacKinnon, D. P. (2012). Multivariate behavioral research. *Multiv. Behav. Res.* 47, 61–87.

Fuchs, D., Fuchs, L. S., and Compton, D. L. (2012). Smart RTI: A next-generation approach to multilevel prevention. *Except. Child.* 78, 263–279.

Fuchs, L. S., and Fuchs, D. (2002). Mathematical problem-solving profiles of students with mathematics disabilities with and without comorbid reading disabilities. *J. Learn. Disab.* 35, 564–574. doi: 10.1177/00222194020350060701

Fuchs, L. S., Fuchs, D., Compton, D. L., Powell, S. R., Seethaler, P. M., Capizzi, A. M., et al. (2006). The cognitive correlates of third-grade skill in arithmetic, algorithmic computation, and arithmetic word problems. *J. Educ. Psychol.* 98:29.

Fuchs, L. S., Gilbert, J. K., Fuchs, D., Seethaler, P. M., and Martin, N. (2018). Text comprehension and oral language as predictors of word-problem solving: Insights into word-problem solving as a form of text comprehension. *Sci. Stud. Read.* 22, 152–166. doi: 10.1080/10888438.2017.1398259

Fuchs, L. S., Seethaler, P. M., Sterba, S. K., Craddock, C., Fuchs, D., Compton, D. L., et al. (2021). Closing the word-problem achievement gap in first grade: Schema-based word-problem intervention with embedded language comprehension instruction. *J. Educ. Psychol.* 113, 86–103. doi: 10.1037/edu0000467

García, J. R., and Cain, K. (2014). Decoding and reading comprehension: A meta-analysis to identify which reader and assessment characteristics influence the strength of the relationship in English. *Rev. Educ. Res.* 84, 74–111.

Geary, D. C. (1993). Mathematical disabilities: Cognitive, neuropsychological, and genetic components. *Psychol. Bull.* 114, 345–362. doi: 10.1037/0033-2909.114.2.345

Geary, D. C. (2011). Consequences, characteristics, and causes of mathematical learning disabilities and persistent low achievement in mathematics. *J. Dev. Behav. Pediatr.* 32, 250–263. doi: 10.1097/DBP.0b013e318209edef

Giménez, A., Ortiz, A., López-Zamora, M., Sánchez, A., and Luque, J. L. (2017). Parents' reading history as an indicator of risk for reading difficulties. *Ann. Dysl.* 67, 259–280. doi: 10.1007/s11881-017-0143-9

Glenberg, A., Willford, J., Gibson, B., Goldberg, A., and Zhu, X. (2012). Improving reading to improve math. *Sci. Stud. Read.* 16, 316–340. doi: 10.1080/10888438.2011.564245

Hamilton, L. G., Hayiou-Thomas, M. E., Hulme, C., and Snowling, M. J. (2016). The home literacy environment as a predictor of the early literacy development of children at family-risk of dyslexia. *Sci. Stud. Read.* 20, 401–419. doi: 10.1080/10888438.2016.1213266

Hart, S. A., Petrill, S. A., Thompson, L. A., and Plomin, R. (2009). The ABCs of math: A genetic analysis of mathematics and its links with reading ability and general cognitive ability. *J. Educ. Psychol.* 101, 388–402.

Hu, L. T., and Bentler, P. M. (1999). Cutoff criteria for fit indexes in covariance structure analysis: Conventional criteria versus new alternatives. *Struct. Equ. Model.* 6, 1–55. doi: 10.1080/10705519909540118

Hulme, C., Nash, H. M., Gooch, D., Lervåg, A., and Snowling, M. J. (2015). The foundations of literacy development in children at familial risk of dyslexia. *Psychol. Sci.* 26, 1877–1886. doi: 10.1177/0956797615603702

Jordan, N. C. (2007). "Do words count? Connections between mathematics and reading difficulties," in *Why is math so hard for some children? The nature and origins of mathematical learning difficulties and disabilities*, eds D. B. Berch and M. M. Mazzocco (Oxford: Brookes), 107–120.

Khanolainen, D., Psyridou, M., Silinskas, G., Lerkkanen, M.-K., Niemi, P., Poikkeus, A.-M., et al. (2020). Longitudinal effects of the home Learning environment and parental difficulties on reading and math development across grades 1-9. *Front. Psychol.* 11:577981. doi: 10.3389/fpsyg.2020.577981

Kirby, J. R., Silvestri, R., Allingham, B. H., Parilla, R., and La Fave, C. B. (2008). Learning strategies and study approaches of postsecondary students with dyslexia. *J. Learn. Disab.* 41, 85–96.

Landerl, K., and Moll, K. (2010). Comorbidity of learning disorders: Prevalence and familial transmission. *J. Child Psychol. Psychiat.* 51, 287–294. doi: 10.1111/j.1469-7610.2009.02164.x

Lefly, D. L., and Pennington, B. F. (2000). Reliability and validity of the adult reading history questionnaire. *J. Learn. Disab.* 33, 286–296. doi: 10.1177/002221940003300306

Light, J. G., and DeFries, J. C. (1995). Comorbidity of reading and mathematics disabilities: Genetic and environmental etiologies. *J. Learn. Disab.* 28, 96–106. doi: 10.1177/002221949502800204

McCloskey, M. (1992). Cognitive mechanisms in numerical processing: Evidence from acquired dyscalculia. *Cognition* 44, 107–157.

Melby-Lervåg, M., Lyster, S.-A. H., and Hulme, C. (2012). Phonological skills and their role in learning to read: A meta-analytic review. *Psycholog. Bull.* 138, 322–352. doi: 10.1037/a0026744

Moll, K., Snowling, M. J., Göbel, S. M., and Hulme, C. (2015). Early language and executive skills predict variations in number and arithmetic skills in children at family-risk of dyslexia and typically developing controls. *Learn. Instr.* 38, 53–62.

Muter, V., and Snowling, M. J. (2009). Children at familial risk of dyslexia: Practical implications from an at-risk study. *Child Adoles. Mental Health* 14, 37–41. doi: 10.1111/j.1475-3588.2007.00480.x

Niemi, P., Nurmi, J.-E., Lyyra, A.-L., Lerkkanen, M.-K., Lepola, J., Poskiparta, E., et al. (2011). Task avoidance, number skills and parental learning difficulties as predictors of poor response to instruction. *J. Learn. Disab.* 44, 459–471. doi: 10.1177/0022219411410290

Parilla, R., Georgiou, G., and Corkett, J. (2007). University students with a significant history of reading difficulties: What is and is not compensated? *Except. Educ. Can.* 17, 195–220.

Pennington, B. F. (2006). From single to multiple deficit models of developmental disorders. *Cognition* 101, 385–413. doi: 10.1016/j.cognition.2006.04.008

Pennington, B. F., and Lefly, D. L. (2001). Early reading development in children at family risk for dyslexia. *Child Dev.* 72, 816–833. doi: 10.1111/1467-8624.00317

Powell, S. R., Doabler, C. T., Akinola, O. A., Therrien, W. J., Maddox, S. A., and Hess, K. E. (2020). A synthesis of elementary mathematics interventions: Comparisons of students with mathematics difficulty with and without comorbid reading difficulty. *J. Learn. Disab.* 53, 244–276. doi: 10.1177/0022219419881646

Revelle, W. (2018). *psych: procedures for personality and psychological research.* Evanston.: Northwestern University.

Ritchie, S. J., and Bates, T. C. (2013). Enduring links from childhood mathematics and reading achievement to adult socioeconomic status. *Psycholog. Sci.* 24, 1301–1308. doi: 10.1177/0956797612466268

Rosenberg, J., Pennington, B. F., Willcutt, E. G., and Olson, R. K. (2012). Gene by environment interactions influencing reading disability and the inattentive symptom dimension of attention deficit/hyperactivity disorder. *J. Child Psychol. Psychiat.* 53, 243–251. doi: 10.1111/j.1469-7610.2011.02452.x

Rosseel, Y. (2012). Lavaan: An R package for structural equation modeling and more. Version 0.5–12 (BETA). *J. Stat. Softw.* 48, 1–36.

Scarborough, H. S. (1989). Prediction of reading disability from familial and individual differences. *J. Educ. Psychol.* 81, 101–108. doi: 10.1037/0022-0663.81.1.101

Shalev, R. S., Manor, O., Kerem, B., Ayali, M., Badichi, N., Friedlander, Y., et al. (2001). Developmental dyscalculia is a familial learning disability. *J. Learn. Disab.* 34, 59–65. doi: 10.1177/002221940103400105

Slot, E. M., van Viersen, S., de Bree, E. H., and Kroesbergen, E. H. (2016). Shared and unique risk factors underlying mathematical disability and reading and spelling disability [Original Research]. *Front. Psychol.* 7:803. doi: 10.3389/fpsyg.2016.00803

Snowling, M. J., Gallagher, A., and Frith, U. (2003). Family risk of dyslexia is continuous: Individual differences in the precursors of reading skill. *Child Dev.* 74, 358–373. doi: 10.1111/1467-8624.7402003

Snowling, M. J., and Melby-Lervåg, M. (2016). Oral language deficits in familial dyslexia: A meta-analysis and review. *Psycholog. Bull.* 142, 498–545. doi: 10.1037/bul0000037

Solari, E. J., Grimm, R. P., McIntyre, N. S., and Denton, C. A. (2018). Reading comprehension development in at-risk vs. not at-risk first grade readers: The differential roles of listening comprehension, decoding, and fluency. *Learn. Indiv. Diff.* 65, 195–206. doi: 10.1016/j.lindif.2018.06.005

Spencer, M., Fuchs, L. S., and Fuchs, D. (2020). Language-related longitudinal predictors of arithmetic word problem solving: A structural equation modeling approach. *Contemp. Educ. Psychol.* 60:101825. doi: 10.1016/j.cedpsych.2019.101825

Stanovich, K. E., and Cunningham, A. E. (1993). Where does knowledge come from? Specific associations between print exposure and information acquisition. *J. Educ. Psychol.* 85, 211–229. doi: 10.1037/0022-0663.85.2.211

Stefansson, H., Meyer-Lindenberg, A., Steinberg, S., Magnusdottir, B., Morgen, K., Arnarsdottir, S., et al. (2014). CNVs conferring risk of autism or schizophrenia affect cognition in controls. *Nature* 505, 361–366. doi: 10.1038/nature12818

Storch, S. A., and Whitehurst, G. J. (2002). Oral language and code-related precursors to reading: Evidence from a longitudinal structural model. *Dev. Psychol.* 38:934. doi: 10.1037/0012-1649.38.6.934

Sury, D., and Gaab, N. (2020). The Adult Arithmetic History Questionnaire. *PsyArXiv* doi: 10.31234/osf.io/zt6ku

Tabachnick, B. G., and Fidell, L. S. (2007). *Using multivariate statistics*, Vol. 5. London: Pearson Education Inc.

Torppa, M., Poikkeus, A.-M., Laakso, M.-L., Tolvanen, A., Leskinen, E., Leppanen, P. H. T., et al. (2007). Modeling the early paths of phonological awareness and factors supporting its development in children with and without familial risk of dyslexia. *Sci. Stud. Read.* 11, 73–103. doi: 10.1080/10888430709336554

Ulfarsson, M. O., Walters, G. B., Gustafsson, O., Steinberg, S., Silva, A., Doyle, O. M., et al. (2017). 15q11.2 CNV affects cognitive, structural and functional correlates of dyslexia and dyscalculia. *Translat. Psychiat.* 7, e1109–e1109. doi: 10.1038/tp.2017.77

van Bergen, E., van der Leij, A., and de Jong, P. F. (2014). The intergenerational multiple deficit model and the case of dyslexia [Hypothesis and Theory]. *Front. Hum. Neurosci.* 8:346. doi: 10.3389/fnhum.2014.00346

van Viersen, S., de Bree, E. H., Zee, M., Maassen, B., van der Leij, A., and de Jong, P. F. (2018). Pathways into literacy: The role of early oral language abilities and family risk for dyslexia. *Psycholog. Sci.* 29, 418–428. doi: 10.1177/0956797617736886

Wechsler, D. (2011). *Wechsler Abbreviated Scale of Intelligence Second Edition (WASI-II)*. San Antonio. *TX*: Pearson.

Welcome, S. E., and Meza, R. A. (2019). Dimensions of the Adult Reading History Questionnaire and their relationships with reading ability. *Read. Writ.* 32, 1295–1317. doi: 10.1007/s11145-018-9912-z

Wijsman, E. M., Robinson, N. M., Ainsworth, K. H., Rosenthal, E. A., Holzman, T., and Raskind, W. H. (2004). Familial aggregation patterns in mathematical ability. *Behav. Genet.* 34, 51–62. doi: 10.1023/B:BEGE.0000009476.33020.b9

Woodcock, R. W., McGrew, K. S., and Mather, N. (2001, 2007). *Woodcock-Johnson III NU Tests of Cognitive Abilities*. Rolling Meadows: Riverside Publishing.

Zijlstra, H., van Bergen, E., Regtvoort, A., de Jong, P. F., and van der Leij, A. (2021). Prevention of reading difficulties in children with and without familial risk: Short- and long-term effects of an early intervention. *J. Educ. Psychol.* 113, 248–267. doi: 10.1037/edu0000489

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# Differential Efficacy of Digital Scaffolding of Numeracy Skills in Kindergartners With Mild Perinatal Aversities

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**Introduction:** Children who experienced mild perinatal adversity (i.e., born late preterm or small for gestational age) are at increased risk for delays in early numeracy and literacy, which increases inequality in educational opportunities. However, this group showed increased susceptibility to the characteristics of their educational environment for literacy, especially for those born late preterm. Intervening in this group may thus be particularly beneficial, provided that their educational environment is highly structured. Delays in numeracy and mathematics are most firmly acknowledged in these children. It remains unclear if these children are also more susceptible to their educational numeracy environment. We test the hypothesis of increased susceptibility to characteristics of their educational environment in the field of numeracy.

**Methods:** We tested the efficacy of a digital intervention of two to 3 months, which focused on visual spatial skills in a large randomized controlled trial in a sample of five-to-six-year-old kindergarten pupils from 140 elementary schools. About 45% of all participants showed delays in numeracy, of whom n = 67 (11%) were born late preterm, n = 157 (26%) were born small for gestational age, and n = 389 (63%) had no mild perinatal adversities. Pupils were assigned to a guiding and structured intervention focused on visual spatial skills (n = 294) or a control program (n = 319), targeting literacy skills. *Results:* The intervention did not show a main effect. The program was not effective in children small for gestational age, but it was for children born late preterm (Cohen's *d* = .71, CI = .07–1.36), showing stronger numeracy skills compared to term-born peers in the intervention condition. Early numeracy skills in children born late preterm fell behind compared to term-born peers in the control condition.

**Conclusion:** A highly structured educational numeracy environment, using repetition and adaptive feedback benefited early numeracy skills of late preterm children. These children outperformed their peers in early numeracy skills, while those in the control condition fell behind. Findings align with earlier findings on promoting early literacy in this group through an equivalent literacy intervention. A relatively simple and cost-effective intervention thus may help reduce the risk of educational inequality for children born late pre-term.

**Keywords: late preterm, scaffolding, differential susceptibility to educational environment, academic skills in kindergarten, digital intervention, RCT—randomized controlled trial**



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## INTRODUCTION

Children who experienced mild perinatal adversity (i.e., born late preterm or small for gestational age) are at increased risk for delays in early numeracy and for literacy delays, increasing inequality in educational opportunities. However, in literacy research children born late preterm, but not the group small for gestational age showed increased susceptibility to the characteristics of the educational environment (Merkelbach et al., 2018). This suggests that intervening is particularly beneficial for the late preterm group provided that the educational environment is highly structured. Moreover, delays in numeracy and mathematics are most firmly acknowledged in this group of children. However, it remains unclear if this group is more susceptible to their educational numeracy environment. Therefore, in the current study we aimed to test the hypothesis of increased susceptibility to the characteristics of their educational environment in the field of numeracy. In early childhood numeracy develops long before formal education starts. Delays in early numeracy skills can however have long lasting effects on the development of mathematical abilities (Desoete et al., 2010). Fortunately, mathematical performance is particularly susceptible to intervention effects (e.g., Gervasoni, 2001), especially when implemented at an early age. Identification of children falling behind in early numeracy could thus prevent serious problems in mathematical performance later in life. In this paper we use the term numeracy to denote the field of numbers, such as understanding numbers, amounts and spatial relations (e.g. bigger, more, less, smaller), in line with Reid and Andrews (2016). Mathematics in this paper refers to learning arithmetic more formally.

### Developmental Challenges in Children Born Late Preterm

Children born late preterm (born between 34 and 37 weeks into pregnancy) may have been subject to altered stress responses (Windhorst et al., 2017), or to neural variations that involve many neurocognitive systems. Walsh and colleagues showed for instance that late preterm children had smaller brain size, less-developed myelination of the posterior limb of the internal capsule, and more immature gyral folding than their full-term peers (Walsh et al., 2014). Even though late preterm birth is considered “merely” a *mild* perinatal adversity (Van der Kooy-Hofland et al., 2012), these children consistently show higher levels of cognitive problems (Shah et al., 2016; Searle et al., 2017) compared to their peers. The experienced cognitive problems are diverse (e.g. Chyi et al., 2008; Woythaler et al., 2015; Martínez-Nadal and Bosch, 2021), but problems in numeracy and mathematics are highly pronounced (e.g. Poulsen, et al., 2013). Mathematics involves many domains (e.g., numbers, quantity, operations, measurement, fractions, geometry, modeling etc.) and is hierarchical in nature, making it a complex skill, especially for children with less well-developed brains (Barnes and Raghubar, 2014).

### Developmental Challenges in Children Born Small for Gestational Age

Similar general outcomes are found in children born small for gestational age (below the 10th percentile), also considered a mild perinatal adversity associated with changes in stress response (Windhorst et al., 2017) and alterations in brain size and maturity (Thompson et al., 2019). In childhood and adolescence this group too, is at risk for experiencing a range of cognitive problems (e.g., Sommerfelt et al., 2000; Ido et al., 1995), such as more frequent as well as more severe learning disabilities (O’Keeffe et al., 2003) and poorer school performance (Larroque et al., 2001). Acknowledged is that adverse perinatal factors can influence brain development throughout childhood (Gonzalez et al., 2020), causing problems at all domains of cognitive functioning. However, the link with math and numeracy problems seems to be more firmly established in the late preterm group than in the small for gestational age group.

### Differential Susceptibility

These biological alterations associated with mild perinatal adversities interact with environmental factors, culminating in either positive or very negative outcomes: Labayru et al. (2021) for instance show that mild developmental problems in toddlers might develop into clinical problems at school age. Increasing environmental demands at school age compared to toddler age could add to the difficulties these children encounter with executive skills, sustained attention, and memory (Ho, 2018; Jin et al., 2019). Although both these mild perinatal adversities are generally associated with increased chances of negative cognitive outcomes, considering mild perinatal adversities as a mere vulnerability factor might be short-sighted. People who have experienced mild perinatal adversities might be more susceptible to qualities of their environment, for better *and* for worse as described in the differential susceptibility model (Belsky and Pluess, 2009). Indications of such increased susceptibility have already been identified in studies into the effects of the rearing environment (Windhorst et al., 2017), as well as in studies into the effect of characteristics of the educational environment (Van der Kooy-Hofland et al., 2012; Merkelbach et al., 2018).

### Importance of Targeting the Learning Environment

High-quality early childhood education for disadvantaged children, improves their early-life environments which in turn boost a variety of early-life skills and later-life achievements (Elango et al., 2016). Identification of effective (digital) programs for this group is therefore crucial to improve early-life opportunities for disadvantaged children. Mild perinatal adversities are more common in groups already at risk for educational problems, such as low-SES populations (Gardosi and Francis, 2005; Kelly and Li, 2019). Adversities of mild perinatal nature might put children at risk for educational disadvantage lasting well into adult life (Larroque et al., 2001; Labayru et al., 2021). To reduce educational inequality, it is of great societal importance that methods are found to offer educational guidance and tutoring to children with mild perinatal problems.

## Susceptibility to the Effects of Scaffolding

Some evidence points towards a possible increased susceptibility to scaffolding in an educational setting in children with mild perinatal adversities. In a small-scale experiment, kindergartners who have experienced mild perinatal adversities were shown to be more susceptible to a digital early literacy intervention. This digital program, *Living Letters*, characterized by scaffolding offering structure, repetition, and adaptive feedback promoted a phonological awareness and alphabetical knowledge (Van der Kooy-Hofland et al., 2012). For children without perinatal adversities Living Letters had no effect on phonological awareness and alphabetical knowledge. However, children with mild perinatal adversities outperformed their peers after working with Living Letters whereas they fell behind even further after working with a digital control program. This control program was highly similar in terms of scaffolding (i.e., offering structure and adaptive feedback), but did not target letter knowledge.

In the study by Van der Kooy-Hofland et al. (2012), children with mild perinatal adversities were treated as a homogenous group, whereas Merkelbach et al. (2018) showed in their large-scale replication study that only children born late preterm were susceptible to Living Letters, while children born small for gestational age showed similar results as their peers without perinatal adversity. Acknowledging subgroups in children with mild perinatal adversity was shown to be crucial: it seems that children with mild perinatal adversities are a heterogeneous group with different educational needs. Based on current evidence discussed above, it is likely that the scaffolding features of the literacy intervention used by Merkelbach et al. (2018) meet the educational needs of children born late preterm particularly well, but not those of children small for gestational age. Vollmer and Edmonds (2019) showed in their review that children small for gestational age are at greater risk of difficulties with attentional control compared to their late preterm peers. As a result, they may need more scaffolding and guidance than was offered by the digital intervention.

## Present Study

The current study was part of a larger research project which focused on promoting literacy. In the current study, to test these hypotheses, we opted for a digital program with similar scaffolding characteristics (structure, repetition etc.) but now in the domain of numeracy; a domain of vulnerability for children with mild perinatal adversities (e.g., Labayru et al., 2021; Poulsen, et al., 2013). This digital program is mainly focused on visual spatial skills. However, in the context of the larger project, children were selected for participation by their teachers based on delays in literacy.

Longitudinal studies have shown that visual spatial abilities (such as encoding and mental manipulation of spatial information) are important for mathematical performance in children (Assel et al., 2003; Bull et al., 2008; Raghubar et al., 2010). A robust finding is that spatial visualization contributes to arithmetic performance via basic number knowledge (LeFevre et al., 2010; Cirino, 2011; Zhang et al., 2017; Yang et al., 2021). That is, the ability of spatial visualization might function as a cognitive tool used by young children to learn basic numerical relations and thus contributes to higher-level mathematics. Also, numeracy and mathematical problems are more prevalent in children born late preterm than in their full-term peers (Nepomnyaschy et al., 2012), and such problems are generally susceptible to the effects of early interventions (e.g., Gervasoni, 2001). Therefore, our research questions are 1) if an early digital numeracy intervention, *Clever Together*, is beneficial for children, and 2) whether intervention efficacy differs for children born small for gestational age and for children born late preterm, compared to children with normal weight for their gestational age and children born at term. In line with Merkelbach et al. (2018), we hypothesized that children born small for gestational age would not benefit exceptionally more from this digital early numeracy intervention compared to their late preterm peers and in comparison, to their normal weight and term-born peers.

We assessed the efficacy of a digital early numeracy program promoting visual spatial skill: Clever Together in children born late preterm, children small for gestational age, and children without mild perinatal adversities. In Clever Together, in accordance with Living Letters, scaffolding is used to teach basic academic skills. Clever Together consists of short early numeracy or visual spatial ability games which are repeated several times creating a highly structured digital learning environment for children in the same way as Living Letters. In addition, Clever Together includes digital tutors that offer the child continuous and adaptive feedback, and high levels of guidance and explanation. Clever Together highly resembles Living Letters in terms of substantive features, as well as in design (e.g., the same digital tutors), duration and dosage (10 minutes, once a week for two to 3 months). Duration, dosage, and teacher involvement were thus also limited in Clever Together, thereby offering a possible time- and cost-effective solution for supporting vulnerable children. In addition, in some schools there is a high concentration of students with learning difficulties. Those schools are more likely to experience teacher shortages, which can lead to a decline in the quality of education in those schools, increasing inequality in education opportunities. A well-designed digital intervention that helps students with learning difficulties has the potential to have a large reach and can thus contribute to reducing differences (Dondorp and Pijpers, 2020).

# MATERIALS AND METHODS

## Design

We evaluated the benefits of a digital program targeting visual spatial skill, Clever Together using an experimental design. The experiment was based on an intervention which took place in two separate cohorts (2012/2013 and 2013/2014). Kindergartners were preselected by their teachers for showing early numeracy delays. After receiving parental consent these children were randomly assigned to either the experimental condition (Clever Together) or to the control condition which consisted of a digital book-reading program (Living Books). Pre- and post-testing of early numeracy skills took place as part of the regular monitoring system applied in Dutch kindergarten classrooms, with a standardized numeracy test (national Cito evaluation) administered group wise by the teacher, blind for the hypotheses of the study, in January/February of the second kindergarten year and in May/June, just preceding first grade of primary school. Testing in January/February preceded the intervention. The test in May/June was administered directly after the intervention. The design was evaluated and approved by the Ethics Committee of the Institute of Education and Child Studies at Leiden University (file ID: ECPW-2012/044).

## Procedure

A total of 1750 randomly selected schools throughout the Netherlands received an email about the study and were invited to participate. Additional information about the educational computer programs was provided through a website, leaflets, letters and personal contact. Schools were offered 3 months of free access to educational computer programs that normally require a paid subscription (http://www.bereslim.nl) for all pupils, after completion of the intervention. A final set of 140 schools signed up for participation.

Parents provided informed written consent and their email address. Parents received a link to a website with information and frequently asked questions about the project. In case of further questions, they could directly contact the researchers (via phone or email). In the first cohort, parental consent for retrieving perinatal information was not a condition for participating in the study and parents were asked for this specific consent after the intervention was completed. This largely (67.7%) explains the high rate of missing perinatal data in this wave. In the second cohort, in effort to counter the high rates of missing data, consent for perinatal information was included as a condition for participation in the study. This resulted in a much lower total rate (31.7%) of missing data, of which a large part (20.1 out of 31.7%) was due to matching errors between the registry and the research database.

Children worked with the assigned program once a week during two to 3 months. Variability in intervention duration was the result of the number of days off or holidays that fell in the intervention period. Also, the adaptive nature of the program resulted in small differences in the number of sessions offered to the child. The program was completed when children finished all offered games. Children were offered a maximum amount of games each week, making sure, the amount of games were spread out equally and could not be completed in a short period of time. Children who made no mistakes worked faster to consecutive levels of the program than children who made one or more mistakes. The "dosage" in the current study was the same as was used in previous studies (e.g. Van der Kooy-Hofland et al., 2012; Plak et al., 2016). Children independently played the games in a classroom setting only receiving adult assistance for logging in. They wore headphones to prevent that the program would attract and distract other children. Teachers merely logged children on, and hence could not influence the assignment procedure.

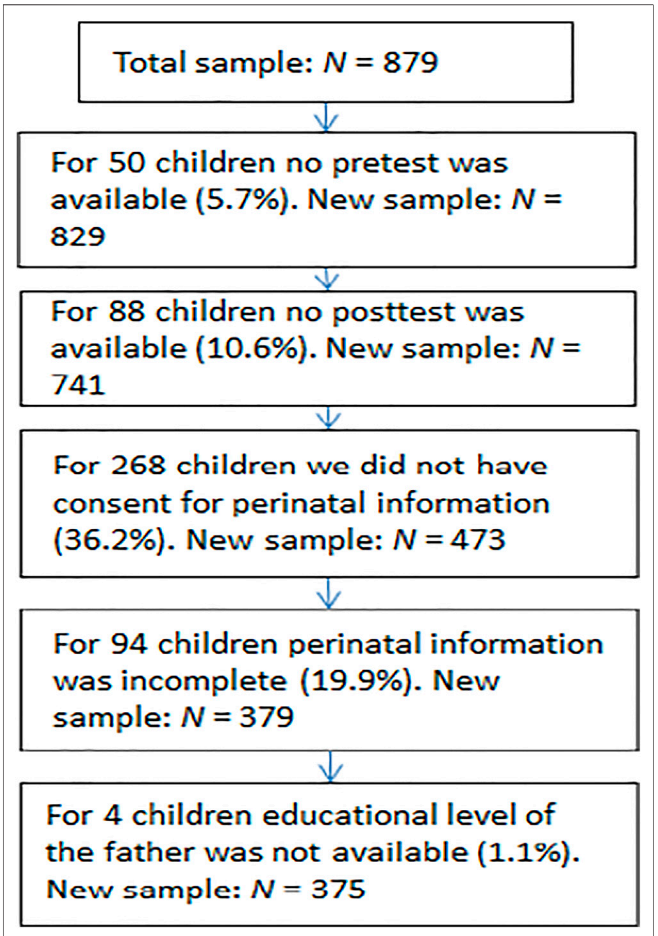



**FIGURE 1** | Flowchart from initial to final participant inclusion.

## Participants

A total of 879 children from kindergarten classrooms of 140 elementary schools, both urban and rural, located across the Netherlands, were initially included in the trial. Children were on average 67.02 months old (*SD* = 4.46).

Children's age (in months), gender, and the educational level of the father were assessed. Following the rationale of Van der Kooy-Hofland et al. (2012) on the strong association between educational level of the father and mild perinatal adversities (as compared to educational level of the mother–also in this study the association was stronger), we used father's educational level instead of that of the mother. The gender and the date of birth of the child were reported by the teacher of the child. The educational level of the father was reported by the parent(s) on a 7-point scale (ranging from no education to university degree or higher).

Children were excluded when there was no consent from the mother to retrieve perinatal information from the national perinatal

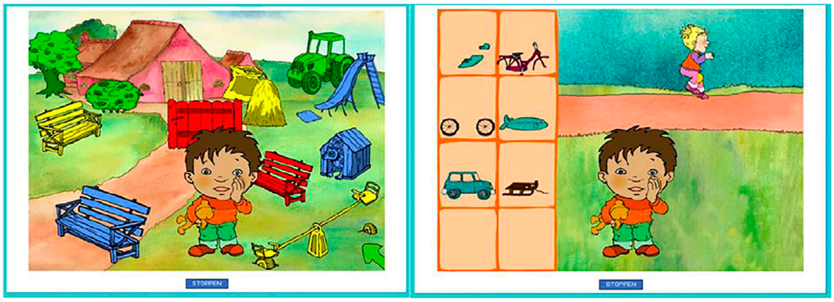


**FIGURE 2 |** Clever Together games: Find Sanne who is hiding behind one of the objects (left) or assemble an object from different parts (right).

registry ($n$ = 266), in case of missing data on the numeracy pretest ($n$ = 50) or numeracy posttest ($n$ = 88), or if the information provided by parents (home address and date of birth of the mother) was incomplete and we were therefore unable to retrieve perinatal information from the registry ($n$ = 96). Lastly, children were excluded when information about the educational level of the father ($n$ = 4) was lacking, for all other covariates data were complete. The final sample for whom data on all study variables were available therefore consisted of 375 children (**Figure 1**). Given the large final sample ($N$ = 375) and the stability of the percentage of perinatal adversities, it was reasonable to assume that random assignment by the researcher would result in a comparable number of children born late preterm and small for gestational age between conditions (Late preterm: Experimental = 10.1%, Control = 11.2%, Small for gestational age: Experimental = 27.4%, Control = 23.0%).

In the final complete case sample of $N$ = 375, $n$ = 179 children were in the experimental condition and $n$ = 196 in the control condition. In the incomplete sample of $N$ = 613 with consent there were $n$ = 294 children were in the experimental condition and $n$ = 319 in the control condition. For explicit comparison, analyses were performed on both the final listwise complete sample ($n$ = 375) and the maximum incomplete sample for whom consent was available ($n$ = 613), after multiple imputation.

## Intervention Programs

***Clever Together*** The program mainly targets visual spatial skills–e.g., recognizing shapes, positions, and measures-, problem solving -e.g., hide and seek games in different situations (the park, the living room and at the farm)- strategies for task approach (Sanne depicts an action -e.g., scootering-in which the right objects have to be searched for by the child), and -although to a lesser extent-numbers -e.g., counting from one to ten. In line with the literature we expect these skills to be foundational for the development of numeracy and mathematics (Kyttälä et al., 2003; Bower et al., 2020; Nahdi et al., 2020). The program Clever Together requires children to mentally visualize, transform, and manipulate objects or scenes with the help of spatial mathematical language (e.g., "in," "behind"). Sim, one of the main characters in the game, asked the child for help in finding Sanne who is hiding behind one of the objects in the illustration (e.g., "I am going to hide behind the blue tree"). In the other 30 games (**Figure 2**), children had to assemble objects (e.g., a bike) from their parts (e.g., tires, frame, steering wheel), and select attributes for an activity (e.g., taking a shower), thereby practicing with spatial prepositions (e.g., "in," "behind").

In the program, a tutor in the form of a teddy bear provided adaptive feedback in a positive and supportive manner. In case of errors a hierarchical set of replies dependent on the child's response was provided including spatial language feedback when giving hints or explaining the correct answer (see **Figure 3**). Spatial language feedback has been shown to help young children attend to and encode spatial information (Pruden et al., 2011). Moreover, assignments that were not answered correctly at a first try were repeated in later sessions followed by similar adaptive feedback loops to create several opportunities for practicing difficult assignments. When children made many mistakes, this could result in them having to complete one or more extra sessions. This way we offered all children comparable learning opportunities, focusing on equity instead of equality (that is practice until they mastered the skill at hand). However, because assignments were of a basic level, addition of extra practice sessions was highly exceptional.

***Control condition*** The control program Living Books not aimed at promoting numeracy skills, consisted of eight digital, age-appropriate, multimedia storybooks with oral text, each read twice. In each individual digital storybook the story text matched the nonverbal, film-like information including animated pictures, music, and sounds. Each storybook was interrupted four times by digital tutors for questions about difficult words that appeared in the text or about story events, followed by a similar set of hierarchical replies as is offered in Clever Together. However, in this program the questions and answers section only occupied a small part of the session, about 10% of the total duration, while in Clever Together assignments were the main part of the program. The questions and answers did not contain spatial language.

## Measures

### Cito Numeracy Skills

The Cito Numeracy Test for Kindergarten Pupils (CNT) is a group-administered standardized numeracy test for kindergarten children orally presented by the teachers in January/February and May/June in the senior year of kindergarten when children were five to 6 years of age (Koerhuis and Keuning, 2011). The psychometric properties of the test has been judged satisfactory by a national independent committee that evaluates test construction, quality of materials, norms, reliability and construct validity (COTAN, 2011). The test

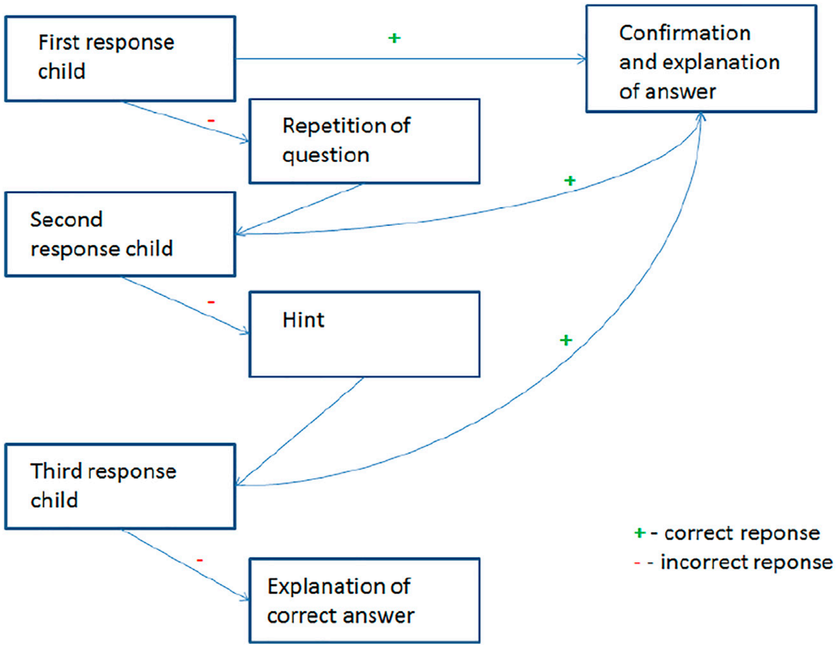



**FIGURE 3 |** Feedback circle in Clever Together.

targets three domains of emergent numeracy and consists of 48 multiple-choice items consisting of three or four answer options in picture-format to choose from: 1. Numbers (i.e. non- and symbolic number knowledge, counting-, organizing-, comparing skills, nonverbal addition and subtraction), 2. Measurement (length, circumference, content, area, time, weight), and 3. Geometry (shape identification, rotation, shape assembly). Teachers scored the test by counting the number of correct responses which were then translated into normative scores, as described in (Frans et al., 2021). Based on these normative scores, the pretest score of the CNT January/February was dichotomized and coded into the 40th percentile or lower (i.e., below average, raw score <78), and average and above (raw score ≥78). At posttest the full range of scores on the CNT May/June was used. Versions of the CNT administered in January/February and the CNT administered in May/June were similar in content and design (derived and matched from the same item pool), but included different items to prevent learning effects (48 items in each version of the test).

## Perinatal Data

Netherlands Perinatal Registry (Centraal Bureau voor de Statistiek, 2013) combines data about duration of pregnancy and weight of the child at birth from three registries: the national obstetric database by midwives, the national obstetric database by gynecologists, and the national neonatal/pediatric database (Méray et al., 2007) and covers about 96% of all pregnancies in the Netherlands.

Duration of pregnancy was dichotomized into being born full term (0) or being born late preterm 1) which was defined as a gestational age at birth of 34–37 weeks +6 days, in concurrence with Van der Kooy-Hofland et al. (2012). Our target sample did not include children born very preterm. Small for gestational age was dichotomized into "not small for gestational age at birth" (0) and "small for gestational age at birth" (1), which was defined as lower than the 10th percentile of birth weight for gestational age, considering gender and parity.

## Statistical Analyses

Scores on the Cito Numeracy Test at posttest as a dependent measure were regressed on the intervention status, late preterm birth and small for gestational age (coded as dummy variables), and the interactions between late preterm birth and intervention, and small for gestational age and intervention. For both susceptibility markers a dummy variable was created. Children could thus be in both groups, as was the case for two children. Group variance imbalances was evaluated through inspection of the residual distribution across the full predictor and outcome range; normality and homoscedasticity.

All main variables were compared between the experimental and control group using *t*-tests and $\chi^2$ tests. As the total amount of missing data was high (57.3%) we followed Little (1986) MCAR $\chi^2$ test procedure to see if data are presumably Missing Completely At Random by testing if the missingness (*missing* = 0 vs *present* = 1) was unrelated to characteristics on other variables and therefore allowing for complete cases analyses. To answer the research questions, multilevel regression models were estimated, twice. First, the model was estimated using the selected complete cases. The second estimation was based on datasets resulting from multiple imputation (MI) approach (Enders et al., 2020). Using MI, missing values were imputed ($m$ = 100 sets) via chained equations. Imputation methods were specified separately

**TABLE 1 |** Percentages, means and standard deviations for all main variables, presented for the complete group of children with complete cases and for the experimental (Clever Together) and control conditions (Living Books); *p*-values for $\chi^2$ or Student's t-test.

| | Total complete group (*N* = 375) | Experimental condition (*n* = 179) | Control condition (*n* = 196) | *p*-value |
|---|---|---|---|---|
| Male[a] | 54.9% | 55.3% | 54.6% | .889 |
| Age (in months) | 67.12 (*4.50*) | 67.58 (*4.64*) | 66.70 (*4.33*) | .060 |
| Father's education[b] | 3.74 (*1.50*) | 3.72 (*1.50*) | 3.77 (*1.51*) | .774 |
| Late preterm (1)[c] | 10.7% | 10.1% | 11.2% | .714 |
| Late preterm (2)[d] | 3.7% | 3.9% | 3.6% | .863 |
| SfGA[e] | 25.1% | 27.4% | 23.0% | .324 |
| CNT pretest[f] | 78.67 (*10.30*) | 79.54 (*11.44*) | 77.88 (*9.09*) | .123 |
| CNT posttest[f] | 87.09 (12.03) | 88.05 (12.87) | 86.22 (11.18) | .145 |
| Delayed children | 45.3% | 40.8% | 49.5% | .091 |

*Note: presentation in means (standard deviation) or percetage (%).*
*[a]Male compared to Female.*
*[b]Maximum level of 6*
*[c]VDK, 2012: Defiition according to Van der Kooy-Hofland et al. (2012).*
*[D]WHO: World health organization.*
*[e]SfGA: small for gestational age.*
*[f]CNT: cito numeracy test.*

per variable, including predictive mean matching, linear and logistic regression and random forests where appropriate. The imputation scheme includes all model variables and appropriate two-way interactions. In this second set, estimates of parameters and standard errors from the multilevel regression model were pooled over imputed datasets to obtain robust parameter point estimates, with potentially increased standard errors to account for multiple estimation of missing information (Van Ginkel et al., 2020). Lastly, to assess robustness of results, estimates and standard errors obtained from the multilevel regression model were compared between the two approaches (complete case and MI). Considerable differences could signal that results derived from complete case analysis might have been biased.

# RESULTS

## Missing Data

Based on Little's MCAR test (1986), we could not reject the null hypothesis, which means that data were missing completely at random ($\chi^2$ (9) = .08, $p$ = .777). Complete case analysis can thus be assumed to lead to unbiased results under a correctly specified model.

## Sample Characteristics

Sample characteristics for the complete case selection ($N$ = 375) are presented in **Table 1** (see **Supplementary Table S1** for the full consenting sample with incomplete information). A small majority of children was male (54.9%), in accordance with the general finding that more boys than girls are delayed in the early years of schooling (Gurian, 2010). Following the definition of late preterm birth by Van der Kooy-Hofland et al. (2012), 40 children (10.7%) were born late preterm. Following the WHO definition of late preterm birth between 34 and 36 weeks and 6 days, 13 children (3.7%) were born late preterm. In total 94 children were born small for gestational age (25.1%).

**Table 2** shows the mean Cito Numeracy Test scores at posttest, standardized on the full sample, presented per experimental condition. Scores are presented separately for late versus full term children, small for gestational age versus normal for gestational age, and for the final sample as a whole.

**TABLE 2 |** Means and Standard Deviations for standardized numeracy post-tests by condition and mild perinatal adversities, based on the complete final sample (n = 375).

| Cito numeracy posttest (standardized) | | | | | | |
|---|---|---|---|---|---|---|
| Group | Experimental condition[a] | | | Control condition[b] | | |
| | *Mean* | *SD* | *n* | *Mean* | *SD* | *n* |
| Full term | .04 | 1.05 | 161 | -.04 | .93 | 174 |
| Late Preterm (VDK 2012)[c] | .43 | 1.26 | 18 | -.33 | .88 | 22 |
| Late Preterm (WHO)[d] | .23 | 1.93 | 7 | -.23 | 1.93 | 7 |
| Not SfGA[e] | .05 | .97 | 130 | -.11 | .87 | 151 |
| SfGA | .16 | 1.30 | 49 | .04 | 1.11 | 45 |
| Total | .08 | 1.07 | 179 | -.07 | .93 | 196 |

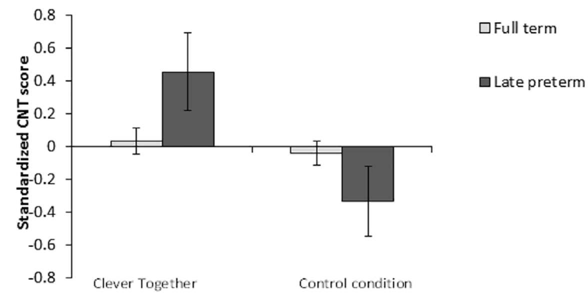
*[a]Experimental condition: Clever Together.*
*[b]Control condition: Living Books.*
*[c]VDK, 2012: Defiition according to Van der Kooy-Hofland et al. (2012).*
*[d]WHO: World health organization.*
*[e]SfGA: small for gestational age.*
*Effects of Clever Together.*

The Cito Numeracy posttest scores (June) were regressed on dichotomized Cito Numeracy pretest scores, preterm status (late preterm versus full term), size for gestational age (small versus normal), and the two-way interactions: late preterm * condition, and small for gestational age * condition. Variance Inflation Factors for all predictors ranged between 1.01 and 2.45. This is widely considered as low inflation (Akinwande et al., 2015), and thus strongly suggests absence of multicollinearity. Therefore, no further action was taken in the model estimations. Next, we tested if it was necessary to allow the intercept and slope to differ between schools in the regression model (Bickel, 2007). The Intra Class Coefficient of the intercept-only model was .12. The difference between the -2log likelihood of the model with a random intercept and the -2log likelihood of the model without a random intercept equaled .94. Following a $\chi^2$ distribution with one

**TABLE 3 |** Cito Numeracy scores at posttest, regressed on Cito numeracy scores pretest, experimental condition, preterm status, size for gestational age, and interactions between conditions and mild perinatal adversities. Results are presented for complete cases (N = 375), nested in 140 schools.

| Measure* | *β* | *SE* | *p*-value |
|---|---|---|---|
| Intercept (fixed effect) | 78.94 | (1.9053) | <.001 |
| Intercept variance (random effect) | 1.39 | 1.179 | *NA* |
| Random effect residual variance | 97.31 | 9.87 | *NA* |
| *Main effects (fixed)* | | | |
| Cohort[a] | -1.55 | 1.14 | .175 |
| Cito Numeracy pretest[b] | 13.45 | 1.04 | <.001 |
| Experimental condition[c] | .15 | 1.24 | .902 |
| Preterm status[d] | -3.29 | 2.27 | .148 |
| Size for gestational age[e] | .95 | 1.71 | .577 |
| *Two-way interaction* | | | |
| Late preterm* Condition | 7.83 | 3.35 | .019 |
| Small for gestational age* Condition | -1.44 | 2.38 | .547 |

**Fixed effects after adjustment for random intercept at school level. No random slopes were estimated.*
[a]*Cohort 2012/2013 compared to 2013/2014.*
[b]*Cohort 2012/2013 compared to 2013/2014.*
[c]*Control (0) compared to Intervention (1).*
[d]*Term born (0) compared to Late Preterm born.*
[e]*Normal (0) compared to Small for Gestational Age.*




*$N_{full\ term/Clever\ Together}$ = 161; $N_{preterm/Clever\ Together}$ = 18; $N_{full\ term/Control}$ = 174; $N_{preterm/Control}$ = 22.*

**FIGURE 4 |** Adjusted, standardized mean scores on the standardized CNT posttest for children born late preterm versus full term assigned to the experimental condition or the control condition.

degree of freedom, this difference was not significant ($p$ > .10). This indicates that variability in scores on the numeracy test administered after the intervention was similar across schools and intervention slopes are similar across as well, therefore we fitted a multilevel model with nesting within schools for increased precision, but we do not interpret the variance at the school level any further. The fixed effects are interpreted as non-hierarchical ordinary least squares (OLS). All main analyses were performed using the definition for late preterm birth by Van der Kooy-Hofland et al. (2012). Group assignment based on the WHO definition yielded insufficient power to perform the current statistical significance tests. Explicit adjustment for group size imbalance was not performed, even though group sizes for gestational age groups and preterm birth groups are imbalanced, since the assumptions of residual normality was not violated, which is an indication of nonbiased estimations. Furthermore, the assumption of residual homoscedasticity was not violated, indicating equivalent precision in all groups.

Results are presented in **Table 3**. The CNT pretest ($t$ (373) = 12.89, $p$ <.001) showed a main effect, children with an average or above score on the pretest scored higher than children with a below average score on the pretest. No main effects were found for late preterm birth ($t$ (373) = −1.45, $p$ = .148) and small for gestational age ($t$ (373) = 0.558, $p$ = .577). There was no significant interaction between small for gestational age * condition ($t$ (373) = −0.06, $p$ = .547), however the interaction, born late preterm * condition was significant ($t$ (373) = 2.34), $p$ = .019). Children born late preterm scored higher on the posttest than their peers when working with Clever Together but lagged further behind with Living Books, the control condition (see **Figure 4**). Four CLT scores were outliers (more than three SDs above the sample mean). The variance of the random intercept at school level ($\sigma^2_{\text{intercept}}$ = 1.39) was not significant ($SD_{\text{random intercept variance}}$ = 1.18).

Repetition of the analysis using MI yielded highly similar results and thus similar substantive conclusions indicating that results derived from complete case analysis were not biased. Estimates were highly comparable across all parameters (**Supplementary Table S2**). The nonsignificant effect for cohort remained non-significant, but was less negative (closer to zero). The adjustment effect for pretest provided the same estimate and remained significant. The effect of the experimental condition switched direction from positive to slightly negative, which showed that the intervention was not effective in the larger sample after imputation either. The estimate for preterm status became less negative but remained nonsignificant. The estimate for gestational age * condition became less negative, and also remained nonsignificant. The estimate for the interaction between preterm status and condition became slightly smaller (from 7.83 to 6.52) but remained significant. As the multiply imputed datasets are generally less biased compared to complete case analysis (van Ginkel et al., 2020), but models fitted on both types of datasets yielded exactly the same interpretations, we conclude that the results and interpretations are robust.

Estimates obtained using the late preterm birth definition by WHO yielded equivalent point estimates and direction for the association but were underpowered and thus yielded nonsignificant results. For completeness, these results are presented in **Supplementary Table S3** (complete cases) and S4 (multiply imputed data).

Effect sizes of the intervention were calculated for the group as a whole and separately for children born late preterm and children born full term (**Table 4**). For the group as a whole, a small, non-significant, positive effect of Clever Together on numeracy skills at the end of senior kindergarten year was found (Cohen's $d$ = .15, CI = −.05/.35). In the group born full term, the effect size was close to zero (Cohen's $d$ = .08, CI = −.13/ .30). However, Clever Together produced a large effect in the late preterm group (Cohen's $d$ = .71, CI = .07/1.36).

## DISCUSSION

We investigated if children with mild perinatal adversities were susceptible to a digital intervention in the domain of numeracy. A

**TABLE 4 |** Effect sizes of Clever Together for the complete group, children born late preterm and children born full term separately.

| Cito numeracy posttest | | | | |
|---|---|---|---|---|
| **Dataset** | **Group** | ***n*** | **Cohen's *d*** | **95% CI** |
| Complete sample*($N$ = 375) | Full term | 335 | .08 | -.13/.30 |
| | Late preterm | 40 | .71 | .07/1.36 |
| | Total group | 375 | .15 | -.05/.35 |

scaffolding and adaptive approach characterized the mainly visual spatial skills' training offered by the program. Late preterm children attending kindergarten, are generally at risk for developing academic delays (Chyi et al., 2008), but on the other hand were found to be highly susceptible to a digital early literacy intervention with the same scaffolding and adaptive approach (Living Letters) (Merkelbach et al., 2018). In line with these results we expected late preterm children also to benefit when the same didactic approach was applied in an intervention in the numeracy domain, another known area of difficulty for this group. We thus tested the hypothesis that children born late preterm need structured scaffolding, that is characterized by repetition, adaptive feedback and guidance irrespective of the domain of learning (literacy or numeracy). Children born small for gestational age and children without mild perinatal adversities were however not expected to benefit. In some studies increased susceptibility in the entire group with mild perinatal adversities is suggested (Van der Kooy-Hofland et al., 2012). However, in later research only the late preterm group is identified as susceptible (Merkelbach et al., 2018), while there was no difference in response between the children small for gestational age and the children without perinatal adversities.

Results offer support for our hypotheses: neither a main effect nor an interaction between small for gestational age and condition was found, while late preterm children clearly benefitted from working with the program (Cohen's $d$ = .71, CI = .07/1.36). Consistent with the differential susceptibility model (Belsky and Pluess, 2009), when assigned to the control condition, late preterm children fell behind as compared to their peers, while they outperformed their peers after having worked with Clever Together.

Key scaffolding characteristics (repetition, structure, guidance, and adaptive feedback) of both Clever Together and Living Letters seem to meet the educational needs of late preterm children particularly well. We hypothesize that these key scaffolding characteristics facilitate learning in late preterm children. A positive effect of these scaffolding characteristics on especially late preterm as compared to small for gestational size children could be explained by the association between specifically preterm birth and increased levels of maternal stress during pregnancy (Mulder et al., 2002; Dole et al., 2003), which in turn is predictive for increased levels of fearfulness (Pike, 2005) and stress reactivity (Meaney, 2001) in offspring. These characteristics could be expressed as performance- and test anxiety, which are known to have detrimental effects on school performance (McDonald, 2001). In schools differentiated instruction by the teacher that meets the needs of all children is challenging (Suprayogi et al., 2017). Late preterm children might fall behind, possibly due to increased levels of stress reactivity which might cause children to shut themselves from learning experiences (Van der Kooy-Hofland et al., 2012). In the digital program Clever Together however, the scaffolding given through repetition, structure, feedback, and guidance central to the program help clarify the task at hand. Task clarity lowers levels of experienced stress (Richter and Gendolla, 2006). The key scaffolding characteristics of Clever Together (and Living Letters) could thus result in lower levels of stress through providing high levels of clarity and predictability, thereby facilitating learning. In addition, since late preterm birth is associated with for example lower SES (Gardosi and Francis, 2005), these adaptive and supportive educational programs may compensate for a possibly suboptimal learning environment in the home setting. Lack of resources in the home environment interfere with the development of academic skills (Aalders et al., 2020). More research is needed to identify which exact features support the learning of late preterm children as well as through which mechanisms.

We replicated the finding by Merkelbach et al. (2018) that children with mild perinatal adversities are a heterogeneous population with different educational needs; children small for gestational age did not benefit from the intervention. In their review Vollmer and Edmonds (2019) conclude that although they may experience problems with attention, children term born small for gestational age are not hugely impacted by the fact that they are born small for gestational age. Late preterm birth seems to contribute more consistently to the presence of educational delays. Children small for gestational age might not have specific educational needs that need to be addressed in order to thrive. Perhaps they might benefit from different interventions, not specifically targeting scaffolding and potential stress reduction.

## Strengths and Limitations

Unavoidably, this study has some limitations. It should be noted that the studies looking into effects of Living Letters (Merkelbach et al., 2018) and Clever Together (current study) are not completely independent. This could be seen as limitation, since in both studies the same control condition was used, thus including largely the same sample of children. However, this approach also allowed for the evaluation of scaffolding in different domains in the same children.

Additionally, teachers selected children based on early literacy delays instead of numeracy problems. Children with literacy delays, thus experience problems in both domains. In line with the literature (e.g., see Davidse et al., 2014; Peng et al., 2020; Purpura et al., 2011) literacy- and numeracy skills of children in this study were highly correlated (in total sample: $r$ = .589, $p$ <.001). However, children might differ from children who only experience problems in the field of numeracy. Additionally, we can only speculate about effective functionalities in Clever Together and mechanisms explaining this effectivity.

Interestingly, although using the late preterm birth definition (34–37 weeks + 6) as in Van der Kooy-Hofland et al. (2012) study yielded a larger number of children classified as born late preterm, compared to the WHO definition (34–36 weeks + 6), the magnitude of the associated parameter estimates was equivalent in both definitions. Since the WHO classification yielded a smaller group, thus lower power, the parameters were not indicated as statistically significant. However, the equivalence of both sets of parameter estimates could be interpreted as evidence for a robust differentially susceptible mechanism via late preterm birth, regardless of its precise definition.

Although details of the Clever Together numeracy intervention require further study, we can conclude that children born late preterm, a vulnerable group, can benefit from this intervention, preventing them from falling behind further in a cost- and time-effective fashion. Findings confirm that intervening in this group is crucial to reduce inequality in education opportunities.

### Future Directions

This study offers strong evidence of increased susceptibility to the educational environment in children born late preterm. Future research should focus on unraveling mechanisms underlying this increased susceptibility. Insight into underlying mechanisms leads to opportunities to adapt existing interventions to the needs of different target groups. Additionally, future research might benefit from the identification of more vulnerable subgroups showing increased susceptibility to the learning environment.

## CONCLUSION

Merkelbach et al. (2018) showed that kindergartners born late preterm are more susceptible to their educational environment than term born control children when learning literacy skills. With the current study these results are expanded to the domain of numeracy. The digital intervention Clever Together boosted the early numeracy performance of kindergartners born late preterm, while children born small for gestational age, or born at term, do not benefit from this intervention. On the other hand, late preterm children fall behind when assigned to a control condition, following the pattern as described by the differential susceptibility model. This pattern does not hold for children born small for gestational age, and aligns with the findings in this group when offering a digital literacy intervention as was done by Merkelbach et al. (2018). As a possible explanation for the effectivity of Clever Together in preterm children we expect that scaffolding via structure, guidance, and feedback provided by this program offer an optimal learning environment for this group. The findings also underline the importance of well-designed early interventions not only to reduce inequality in education achievement but to give susceptible children a head start.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, upon request, without undue reservation.

## ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethics Committee Institute of Education and Child Studies—Leiden University file ID: ECPW-2012/044. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

## AUTHOR CONTRIBUTIONS

IM, RP, and RR were involved in the study design. IM and RR were involved in the statistical analyses. IM, RP, MS-dJ, and RR were involved in the discussion on the manuscript and in writing the manuscript.

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## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feduc.2022.709809/full#supplementary-material

## REFERENCES

Aalders, P., van Langen, A. M. L., Smits, K., van den Tillaart, D., and Wolbers, M. H. J. (2020). PISA-2018 De Verdieping: Kansenongelijkheid in Het Voortgezet Onderwijs. Nijmegen: KBA Nijmegen. Available at: https://hdl.handle.net/2066/227137.

Akinwande, M. O., Dikko, H. G., and Samson, A. (2015). Variance Inflation Factor: As a Condition for the Inclusion of Suppressor Variable(s) in Regression Analysis. *Ojs* 05 (07), 754–767. doi:10.4236/ojs.2015.57075

Assel, M. A., Landry, S. H., Swank, P., Smith, K. E., and Steelman, L. M. (2003). Precursors to Mathematical Skills: Examining the Roles of Visual-Spatial Skills, Executive Processes, and Parenting Factors. *Appl. Dev. Sci.* 7, 27–38. doi:10.1207/s1532480xads0701_3

Barnes, M. A., and Raghubar, K. P. (2014). Mathematics Development and Difficulties: the Role of Visual-Spatial Perception and Other Cognitive Skills. *Pediatr. Blood Cancer* 61 (10), 1729–1733. doi:10.1002/pbc.24909

Belsky, J., and Pluess, M. (2009). Beyond Diathesis Stress: Differential Susceptibility to Environmental Influences. *Psychol. Bull.* 135 (6), 885–908. doi:10.1037/a0017376

Bickel, R. (2007). *Multilevel Analysis for Applied Research It's Just Regression!*. New York: The Guilford Press.

Bower, C., Zimmermann, L., Verdine, B., Toub, T. S., Islam, S., Foster, L., et al. (2020). Piecing Together the Role of a Spatial Assembly Intervention in Preschoolers' Spatial and Mathematics Learning: Influences of Gesture, Spatial Language, and Socioeconomic Status. *Dev. Psychol.* 56 (4), 686–698. doi:10.1037/dev0000899

Bull, R., Espy, K. A., and Wiebe, S. A. (2008). Short-term Memory, Working Memory, and Executive Functioning in Preschoolers: Longitudinal Predictors of Mathematical Achievement at Age 7 Years. *Dev. Neuropsychol.* 33, 205–228. doi:10.1080/87565640801982312

Centraal Bureau voor de Statistiek (2013). *Documentatierapport Perinatale Registratie (PRN)*.

Chyi, L. J., Lee, H. C., Hintz, S. R., Gould, J. B., and Sutcliffe, T. L. (2008). School Outcomes of Late Preterm Infants: Special Needs and Challenges for Infants Born at 32 to 36 Weeks Gestation. *J. Pediatr.* 153 (1), 25–31. doi:10.1016/j.jpeds.2008.01.027

Cirino, P. T. (2011). The Interrelationships of Mathematical Precursors in Kindergarten. *J. Exp. Child. Psychol.* 108, 713–733. doi:10.1016/j.jecp.2010.11.004

COTAN (2011). *Toelichting bij de beoordeling Rekenen voor Kleuter Groep 1 en 2 LOVS Cito [Commentary on the Assessment of Mathematics for Preschoolers and Kindergarteners LOVS Cito]*. Amsterdam: NIP.

Davidse, N. J., De Jong, M. T., and Bus, A. G. (2014). Explaining Common Variance Shared by Early Numeracy and Literacy. *Read. Writ* 27 (4), 631–648. doi:10.1007/s11145-013-9465-0

Desoete, A., Ceulemans, A., De Weerdt, F., and Pieters, S. (2010). Can We Predict Mathematical Learning Disabilities from Symbolic and Non-symbolic Comparison Tasks in Kindergarten? Findings from a Longitudinal Study. *Br. J. Educ. Psychol.* 82 (1), 64–81. doi:10.1348/2044-8279.002002

Dole, N., Savitz, D. A., Hertz-Picciotto, I., Siega-Riz, A. M., McMahon, M. J., and Buekens, P. (2003). Maternal Stress and Preterm Birth. *Am. J. Epidemiol.* 157 (1), 14–24. doi:10.1093/aje/kwf176

Dondorp, l., and Pijpers, R. (2020). *Gelijke kansen en digitalisering? Goede toegang is niet genoeg. [Equal opportunities and digitalization? Good access is not sufficient*. Kennisnet: Zoetermeer.

Elango, S., García, J. L., and Heckman, J. J. (2016). "Andrés Hojman. Early Childhood Education," in *Economics of Means-Tested Transfer Programs in the United States*. Editor R. A. Moffitt (University of Chicago Press), 235–298.

Enders, C. K., Du, H., and Keller, B. T. (2020). A Model-Based Imputation Procedure for Multilevel Regression Models with Random Coefficients, Interaction Effects, and Nonlinear Terms. *Psychol. Methods* 25 (1), 88–112. doi:10.1037/met0000228

Frans, N., Post, W., Oenema-Mostert, I., and Minnaert, A. (2021). Defining and Evaluating Stability in Early Years Assessment. *Int. J. Res. Method Edu.* 44 (2), 151–163. doi:10.1080/1743727X.2020.1736024

Gardosi, J., Kady, S. M., McGeown, P., Francis, A., and Tonks, A. (2005). Classification of Stillbirth by Relevant Condition at Death (ReCoDe): Population Based Cohort Study. *Bmj* 331 (7525), 1113–1117. doi:10.1136/bmj.38629.587639.7C

Gervasoni, A. (2001). "Special Programs for Children Who Are Low Attaining in Mathematics: Do They Help," in 24th Annual MERGA conference.

Gonzalez, M. R., Palmer, C. E., Uban, K. A., Jernigan, T. L., Thompson, W. K., and Sowell, E. R. (2020). Positive Economic, Psychosocial, and Physiological Ecologies Predict Brain Structure and Cognitive Performance in 9-10-Year-Old Children. *Front. Hum. Neurosci.* 14, 578822. doi:10.3389/fnhum.2020.578822

Gurian, M. (2010). *Boys and Girls Learn Differently! A Guide for Teachers and Parents*. San Fransisco: Jossey-Bass.

Ho, L. Y. (2018). Follow-Up Care and Outcome Evaluation of High-Risk Preterm Infants: A Life-Course Commitment. *Annals of the Academy of Medicine, Singapore* 47 (2), 51–55.

Jin, J. H., Yoon, S. W., Song, J., Kim, S. W., and Chung, H. J. (2019). Long-term Cognitive, Executive, and Behavioral Outcomes of Moderate and Late Preterm at School Age. *Clin. Exp. Pediatr.* 63 (6), 219–225. doi:10.3345/kjp.2019.00647

Kelly, M. M., and Li, K. (2019). Poverty, Toxic Stress, and Education in Children Born Preterm. *Nurs. Res.* 68 (4), 275–284. doi:10.1097/NNR.0000000000000360

Koerhuis, I., and Keuning, J. (2011). *Wetenschappelijke verantwoording van de toetsen rekenen voor kleuters*. Arnhem: Cito.

Kyttälä, M., Aunio, P., LehtoVan Luit, J. E. J., and Hautamäki, J. (2003). Visual Spatial Working Memory and Early Numeracy. *Educ. Child Psychol.* 20 (3), 65–76.

Labayru, G., Aliri, J., Santos, A., Arrizabalaga, A., Estevez, M., Cancela, V., et al. (2021). Small for Gestational Age Moderate to Late Preterm Children: A Neuropsychological Follow-Up. *Dev. Neuropsychol.* 28, 1–11. doi:10.1080/87565641.2021.1939349

Larroque, B., Bertrais, S., Czernichow, P., and Léger, J. (2001). School difficulties in 20-Year-Olds Who Were Born Small for Gestational Age at Term in a Regional Cohort Study. *Pediatrics* 108 (1), 111–115. doi:10.1542/peds.108.1.111

LeFevre, J. A., Fast, L., Skwarchuk, S. L., Smith-Chant, B. L., Bisanz, J., Kamawar, D., et al. (2010). Pathways to Mathematics: Longitudinal Predictors of Performance. *Child. Dev.* 81, 1753–1767. doi:10.1111/j.1467-8624.2010.01508.x

Little, R. J. A. (1986). Survey Nonresponse Adjustments for Estimates of Means. *Int. Stat. Rev./Revue Internationale de Statistique* 54 (2), 139–157. doi:10.2307/1403140

Martínez-Nadal, S., and Bosch, L. (2021). Cognitive and Learning Outcomes in Late Preterm Infants at School Age: A Systematic Review. *Ijerph* 18 (1), 74. doi:10.3390/ijerph18010074

McDonald, A. S. (2001). The Prevalence and Effects of Test Anxiety in School Children. *Educ. Psychol.* 21 (1), 89–101. doi:10.1080/01443410020019867

Meaney, M. J. (2001). Maternal Care, Gene Expression, and the Transmission of Individual Differences in Stress Reactivity across Generations. *Annu. Rev. Neurosci.* 24 (1), 1161–1192. doi:10.1146/annurev.neuro.24.1.1161

Méray, N., Reitsma, J. B., Ravelli, A. C., and Bonsel, G. J. (2007). Probabilistic Record Linkage Is a Valid and Transparent Tool to Combine Databases without a Patient Identification Number. *J. Clin. Epidemiol.* 60 (9), 883–891. doi:10.1016/j.jclinepi.2006.11.021

Merkelbach, I., Plak, R. D., and Rippe, R. C. A. (2018). Reproducibility of Young Learners' Susceptibility to the Learning Context. *Learn. Individual Differences* 65, 167–175. doi:10.1016/j.lindif.2018.05.020

Mulder, E. J., Robles de Medina, P. G., Huizink, A. C., Van den Bergh, B. R., Buitelaar, J. K., and Visser, G. H. (2002). Prenatal Maternal Stress: Effects on Pregnancy and the (Unborn) Child. *Early Hum. Dev.* 70 (1-2), 3–14. doi:10.1016/S0378-3782(02)00075-0

Nahdĭ, D. S., Jatĭsunda, M. G., Cahyanĭngsĭh, U., and Sucĭawatĭ, V. (2020). Pre-service Teacher's Ability in Solving Mathematics Problem Viewed from Numeracy Literacy Skills. *ilkogretim Online* 19 (4), 1902–1910. doi:10.17051/ilkonline.2020.762541

Nepomnyaschy, L., Hegyi, T., Ostfeld, B. M., and Reichman, N. E. (2012). Developmental Outcomes of Late-Preterm Infants at 2 and 4 Years. *Matern. Child. Health J.* 16 (8), 1612–1624. doi:10.1007/s10995-011-0853-2

O'Keeffe, M. J., O'Callaghan, M., Williams, G. M., Najman, J. M., and Bor, W. (2003). Learning, Cognitive, and Attentional Problems in Adolescents Born Small for Gestational Age. *Pediatrics* 112 (2), 301–307. doi:10.1542/peds.112.2.301

Paz, I., Gale, R., Laor, A., Danon, Y. L., Stevenson, D. K., and Seidman, D. S. (1995). The Cognitive Outcome of Full-Term Small for Gestational Age Infants at Late Adolescence. *Obstet. Gynecol.* 85 (3), 452–456. doi:10.1016/0029-7844(94)00430-L

Peng, P., Lin, X., Ünal, Z. E., Lee, K., Namkung, J., Chow, J., et al. (2020). Examining the Mutual Relations between Language and Mathematics: A Meta-Analysis. *Psychol. Bull.* 146 (7), 595–634. doi:10.1037/bul0000231

Pike, I. L. (2005). Maternal Stress and Fetal Responses: Evolutionary Perspectives on Preterm Delivery. *Am. J. Hum. Biol.* 17 (1), 55–65. doi:10.1002/ajhb.20093

Plak, R. D., Merkelbach, I., Kegel, C. A. T., van IJzendoorn, M. H., and Bus, A. G. (2016). Brief Computer Interventions Enhance Emergent Academic Skills in Susceptible Children: A Gene-By-Environment experiment. *Learn. Instruction* 45, 1–8. doi:10.1016/j.learninstruc.2016.06.002

Poulsen, G., Wolke, D., Kurinczuk, J. J., Boyle, E. M., Field, D., Alfirevic, Z., et al. (2013). Gestational Age and Cognitive Ability in Early Childhood: a Population-Based Cohort Study. *Paediatr. Perinat Epidemiol.* 27 (4), 371–379. doi:10.1111/ppe.12058

Pruden, S. M., Levine, S. C., and Huttenlocher, J. (2011). Children's Spatial Thinking: Does Talk about the Spatial World Matter? *Dev. Sci.*, 14, 1417–1430. doi:10.1111/j.1467-7687.2011.01088.x

Purpura, D. J., Hume, L. E., Sims, D. M., and Lonigan, C. J. (2011). Early Literacy and Early Numeracy: The Value of Including Early Literacy Skills in the Prediction of Numeracy Development. *J. Exp. Child. Psychol.* 110 (4), 647–658. doi:10.1016/j.jecp.2011.07.004

Raghubar, K. P., Barnes, M. A., and Hecht, S. A. (2010). Working Memory and Mathematics: A Review of Developmental, Individual Difference, and Cognitive Approaches. *Learn. Individual Differences* 20, 110–122. doi:10.1016/j.lindif.2009.10.005

Reid, K., and Andrews, N. (2016). *Fostering Understanding of Early Numeracy Development*. Melbourne, Victoria, Australia: Australian Council for Educational Research.

Richter, M., and Gendolla, G. H. (2006). Incentive Effects on Cardiovascular Reactivity in Active Coping with Unclear Task Difficulty. *Int. J. Psychophysiol* 61 (2), 216–225. doi:10.1016/j.ijpsycho.2005.10.003

Searle, A. K., Smithers, L. G., Chittleborough, C. R., Gregory, T. A., and Lynch, J. W. (2017). Gestational Age and School Achievement: a Population Study. *Arch. Dis. Child. Fetal Neonatal. Ed.* 102 (5), F409–F416. doi:10.1136/archdischild-2016-310950

Shah, P., Kaciroti, N., Richards, B., Oh, W., and Lumeng, J. C. (2016). Developmental Outcomes of Late Preterm Infants from Infancy to Kindergarten. *Pediatrics* 138 (2), 1–10. doi:10.1542/peds.2015-3496

Sommerfelt, K., Andersson, H. W., Sonnander, K., Ahlsten, G., Ellertsen, B., Markestad, T., et al. (2000). Cognitive Development of Term Small for Gestational Age Children at Five Years of Age. *Arch. Dis. Child.* 83 (1), 25–30. doi:10.1136/adc.83.1.25

Suprayogi, M. N., Valcke, M., and Godwin, R. R. (2017). Teachers and Their Implementation of Differentiated Instruction in the Classroom. *Teach. Teach. Edu.* 67, 291–301. doi:10.1016/j.tate.2017.06.020

Thompson, D. K., Kelly, C. E., Chen, J., Beare, R., Alexander, B., Seal, M. L., et al. (2019). Early Life Predictors of Brain Development at Term-Equivalent Age in Infants Born across the Gestational Age Spectrum. *Neuroimage* 185, 813–824. doi:10.1016/j.neuroimage.2018.04.031

Van der Kooy-Hofland, V. A. C., Van der Kooy, J., Bus, A. G., Van IJzendoorn, M. H., and Bonsel, G. J. (2012). Differential Susceptibility to Early Literacy Intervention in Children with Mild Perinatal Adversities: Short- and Long-Term Effects of a Randomized Control Trial. *J. Educ. Psychol.* 104 (2), 337–349. doi:10.1037/a0026984

van Ginkel, J. R., Linting, M., Rippe, R. C. A., and van der Voort, A. (2020). Rebutting Existing Misconceptions about Multiple Imputation as a Method for Handling Missing Data. *J. Pers Assess.* 102 (3), 297–308. doi:10.1080/00223891.2018.1530680

Vollmer, B., and Edmonds, C. J. (2019). School Age Neurological and Cognitive Outcomes of Fetal Growth Retardation or Small for Gestational Age Birth Weight. *Front. Endocrinol. (Lausanne)* 10, 186. doi:10.3389/fendo.2019.00186

Walsh, J. M., Doyle, L. W., Anderson, P. J., Lee, K. J., and Cheong, J. L. (2014). Moderate and Late Preterm Birth: Effect on Brain Size and Maturation at Term-Equivalent Age. *Radiology* 273 (1), 232–240. doi:10.1148/radiol.14132410

Windhorst, D. A., Rippe, R. C., Mileva-Seitz, V. R., Verhulst, F. C., Jaddoe, V. W., Noppe, G., et al. (2017). Mild Perinatal Adversities Moderate the Association between Maternal Harsh Parenting and Hair Cortisol: Evidence for Differential Susceptibility. *Dev. Psychobiol* 59 (3), 324–337. doi:10.1002/dev.21497

Woythaler, M., McCormick, M. C., Mao, W. Y., and Smith, V. C. (2015). Late Preterm Infants and Neurodevelopmental Outcomes at Kindergarten. *Pediatrics* 136 (3), 424–431. doi:10.1542/peds.2014-4043

Yang, X., Huo, S., and Zhang, X. (2021). Visual-spatial Skills Contribute to Chinese reading and Arithmetic for Different Reasons: A Three-Wave Longitudinal Study. *J. Exp. Child. Psychol.* 208, 105142. doi:10.1016/j.jecp.2021.105142

Zhang, X., Räsänen, P., Koponen, T., Aunola, K., Lerkkanen, M. K., and Nurmi, J. E. (2017). Knowing, Applying, and Reasoning about Arithmetic: Roles of Domain-General and Numerical Skills in Multiple Domains of Arithmetic Learning. *Dev. Psychol.* 53, 2304–2318. doi:10.1037/dev0000432

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