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Cross-domain associations of key cognitive correlates of early reading and early arithmetic in 5-year-olds

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ABSTRACT

Disabilities in reading and arithmetic often co-occur, but (dis)abilities in reading and arithmetic have mostly been studied in isolation from each other. This study explicitly focused on the co-development of early reading and early arithmetic before primary education. The Multiple Deficit Model was used as theoretical framework (Pennington, 2006). According to this model, the overlap between early reading and early arithmetic is due to a constellation of shared and unique cognitive correlates. Therefore, we investigated whether key cognitive correlates of one academic ability also correlate with the other. Participants were 188 five-year-old kindergartners who had not yet been formally instructed in reading and arithmetic. Phonological awareness was selected as reading-specific cognitive correlate and (non)symbolic numerical magnitude processing and numeral recognition were considered as arithmetic-specific cognitive correlates. We administered a productive letter knowledge task as a proxy of early reading. Early arithmetic was assessed with simple problems such as 2 + 3 =? . Regression analyses and Bayesian hypothesis testing revealed significant correlations between early reading and early arithmetic before children start primary education. Phonological awareness predicted not only early reading but also, early arithmetic, even when controlling for early reading and arithmetic-specific cognitive correlates. Likewise, numeral recognition predicted not only early arithmetic, but also early reading, even when controlling for early arithmetic and phonological awareness. Phonological awareness and numeral recognition can be considered shared cognitive correlates of both academic domains. In contrast, non-symbolic and symbolic numerical magnitude processing skills were specifically correlated to early arithmetic, and not to early reading, indicating that they are unique to only one academic domain. In line with the Multiple Deficit Model, our data suggest that early reading and early arithmetic have a shared as well as unique underlying cognitive basis. Further unravelling what these academic abilities have in common can be of high value for detecting children at risk already before their transition to formal primary education.

1. Introduction

Reading and arithmetic constitute two quintessential building blocks of children's primary education, and they both independently predict educational level and income in later life (Ritchie & Bates, 2013). Disabilities in reading and arithmetic often co-occur (Landerl & Moll, 2010), but (dis)abilities in reading and arithmetic have mostly been studied in isolation from each other. This has resulted in two segregated research domains, and each domain has separately identified cognitive correlates for reading or for arithmetic and their associated learning difficulties. By considering early reading and early arithmetic simultaneously in one sample of 5-year old kindergartners, the present study aimed to explore associations between these academic abilities before children receive formal instruction. On top, we aimed to investigate whether major cognitive correlates of one academic domain also correlate with the other. Associations across academic domains have the potential to unravel cognitive correlates that are shared between reading and arithmetic, which might help us to understand the co-development of both skills (Brock, Kim, & Grissmer, 2018; Cameron, Kim, Duncan, Becker, & McClelland, 2019) as well as the co-occurrence of disabilities in reading and mathematics (Cramer, Waldorp, van der Maas, & Borsboom, 2010).

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1.1. Multiple deficit model as a framework for understanding individual differences

Decades of research on learning (dis)abilities illustrates that being a poor (versus good) reader or arithmetician cannot exclusively be determined by one single underlying cognitive deficit (versus strength) (Pennington, 2006). Instead, individual differences in reading and arithmetic have been related to a range of cognitive correlates, and likewise, disabilities in these domains to a range of cognitive deficits (De Smedt, Noël, Gilmore, & Ansari, 2013; Melby-Lervåg, Lyster, & Hulme, 2012; Schneider et al., 2017). Multiple cognitive deficits, rather than a single one, are accommodated in the Multiple Deficit Model (Pennington, 2006; van Bergen, van der Leij, & de Jong, 2014). This model provides a useful theoretical framework, especially for the study of developmental disorders' comorbidity, such as the comorbidity between dyslexia (Ozernov-Palchick, Yu, Wang, & Gaab, 2016) and dyscalculia (Willcutt et al., 2013). The premise of this model is that disability must be conceptualized as the lower tail of a normal distribution of ability (Shaywitz, Escobar, Shaywitz, Fletcher, & Mukugh, 1992). This suggests that findings from studies focusing on the lower tail, or hence disability, can be extended to the entire distribution of individual differences, and interestingly, also the other way around. Indeed, phonological awareness, for example, is correlated with reading ability in the full distribution, typically impaired in dyslexic readers, and typically a strength in good readers (Melby-Lervåg et al., 2012). Against this background, we propose that the Multiple Deficit Model is a suitable model not only to investigate the lower tail of the distribution (disability), but also the entire distribution of ability (individual differences). Hence, the word 'deficit' in Multiple Deficit Model might as well be replaced by 'strength'. The present study will use the Multiple Deficit (or Strength?) Model to investigate the co-development of individual differences in reading and arithmetic.

The Multiple Deficit Model, as previously described in the context of dyslexia (Pennington, 2006; van Bergen, van der Leij et al., 2014), posits that a learning disability is caused by multiple deficits at several levels. Etiological risk factors (that is, genetic and environmental risk factors) manifest themselves probabilistically through deficits at the neural and cognitive levels; the same goes for protective etiological factors that manifest themselves probabilistically as strengths higher up. Importantly, the model does not specify for a certain combination of (dis)abilities which factors are at play. More specifically, it remains to be investigated which factors contribute to the associations between reading and arithmetic development, and which contribute to their dissociation. The overall goal of this study was to concretize the cognitive level of the Multiple Deficit Model by investigating emergent literacy and numeracy jointly.

1.2. Co-development of early reading and early arithmetic

Behavioral studies have found an overlap between (dis)abilities in reading and arithmetic, but correlations and comorbidity rates are far from unity (Landerl & Moll, 2010; Shalev, 2007; Simmons & Singleton, 2008). Measures of reading and arithmetic correlate at all ages, but the size of their correlation coefficients varies across studies (i.e., van Bergen, 2013: $r = .49$ for 7-year-olds; van Bergen, de Jong, Maassen, & van der Leij, 2014: $r = .45$ for 8-year-olds; Vanbinst, Ansari, Ghesquière, & De Smedt, 2016: $r = .32$ for 8-year-olds, but $r = .42$ for the same group of children at age 9). Research on the comorbidity between disabilities in reading and mathematics (Landerl & Moll, 2010; Willcutt et al., 2013) has demonstrated that in children with reading disabilities, the prevalence of mathematical disabilities varies between 17% and 70%; in children with mathematical disabilities, the prevalence of reading disabilities varies between 11% and 56%. And even in the absence of comorbidity, children with reading disabilities typically show lower arithmetic performance (Boets & De Smedt, 2010; Moll, Göbel, & Snowling, 2015) and children with mathematical disabilities perform lower on reading decoding tasks (Vanbinst, Ghesquière, & De Smedt, 2014). These data suggest that reading and arithmetic have a shared as well as unique underlying (cognitive) basis.

According to the Multiple Deficit Model the overlap between (dis)abilities in reading and arithmetic is due to a constellation of shared and unique factors, at each level of analysis. The etiological level includes genetic and environmental factors. Behavioral-genetic studies have shown that the genetic influences on reading and the genetic influences on arithmetic correlate about 0.70 (Krapohl et al., 2014; Mascheretti et al., 2017; Plomin & Kovas, 2005). Kovas and Plomin (2007) termed the overlapping genetic influences "generalist genes". The genetic basis that is shared lies at the basis of developing competence in both reading and arithmetic, while the genetic basis that is unique contributes to the dissociation between these academic abilities (Davis et al., 2014; Rimfeld, Kovas, Dale, & Plomin, 2015). The same behavioral-genetic studies also have shown that some influences of the environment are shared and some are unique. Note that behavioral-genetic studies quantify but do not identify genetic and environmental influences. These genetic and environmental influences are reflected through (dis)abilities at the neural and cognitive level.

At the neural level, brain imaging data on reading versus arithmetic suggest overlapping neural networks with shared activations in subsections of the left temporo-parietal cortex, including the left angular and supramarginal gyri (Peters & De Smedt, 2018; Schlaggar & McCandliss, 2007). Two recently published studies contrasted groups of children with learning disabilities (reading disabilities, mathematical disabilities, comorbid reading/mathematical disabilities) and surprisingly observed more neural similarities than differences between these groups (Moreau, Wilson, McKaya, Nihillc, & Waldie, 2018; Peters, Bulthé, Daniels, Op de Beeck, & De Smedt, 2018). Peters et al. (2018) observed for instance higher activation levels in frontal and parietal areas in typically developing children compared to children with learning disabilities, who did not differ from each other regardless of differences in their type of learning disability.

At the cognitive level, individual differences in either reading or arithmetic have been related to specific cognitive correlates. Studies on reading have found that phonological awareness, or the conscious sensitivity to the sound structure of oral language, is a major cognitive correlate of individual differences in learning to read (Melby-Lervåg et al., 2012) and is a key cognitive cause of disabilities in reading (Snowling, 2000). Phonological deficits at an early age have also been associated with having a familial history of reading problems (Snowling & Melby-Lervåg, 2016). Interestingly, phonological awareness, generally considered to be a reading-specific cognitive correlate, has also been associated with individual differences in arithmetic (Bull & Johnston, 1997; De Smedt, Taylor, Archibald, & Ansari, 2010; Fuchs et al., 2005), in particular with people's ability to rely on arithmetic facts (De Smedt, 2018). Hecht et al. (2001) even demonstrated that phonological awareness predicts arithmetic development throughout primary education. The observation that phonological awareness not only contributes to children's reading development, but also to their development in arithmetic, challenges most previous studies that solely focused on reading or arithmetic separately but did not consider them simultaneously.

The prediction of arithmetic ability is a much more recent research topic but there is now converging evidence that numerical magnitude processing skills, or people's elementary intuitions about quantity and their ability to understand the numerical meaning of Arabic numerals (that they represent quantity), are associated with individual differences in arithmetic, and this at all ages (Schneider et al., 2017). Numerical magnitude processing skills are typically investigated by means of comparison tasks, presented in symbolic (Arabic numerals) or non-symbolic (dots) formats, in which people have to identify the larger of two numerical magnitudes. The respective roles of non-symbolic versus symbolic numerical magnitude processing skills remain a source of debate. Both skills have, however, been associated with arithmetic performance (Schneider et al., 2017) and deficits in both have been observed in children with mathematical disabilities (Schwenk et al., 2017). To perform adequately on a symbolic comparison task, it is indispensable that children have to start with the correct and rapid identification of each presented Arabic numerical symbol, before a decision can be made on selecting the larger one (Merkley & Ansari, 2016). Indeed, Purpura et al. (2013) revealed that numeral recognition skills fully mediated the longitudinal association between preschool math abilities of 3- to 5-year-olds and their future mathematical knowledge. Relatedly, Göbel, Watson, Lervåg, and Hulme, (2014) found that knowledge of Arabic numerical symbols at age 6 predicted children's acquisition of arithmetic in early primary education, over and above these children's (non-)symbolic numerical magnitude processing skills. In all, this body of research suggests that the knowledge of Arabic numerical symbols as well as numerical magnitude processing skills are important determinants of arithmetic competence. Against this background, we decided to include a numeral recognition task together with a non-symbolic and a symbolic comparison task in our design. These measures allowed us to explore whether these cognitive correlates appeared important for early arithmetic as well as early reading.

1.3. Study goals

The current study will focus on the underlying cognitive basis of early reading and early arithmetic and test whether cognitive correlates of either reading or arithmetic are shared between these academic domains or unique to one academic domain. The present study had three main goals. First, we aimed to investigate correlations between early reading and early arithmetic, in order to explore whether these academic abilities are already intertwined before the start of primary education. Against the studies reviewed above, we expected to find a significant correlation between early reading and early arithmetic. Because kindergartners in Belgium (where our study was set) cannot yet decode words but do know some letters (Torppa, Poikkeus, & Laakso, 2006; Vandermosten, Cuynen, Vanderauwera, Wouters, & Ghesquière, 2017), we administered a productive letter knowledge task as a proxy of early reading ability. Many kindergartners are able to solve basic arithmetic problems such as 2 + 1 before receiving formal instruction (Jordan, Kaplan, Olah, & Locuniak, 2006; Jordan, Huttenlocher, & Levine, 1994) and therefore we asked our participants to solve basic additions and subtractions.

The second goal was to explore whether cognitive abilities that are known to predict (future) individual differences in reading or arithmetic, also correlate with the other academic domain. In view of the Multiple Deficit Model for atypical development, we expected to observe cross-domain associations to occur. It is well established that phonological awareness correlates with reading ability (Melby-Lervåg et al., 2012; Swanson, Trainin, Necoechea, & Hammill, 2003) and therefore, phonological awareness was selected as reading-specific cognitive correlate. Concerning the prediction of individual differences in arithmetic ability, previous studies have emphasized the importance of children's numerical magnitude processing skills (Schneider et al., 2017) and their knowledge of Arabic numerals for learning formal competencies in mathematics (Göbel et al., 2014; Merkley & Ansari, 2016). Therefore non-symbolic and symbolic numerical magnitude processing as well as numeral recognition were considered as arithmetic-specific cognitive correlates.

The third goal of this study was to investigate the domain-specificity of cognitive correlates of research and arithmetic. By controlling for the other academic skill, and consequently taking into account the reading-arithmetic overlap, we aimed to explore whether early reading and early arithmetic share underlying cognitive correlates. For instance, if phonological awareness predicts early arithmetic over and beyond early reading, then phonological awareness is a shared cognitive correlate. If not, then phonological awareness is a cognitive correlate specific to early reading. The same rationale will be used to explore whether key domain-specific cognitive correlates of future arithmetic are associated with early reading.

By addressing the three study goals described above, this study tried to explore whether individual differences in early reading and early arithmetic are already intertwined before the start of formal schooling and whether this overlap is inter alia driven by a shared cognitive basis.

2. Method

2.1. Participants

Participants were 188 kindergartners (101 girls, 87 boys) from seven different schools. It is important to keep in mind that in Flanders (Belgium), parents can freely choose the school of their child and education is fully subsidized by the government. This implies that the quality of kindergarten is controlled by the government, providing guidelines to schools what they should focus on in their curriculum. As a result, 98% of all Flemish children start noncompulsory government subsidized Kindergarten at the age of 30 months, where they participate in play-based preparatory academic learning activities. Children enter compulsory primary education in September of the year they turn 6 years old. Formal education only starts in primary education, meaning that none of the participants of the current study had yet received formal reading and arithmetic instruction. All participating kindergartners were native Dutch speakers, with an average age of 5 years and 7 months (*SD* = 3 months). They came from middle- to upper-middle-class families. None of the participants had a history of intellectual disability, no child was at the time of assessment diagnosed with an autism spectrum disorder, an attention-deficit/hyperactivity disorder or a learning disorder, such as dyslexia or dyscalculia. Parents of all participants received an information sheet about the study and provided written informed consent for their child. Given the age of our participants, kindergartners did not sign written consent but they all gave verbal agreement before undertaking the different experiments and tasks. The study and consent procedures were approved by the Social and Societal Ethics Committee of the University of Leuven, Belgium (G-2016 03 533).

2.2. Materials

2.2.1. Academic abilities

2.2.1.1. Early reading. As a proxy of early reading, we administered a productive letter knowledge task that was previously used in children of the same age group from the same country (Vandermosten et al., 2017). Kindergartners had to name the 16 most frequently used Latin letters in Dutch books (a, d, u, r, g, v, l, h, k, e, s, m, o, n, i, t), one by one. Each correctly identified letter was rewarded with one point. The reliability of this task was .90.

2.2.1.2. Early arithmetic. Kindergartners' early arithmetic was assessed with a task consisting of basic addition and subtraction problems (Jordan, Kaplan, Nabors Oláh, & Locuniak, 2006). The problems were presented with symbolic representations such as 3 + 2, but they were also read aloud as follows: “How much is 3 and 2?” and “How much is 7 take away 3?”. The task consisted of two practice items (1 + 1, 2 – 1) and eight problems (3 – 1, 2 + 4, 6 – 4, 4 + 3, 2 + 1, 5 – 2, 3 + 2, 7 – 3), with sums and minuends of seven or less. Participants received one point for each correctly solved problem. The reliability of this test was 0.84.

2.2.2. Cognitive correlates

2.2.2.1. Phonological awareness. Phonological awareness was assessed with *end-rhyme* and *end-phoneme* identification tasks (de Jong, Seveke, & van Veen, 2000). Each task consisted of 12 items. Each item consisted of a pictured object that was pronounced out loud (high frequent one-syllable Dutch word), followed by a row of five pictures presented and also verbalized by the experimenter. The child had to point to one of the five pictures that contained the same end-rhyme or end-phoneme as the first given one-syllable Dutch word. Task performance was assessed by the number of correct answers and the scores on the two identification tasks were converted into one composite score for phonological awareness (see Boets et al., 2010, for more details). The reliability of the end rhyme task was 0.69 and of the end phoneme task was .63.

2.2.2.2. Non-symbolic numerical magnitude processing. Non-symbolic numerical magnitude processing skills were measured with a comparison task in which kindergartners had to indicate the larger of two presented dot arrays (Vanbinst, Ceulemans, Peters, Ghesquière, & De Smedt, 2018). The number of dots per array varied from 1 to 9. A trial started with a 200 ms fixation point in the center of the screen. The dot arrays were generated with the MATLAB script provided by Piazza et al. (2004) and they were controlled for non-numerical parameters, such as dot size, total occupied area and density. The dot arrays appeared after 1000 ms and disappeared again after 840 ms, to avoid counting the number of dots. A total of 36 trials were presented to the participants, each trial being initiated by the experimenter. Kindergartners were instructed to perform both accurately and quickly, and to press a stickered key on the side of the larger dot array (D for the left and K for the right). Answers were registered by the computer. Task performance was the overall accuracy. To familiarize participants with the key assignments, three practice trials were included per task. The reliability of this task was .57.

2.2.2.3. Symbolic numerical magnitude processing. Symbolic numerical magnitude processing skills were measured with a comparison task that was the same as the non-symbolic numerical magnitude processing, except that the dot arrays were replaced by Arabic numerals, ranging from 1 to 9. The trial sequence was the same as in the non-symbolic comparison task, except that the stimuli remained visible until response. Task performance was the overall accuracy and three practice trials preceded the task. The reliability of this task was .67.

2.2.2.4. Numeral recognition. A numeral recognition task was used to examine whether kindergartners can already recognize Arabic numerals consisting of single-digits as well as more complex numerals that consisted of multiple digits (Bakker, Torbeyns, Wijns, Verschaffel, & De Smedt, 2018). Single-digits were randomly presented and kindergartners were asked to name each numeral (2 – 1 – 4; 3–7 – 6 ; 5–9 – 8). Subsequently, a series of complex numerals were presented and participants were asked to name these. The complex numerals were presented in blocks of increasing difficulty (10–17 – 13; 11–14 – 18; 31 – 26 – 45; 27–56 – 80; 107–164 – 270; 1007–1052 – 3204; 90,080 – 15,029 – 24,356). We applied a stopping rule and the task was terminated if a child made three consecutive errors. Each correctly recognized (single and complex) numeral was rewarded with one point and total accuracy was used to indicate performance. The reliability of this task was 0.92.

2.2.3. Controlling variables

To get an indication of kindergartners' intellectual ability, we administered the Matrix Reasoning subtest of the Dutch Wechsler Intelligence Scale for Children, Third Edition (WISC-III-NL; Wechsler, 2011). This allowed us to investigate whether a common reliance on intellectual ability could explain the expected associations between early reading and early arithmetic.

2.3. Procedure

All kindergartners were individually tested in a silent room at their own school. Tasks were always administered in the same order as follows: symbolic comparison, productive letter knowledge, arithmetic, end-phoneme identification, non-symbolic comparison, numeral recognition, end-rhyme identification, matrix reasoning. Tasks were alternated with funny movement exercises after a set of three tasks. Kindergartners were for example asked to ‘march as a soldier’, ‘wobble like a penguin’, ‘swim as a fish’, ‘jump as a frog’, etc., together with the experimenter. The duration of the test session varied between 25 to 35 min.

3. Results

3.1. Descriptive statistics

Descriptive statistics are presented in Table 1. All measures were well-distributed, with no floor or ceiling effects. Large individual differences exist in early reading as well as early arithmetic at this stage, as evidenced by the large standard deviations (relative to the means) for both academic abilities.

3.2. Correlations

We applied both Frequentist and Bayesian approaches in our statistical analyses (For a similar approach, see Bellon, Fias, & De Smedt, 2019). Concretely, Pearson correlation coefficients as well as Bayes factors (BF_{10}) were calculated to examine correlations between all variables via the JASP 0.8.4.0 software (JASP Team, 2018). The recommendations of Andraszewicz et al. (2015) were used to interpret the evidential strength of the Bayes factors (BF_{10} between 0–3 anecdotal support for a correlation; between 3–10 moderate support; between 10–30 strong support; between 30–100 very strong support; >100 extremely strong support).

Concerning the first goal of this study. Early reading and early arithmetic were already correlated before formal education (Table 2), and this correlation remained significant also after controlling for effects of age and intellectual ability (Table 3, Step 2).

The second goal of this study was to explore whether key cognitive correlates of one academic domain also correlated with the other (Table 2). Before exploring correlations across academic domains, we first replicated findings within domains. As expected, phonological awareness was correlated with early reading. Similarly, non-symbolic and symbolic numerical magnitude processing as well as numeral recognition were correlated with early arithmetic. Turning to cross-domain correlations, phonological awareness was correlated with early arithmetic. Symbolic numerical magnitude processing and numeral recognition, but not non-symbolic numerical magnitude processing, were correlated with early reading.

Table 1
Descriptive statistics of all measures (n = 188). Please check the presentation of tables for correctness.

	M	*SD*	Min	Max	Theoretical max
Academic abilities					
Early reading (letter knowledge)	6.26	4.70	0	16	16
Early arithmetic	3.40	2.57	0	8	8
Cognitive correlates					
Phonological awareness	15.84	3.97	2	22	24
Non-symbolic numerical magnitude processing	80.69	13.93	11.11	100	100
Symbolic numerical magnitude processing	82.18	16.01	41.67	100	100
Numeral recognition	13.11	5.41	0	29	30
Controlling variables					
Age	68	4	62	75	
Intellectual ability	13.73	4.28	5	26	

Note. Min = minimum; Max = maximum; Age was expressed in months; All measures reflect the number of correctly solved items per task, except for the non-symbolic and symbolic numerical magnitude processing tasks for which we used total % correct.

Table 2
Correlations between all measures (n = 188).

		1	2	3	4	5	6	7	8
1. Early reading (letter knowledge)	r	–							
	BF_1O	–							
2. Early arithmetic	r	0.465***	–						
	BF_1O	4.734e +8	–						
3. Phonological awareness	r	0.568***	0.489***	–					
	BF_1O	3.421e +14	7.393e +9	–					
4. Non-symbolic NMP	r	0.140	0.264***	0.155*	–				
	BF_1O	0.558	70	0.862	–				
5. Symbolic NMP	r	0.228**	0.294***	0.213**	0.201**	–			
	BF_1O	12	374	7	4	–			
6. Numeral recognition	r	0.548***	0.533***	0.374***	0.260***	0.445***	–		
	BF_1O	1.723e +13	2.105e +12	99,297	58	6.305e +7	–		
7. Age	r	0.044	0.312***	0.152*	0.258***	0.253***	0.185*		
	BF_1O	0.109	1161	1	52	40	2		
8. Intellectual ability	r	0.286***	0.433***	0.386***	0.132	0.070	0.321***	0.288***	–
	BF_1O	230	1.762e +7	248,422	0.462	0.143	2056	269	–

Note. NMP = Numerical Magnitude Processing. r = Pearson correlation coefficients. * $p < .05$. ** $p < .01$. *** $p < .001$. BF_1O = Bayes factor in support of alternative hypothesis over null hypothesis. BF_1O between 0–3 anecdotal support for a correlation. BF_1O between 3–10 moderate support for a correlation. BF_1O between 10–30 strong support for a correlation. BF_1O between 30–100 very strong support for a correlation. BF_1O > 100 extremely strong support for a correlation.

Table 3
Regression analyses predicting early reading and early arithmetic (n = 188).

	B	*t*	*p*	$BF_{inclusion}$
Early reading				
Step 1				
Age	−.041	−0.563	.574	0.226
Intellectual ability	0.298	4.047	<.001	288
Step 2				
Early arithmetic	0.450	6.167	<.001	2681e+6
Step 3				
Phonological awareness	0.396	6.138	<.001	2724e +6
Non-symbolic numerical magnitude processing	−.017	−0.285	.776	0.184
Symbolic numerical magnitude processing	−.027	−0.430	.668	0.194
Numeral recognition	0.374	5.304	<.001	123,903
Early arithmetic				
Step 1				
Age	0.205	3.029	.003	11.29
Intellectual ability	0.374	5.531	<.001	144,185
Step 2				
Early reading	0.380	6.167	<.001	2901e+6
Step 3				
Phonological awareness	0.208	2.965	.003	14
Non-symbolic numerical magnitude processing	0.076	1.299	.196	0.429
Symbolic numerical magnitude processing	0.038	0.597	.551	0.229
Numeral recognition	0.267	3.594	<.001	385

Note. **Early reading**: Step 1: $F(2187) = 8.388$, $R^2 = .083$, $p < .001$; Step 2: $F(3184) = 22.57$, $R^2 = .269$, $p < .001$; Step 3: $F(7180) = 15.71$, $R^2 = .379$, $p < .001$. **Early arithmetic**: Step 1: $F(2185) = 26.25$, $R^2 = .226$, $p < .001$; Step 2: $F(3184) = 34.23$, $p < .001$, $R^2 = .358$; Step 3: $F(7180) = 21.45$, $R^2 = .455$, $p < .001$.

3.3. Regressions

Step-wise regression models are presented in Table 3. We started by examining whether on top of controlling variables such as age and intellectual ability (Step 1), one academic skill contributed to the other (Step 2). In step 3 we addressed the third goal of this study and tested whether the considered cognitive correlates continued to predict early reading, after controlling for age, intellectual ability and even early arithmetic, and vice versa whether these cognitive correlates continued to predict early arithmetic, when age, intellectual ability and early reading were taken into account.

For each predictor we reported the $BF_{inclusion}$. This type of Bayes Factor reflects the extent to which data support the inclusion of that specific predictor, after taking all other predictors of that model into account. Concretely, a $BF_{inclusion}$ of 10 means that there is 10 times more evidence for the model that includes that predictor than for the model that does not include that predictor.

Table 3 illustrates that the correlation between early reading and early arithmetic holds after controlling for effects of age and intellectual ability (Step 2). Both phonological awareness and numeral recognition predicted a unique amount of variance in early reading as well as early arithmetic, even when taking into account age, intellectual ability and the other academic skill (Step 3). Our results indicated that phonological awareness and numeral recognition uniquely contributed to both early reading and arithmetic above and beyond their strong interconnection.

4. Discussion

This study showed that already before the start of formal education, large individual differences exist between kindergartners in their early reading as well as early arithmetic. On top, these academic abilities were already correlated in Kindergarten. Note that we defined early reading as knowledge of letters as kindergartners in our sample have not yet been instructed to read. Phonological awareness and numeral recognition contribute to the association between early reading and early arithmetic. Concretely, phonological awareness predicted not only early reading but also early arithmetic even when controlling for age, intellectual ability, arithmetic-specific cognitive correlates and early reading. Likewise, numeral recognition predicted not only early arithmetic, but also early reading even when controlling for age, intellectual ability, phonological awareness, (non-)symbolic numerical magnitude processing skills and early arithmetic. Phonological awareness and numeral recognition are consequently shared cognitive correlates of both academic domains. In contrast, non-symbolic and symbolic numerical magnitude processing skills were specifically correlated to early arithmetic, and not to early reading, indicating that they are more unique to only one academic domain. Our results highlight that abilities in reading and arithmetic should be investigated together as these academic abilities share cognitive correlates. Carefully unravelling what these academic abilities have in common can be of high value for detecting children at risk already before their transition to formal primary education.

4.1. Phonological awareness

We replicated that phonological awareness is an important cognitive correlate of early reading (Melby-Lervåg et al., 2012) but also found that it is a critical predictor of early arithmetic at the end of kindergarten. This also replicates what has been observed at older ages (Bull & Johnston, 1997; De Smedt et al., 2010; Fuchs et al., 2005; Hecht et al., 2001). Critically, phonological awareness still correlates with early arithmetic after taking into account age, intellectual ability, (non-)symbolic numerical magnitude processing, numeral recognition and early reading ability. Our results show that phonological awareness can be considered a shared cognitive correlate of early reading and early arithmetic. This fits with neuroimaging studies that observed similar neural activations in the left temporo-parietal cortex during reading and arithmetic (Dehaene, Piazza, Pinel, & Cohen, 2003; Schlaggar & McCandliss, 2007). The overlap between early reading and early arithmetic might be explained by a common reliance on phonological codes or an individual's sensitivity to the sound structure of oral language (De Smedt et al., 2010; Koponen, Salmi, Eklund, & Aro, 2013; Robinson, Menchetti, & Torgesen, 2002; Vukovic & Lesaux, 2013). This also matches with the observation that many children with reading disabilities, who typically have deficits in phonological awareness, experience difficulties learning to calculate (Boets & De Smedt, 2010; Simmons & Singleton, 2008). In all, phonological awareness is critical to the development of both reading and arithmetic and, it might constitute a risk factor for developing disabilities in these two academic domains in primary education.

4.2. Numerical magnitude processing

Not surprisingly, non-symbolic and symbolic numerical magnitude processing correlated with early arithmetic. The size of our correlations is in line with the meta-analysis by Schneider et al. (2017) who reported associations of $r = .241$ for non-symbolic numerical magnitude processing and $r = .302$ for symbolic numerical magnitude processing with mathematical competence. Importantly, (non-)symbolic numerical magnitude processing skills were not correlated with early reading, indicating that these skills are somewhat specific to only one academic domain. The dissociation between behavioral measures of reading and arithmetic might partially be driven by (non-)symbolic numerical magnitude processing skills. The letter knowledge task that was assessed for early reading, might be a less complex task than for instance the symbolic comparison task that was used for symbolic numerical magnitude processing. During this comparison task, one first has to identify numerical symbols (analogous to the identification of letter symbols) and only subsequently one can compare the corresponding numerical quantities and decide on the larger one. Our results might be affected by the complexity of the selected tasks, although we selected tasks that have extensively been studied in each academic domain separately and that are age appropriate; as apparently before receiving formal instruction, 5-year olds are able to solve basic arithmetic (Jordan, Kaplan, Nabors Oláh et al., 2006; Jordan, Kaplan, Olah et al., 2006) but cannot yet decode words (Vandermosten et al., 2017; Torppa et al., 2006).

4.3. Numeral recognition

It is interesting to note that when non-symbolic and symbolic numerical magnitude processing skills were considered together with numeral recognition, the latter variable turned out to be the strongest cognitive correlate of early arithmetic. This is in line with Göbel et al. (2014) who observed that early numeral knowledge and not non-symbolic or symbolic numerical magnitude processing skills predicted children's growth in arithmetic during the first years of primary education. The current study adds that numeral knowledge is already associated with early arithmetic before formal schooling in arithmetic. Numerous studies have shown that children's understanding of magnitude is important for learning arithmetic, but their knowledge of Arabic numerals appears at least as crucial, or even more important (Göbel et al., 2014; Krajewski & Schneider, 2009). During the comparison tasks, our 5-year olds were asked to compare the number of dots or Arabic numerals, ranging from 1 to 9. However, in the numerical recognition task, they had to identify not only the same single-digit numerals, as in the comparison tasks, but also complex numerals that consisted of multiple digits. The increased complexity of the numeral recognition task might have affected our results and might explain why it was a stronger predictor of performance than the comparison tasks.

It would therefore be interesting to use a (non-)symbolic numerical magnitude comparison task with numbers that are beyond the single-digit range in future studies to further understand the association between (more complex) numerical magnitude processing and arithmetic.

Numeral recognition did not only predict early arithmetic, but also early reading, even after controlling for age, intellectual ability, phonological awareness and early arithmetic. Why is the ability to recognize (complex) numerals important for both early arithmetic and early reading? For both academic abilities, it is crucial to learn symbolic representations (numerals versus letters) and their corresponding verbal labels. Indeed, the same underlying skills are addressed when identifying numerals and letters (Yeo et al., 2017). The common importance of symbolic representations might thus clarify why the numeral recognition task contributes in this study to both academic abilities. Importantly, identifying (letter) symbols was also precisely what children were asked to do during the early reading task (productive letter knowledge). The numeral recognition task in this study contained not only numerals consisting of single digits such as 5 or 3 (and all other numerals between 1 and 9), but also numerals with multiple digits, such as 17, 164, and 1052. Additional analyses on our data revealed that those kindergartners who scored high on early reading and early arithmetic, were remarkably skilled in correctly naming multi-digit numerals. We argue that children's fluency of naming multi-digit numerals might be affected by their language skills, which in turn might mediate the associations between numeral recognition and early academic abilities. The language for number words of the children in the current study is characterized by an inversion of decades and units. More specifically, the number words do not match with the left-to-right order of multiple digits in numerals: 36 is named as 'six and thirty' and 368 as 'three hundred eight and sixty'. Children learn these language-specific rules of number words without direct instruction (Mix, Prather, Smith, & DaSha, 2014). The inconsistency between number words and position of the digits in a multi-digit number, might also influence children's understanding of place value, namely that 5 in 65 has a different value than the 5 in 58. It remains to be investigated whether the current findings in Dutch can be replicated in another language with more consistency between number words and Arabic numerals, such as English. Research shows that language skills play a crucial role in reading (Dickinson, Golinkoff, & Hirsh-Pasek, 2010; McDonald Connor, 2016; Roth, Speece, & Cooper, 2002) and arithmetic (Purpura & Reid, 2016). Including broader language skills in future studies, can help to explore whether numeral recognition and phonological awareness still correlate with early reading and early arithmetic when language skills are simultaneously taken into account. The overlap between early reading and early arithmetic might be driven by a common reliance on broader language skills, and future studies should further investigate this potentially shared cognitive correlate.

4.4. Associations versus dissociations between early reading and early arithmetic

Early reading and early arithmetic were already correlated before the start of formal education. We found that these academic abilities share underlying cognitive correlates, namely, phonological awareness and numeral recognition. Cognitive correlates that have been considered to be specific to one academic domain in many previous studies, may seem not so domain-specific after all. Cross-domain associations help us to understand what reading and arithmetic have in common. Based on the current findings, we want to highlight the importance of studying these academic abilities together. Researchers focusing on research questions within one specific academic domain can, nevertheless, enrich their research by taking into account (new) scientific insights obtained in the other academic domain.

The association (and simultaneously dissociation) between behavioral measures of reading and arithmetic is driven by a complex combination of genetic and environmental risk factors manifested by shared (and distinct) deficits or strengths at the neural and cognitive levels. We estimate that future studies should additionally explore the contribution of the home as well as school environment when investigating early academic abilities, as activities in this environment might mediate our research findings. This explorative study found shared, i.e. phonological awareness and numeral recognition, but also distinct, i.e. (non-)symbolic numerical magnitude processing skills, cognitive correlates for early reading and early arithmetic in 5-year old kindergartners. Our findings should be considered as a starting point to concretize the Multiple Deficit Model in research on arithmetic, but also in research on the co-development of arithmetic and reading (Cramer et al., 2010; Ozernov-Palchick et al., 2016; van Bergen, van der Leij et al., 2014). Researchers must acknowledge the etiological complexity of individual differences in learning (dis)abilities, and take into account this complexity when designing new studies. We contend that these future studies must continue to dismantle shared as well as distinct cognitive correlates of individual differences in arithmetic and reading. On top, the cognitive development of children should not be studied in a fragmented way, but in a way that takes into consideration that cognitive skills co-develop across time and therefore continuously interact (Brock et al., 2018; Cameron et al., 2019).

For educational practice, our findings underscore that children's development in reading and arithmetic is intertwined and that their progression in these academic abilities should be monitored simultaneously. Knowledge of letters and numerals are important preparatory skills for a fluent transition to formal instruction in reading and arithmetic in early primary education. Educational practitioners, and especially teachers, should remain vigilant when early signals of difficulties arise in one academic domain, as they might also occur in the academic domain.

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