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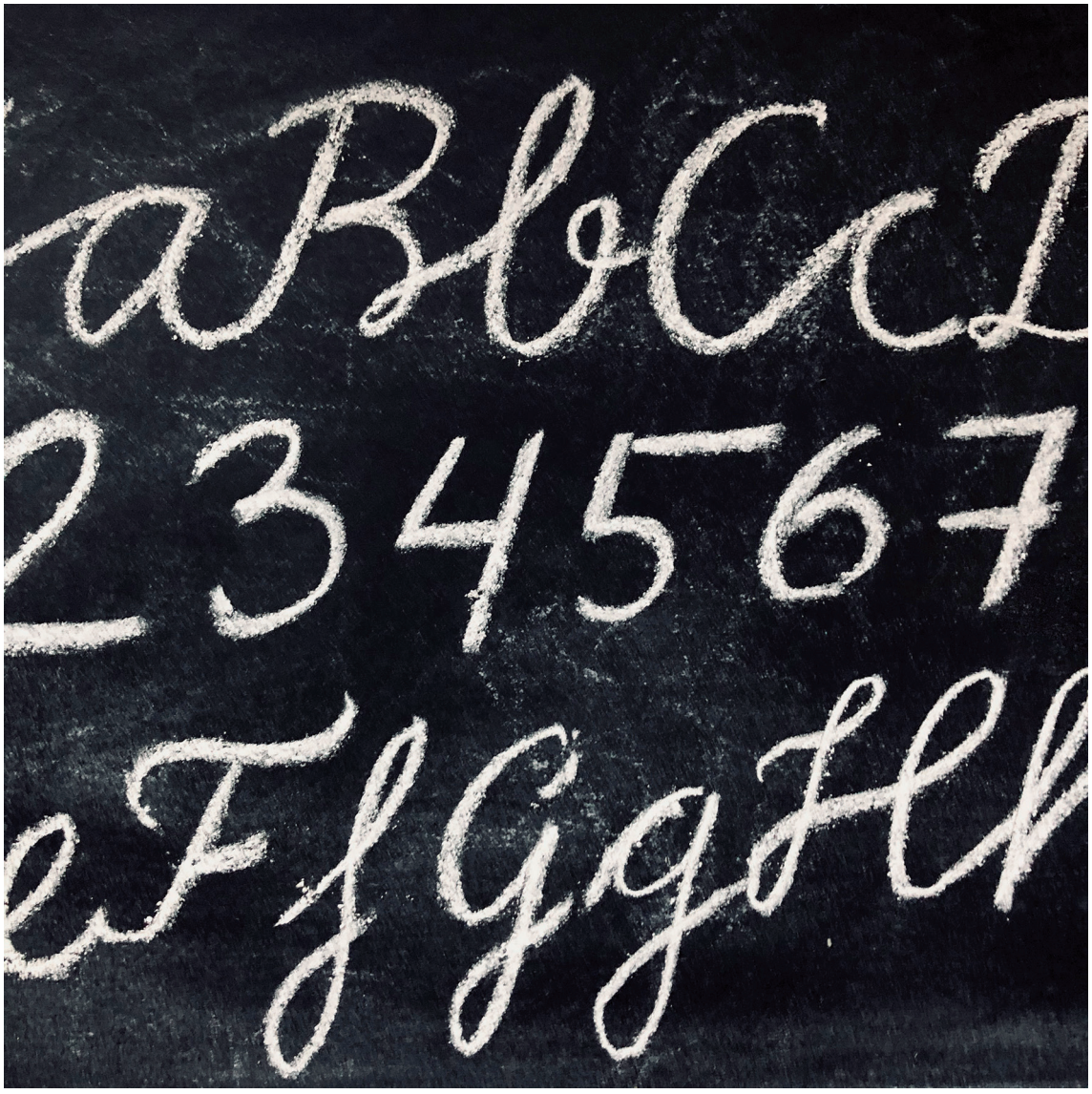
Heidi Korpipää

Overlap between Reading and Arithmetic Skills from Primary to Lower Secondary School and the Underlying Cognitive Mechanisms



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Overlap between Reading and Arithmetic Skills from Primary to Lower Secondary School and the Underlying Cognitive Mechanisms

Esitetään Jyväskylän yliopiston kasvatustieteiden ja psykologian tiedekunnan suostumuksella
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in building Seminarium, old festival hall S212, on January 24th 2020 at 12 o´clock noon.

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ABSTRACT

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Reading and math skills are fundamental for school achievement, and these two basic academic skills have been shown to be strongly related. However, there is a lack of knowledge regarding the longitudinal relationship between reading and arithmetic skills, as well as on the underlying cognitive mechanisms. Investigating the overlap (i.e., shared variance) between reading and arithmetic skills across grade levels can provide valuable information about the development of these skills in relation to each other, which is important in understanding the comorbidity of learning difficulties and in designing more effective interventions. This research aimed to complement the current understanding of the overlap between reading and arithmetic skills with three separate studies. In Study I, an unselected population was used to investigate the extent to which reading and arithmetic skills show overlap in Grades 1 and 7, and the extent to which this overlap is time-invariant, on the one hand, and time-specific, on the other. Furthermore, the study investigated the extent to which different cognitive antecedents, along with parental education, predict the time-invariant and time-specific parts of the overlap. In Study II, a person-oriented approach was applied to complement the variable-oriented research by investigating individual differences in cognitive profiles composed of shared predictors of reading and arithmetic skills. In addition, the relations of these profiles to subsequent reading and arithmetic skills and to the overlap between these skills during primary and lower secondary school were investigated. Finally, Study III focused on the association of prematurity with the overlapping part of reading and arithmetic skills at the beginning of school and the cognitive antecedents explaining this association. Overall, the results revealed that reading and arithmetic skills show substantial overlap across grade levels from primary to lower secondary school, which is predicted mainly by linguistic and basic number skills related to developing fluency in these two domains (Study I). The results showed further that individual variations in patterns of performance exist across linguistic and basic number skills that differentially predict the overlap of subsequent reading and arithmetic skills (Study II). Finally, the results showed that prematurity was negatively associated with the overlapping part of reading and arithmetic skills rather than the unique variation of these skills, and this association was due to the premature children's weaknesses in cognitive antecedents predicting the overlap between reading and arithmetic skills (Study III). In general, the results suggested that reading and arithmetic skills develop in tandem among most of the children due to the partly shared cognitive background; thus, children with difficulties in one domain should be closely monitored for difficulties in the other domain as well.

Keywords: reading, arithmetic, overlap, development, comorbidity, kindergarten, primary school, lower secondary school

TIIVISTELMÄ (FINNISH ABSTRACT)

Korpipää, Heidi
Luku- ja laskutaidon kehityksen päällekkäisyys alakoulusta yläkouluun ja taustalla vaikuttavat kognitiiviset mekanismit
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Luku- ja laskutaidon sujuvuus ovat koulumenestyksen kannalta keskeisiä taitoja. Aikaisemmissa tutkimuksissa näiden taitojen on havaittu olevan melko voimakkaasti yhteydessä toisiinsa, ja luku- ja laskutaidon ongelmien yhteisesiintymisen tiedetään olevan yleistä. Tähän saakka luku- ja laskutaidon kehitystä on kuitenkin tutkittu lähinnä toisistaan erillään, ja tietoa siitä miten voimakkaasti näiden taitojen kehitys on yhteydessä toisiinsa läpi kouluvuosien, ja minkälaiset alkuvalmiudet tai niiden yhdistelmät tätä yhteyttä ennustavat kehityksen eri vaiheissa, on vähän. Tieto luku- ja laskutaidon kehityksen yhteyden pysyvyydestä ja sen ennustajista on tärkeää päällekkäisten oppimisvaikeuksien ennaltaehkäisemiseksi. Tämän tutkimuksen tavoitteena oli kolmen eri osatutkimuksen avulla lisätä ymmärrystä luku- ja laskutaidon kehityksen päällekkäisyydestä ja yhteisestä tiedonkäsittelytaustasta peruskoulun aikana. Ensimmäinen osatutkimus tarkasteli luku- ja laskutaidon päällekkäisyyden pysyvyyttä ja ennustajia (lukemisen ja laskemisen erilaiset alkuvalmiudet, yleisemmät tiedonkäsittelytaidot ja vanhempien koulutus) peruskoulun 1. luokalta 7. luokalle. Toisessa osatutkimuksessa selvitettiin yksilöllisiä eroja lukemisen ja laskemisen alkuvalmiuksien muodostamissa profiileissa sekä näiden profiilien yhteyttä luku- ja laskutaitoon ja näiden taitojen päällekkäisyyteen 1. ja 7. luokalla. Kolmannessa osatutkimuksessa selvitettiin keskosuuden muodostamaa riskiä samanaikaisille luku- ja laskutaidon kehityksen viiveille koulun alkaessa. Tulokset osoittivat, että 1. luokalla n. 40–50% ja 7. luokalla n. 30–35% luku- ja laskutaidossa ilmenevästä vaihtelusta on näille taidoille yhteistä, ja n. 30 % yhteisvaihtelusta on yli ajan 1. luokalta 7. luokalle ilmenevää. Tulokset myös osoittivat, että tämä yhteys selittyy osittain luku- ja laskutaidon yhteisellä tiedonkäsittelytaustalla erityisesti alkuvalmiuksissa, jotka ovat yhteydessä luku- ja laskutaidon automatisoitumiseen (nopean nimeämisen taidot, lukujonotaidot). Lisäksi tulokset osoittivat, että lasten välillä on yksilöllisiä eroja luku- ja laskutaidon alkuvalmiuksien muodostamissa taitoprofiileissa, jotka ennustavat eri tavoin luku- ja laskutaidon yhteyttä 1. ja 7. luokalla. Valtaosalla lapsista (n. 65%) havaittiin voimakas yhteisvaihtelu sekä esikouluiän alkuvalmiuksien välillä, että luku- ja laskutaidon välillä 1. ja 7. luokilla. Tulokset myös osoittivat, että ennenaikaisesti syntyneiden lasten täysiaikaisina syntyneitä lapsia keskimäärin alhaisempi taitotaso luku- ja laskutaidossa liittyy näiden taitojen yhteiseen taitotasoon ja tiedonkäsittelytaustaan. Kaiken kaikkiaan tutkimuksen tulokset osoittivat, että luku- ja laskutaito kehittyvät yhtä matkaa kehityksen eri vaiheissa osittain yhteisen tiedonkäsittelytaustan vuoksi. Tämän vuoksi erityisesti niiden lasten taitojen kehitystä, joilla ilmenee ongelmia toisella näistä alueista koulussa tai jo esikouluiässä, tulisi seurata myös toisella alueella.

Avainsanat: lukutaito, laskutaito, päällekkäisyys, kehitys, esikoulu, alakoulu, yläkoulu

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II Korpipää, H., Moll, K., Aunola, K., Tolvanen, A., Koponen, T., Aro, M., & Lerkkanen, M.-K. (2020). Early cognitive profiles predicting reading and arithmetic skills in grades 1 and 7. *Contemporary Educational Psychology, 60,* 101830. https://doi.org/10.1016/j.cedpsych.2019.101830

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Taking into account the comments and instructions given by the co-authors, the author of the present dissertation wrote the original research plan, conducted the analyses in collaboration with co-authors and wrote the reports of the three publications.

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1 INTRODUCTION

Reading and arithmetic are the most fundamental skills taught in formal education (Durand, Hulme, Larkin, & Snowling, 2005), and success in these domains has been shown to predict later academic performance (Duncan et al., 2007; Rabiner, Godwin, & Dodge, 2016). Achieving fluency, i.e., automatization, in basic skills is especially crucial for academic learning (Denckla, 2007). Although a growing body of research suggests that reading and arithmetic skills are related strongly during primary school (Chen & Chalhoub-Deville, 2016; Davis et al., 2014; Koponen, Aunola, Ahonen, & Nurmi, 2007; Rutherford-Becker & Vanderwood, 2009) and lower secondary school (Chen & Chalhoub-Deville, 2016; Codding, Petscher, & Truckenmiller, 2015), and that the development of these skills partly shares the same underlying cognitive mechanisms in linguistic skills, basic number skills, and general cognitive abilities (Cirino, Child, & Macdonald, 2018; Hecht, Torgesen, Wagner, & Rashotte, 2001; Koponen et al., 2007), research on the development of these skills mainly has focused on each skill domain separately. Consequently, knowledge is lacking on the longitudinal relationship between reading and arithmetic skills, and fundamental questions remain unanswered: (1) Is the overlap between reading and arithmetic skills time-invariant or time-specific for certain developmental stages? (2) Do predictors of the overlap vary depending on the phase of skills development? In addition, as most previous research has focused on unique impacts of different cognitive antecedents with the overlap of reading and arithmetic, less is known about how the combinations of these cognitive antecedents (i.e., different cognitive profiles), rather than the unique impact of different variables, predict subsequent development and overlap of reading and arithmetic skills. Knowledge of the extent to which reading and arithmetic are related at different phases of skills development—and the extent to which they share the same underlying cognitive mechanisms—is important for understanding the cognitive mechanisms that underlie comorbid learning difficulties, as well as for developing effective interventions to support overall level of these skills.

The main focus of this research lies in the shared variance (i.e., overlap) between reading and arithmetic skills from primary to lower secondary school and in various cognitive antecedents that predict the overlap. By applying both variable-oriented and person-oriented approaches, the research aimed to complement the current understanding of the extent to which reading and arithmetic skills develop in relation to each other across grade levels and share the same cognitive mechanisms at different phases of skills development. Furthermore, the association of prematurity with the overlap between reading and arithmetic through the cognitive antecedents of both skills was investigated to add insight into reading and arithmetic's shared background, as well as into how to take prematurity into account when supporting children's school learning.

1.1 The development of reading and arithmetic skills

Learning to read involves translating visual codes into meaningful language, i.e., decoding letters into corresponding sounds and linking the sounds to single words (Lonigan, Burgess, & Anthony, 2000). With practice, recognizing words become automatized, which allows attentional resources to be used for comprehension (Schwanenflugel et al., 2006). Cross-linguistic research on children's reading acquisition suggests that in orthographically consistent languages, such as Finnish, learning to read generally is a faster learning process than in orthographically inconsistent languages, such as English (Aro & Wimmer, 2003; Seymour, Aro, & Erskine, 2003). In an orthographically consistent language, letters or letter clusters map consistently onto sounds, whereas in an orthographically inconsistent language, the relation between letters and sounds is often equivocal (Georgiou, Parrila, & Liao, 2008). Due to the one-to-one correspondence of graphemes and phonemes in the Finnish language, word-reading accuracy among Finnish children comes close to ceiling during the first year of formal schooling, and any individual variations are mostly observable in reading fluency, i.e., combined measures of accuracy and speed (Seymour et al., 2003).

Pre-reading development covers the time from becoming aware of letters and phonemes to the start of reading instruction (Lyytinen et al., 2006). Phonological awareness, i.e., awareness of a language's phonological structure, is an important predictor of variations in decoding and word-recognition ability (Durand et al., 2005). In addition to phonological awareness, knowledge of letter names has been shown to be one of the best predictors of learning to read (for a review, see Foulin, 2005). It has been shown that learning letter names helps children learn basic letter-sound (grapheme–phoneme) relations because most names contain the relevant sounds (Share, 2004). Whereas phonological awareness and letter knowledge are critical foundations for the development of early reading skills, rapid automatized naming (RAN), i.e., the ability to name highly familiar visual stimuli—such as digits, letters, colors, and objects—is a

strong, independent predictor of subsequent variations in reading fluency (Lervåg & Hulme, 2009). It has been suggested that RAN is associated with reading ability because they both tap the speed with which phonological representations can be retrieved from long-term memory (Lervåg & Hulme, 2009; Wagner & Torgesen, 1987). Studies have shown that children's performances of RAN tasks correlate with variations in reading across different languages, and that RAN-reading fluency correlations generally are higher than RAN-reading accuracy correlations (Georgiou et al., 2008). Overall, the predictors of reading performance in alphabetic languages are relatively universal (Ziegler et al., 2010).

Besides reading skills, another important basic academic skill is arithmetic. Achieving competence in arithmetic provides the basis for learning more advanced mathematics (Geary, Hoard, Nugent, & Bailey, 2003). The development of arithmetic skills can be viewed as an increasingly sophisticated understanding of numerosity and its implications, as well as in increasing skill in manipulating numerosities (Butterworth, 2005). According to Butterworth (2005), counting serves as a bridge from the child's innate capacity for numerosity to more advanced mathematical achievements. Children apply their knowledge of the counting sequence to enumerate sets of objects by mapping each number word onto each item in a set to acknowledge the exact number of items in a collection (Gelman & Galistell, 1978; Raghubar & Barnes, 2017). Solving arithmetic problems is first based on these counting procedures and relies on fingers or other external referents, such as blocks (Siegler & Shrager, 1984; see Raghubar & Barnes, 2017). According to Siegler (1987), the counting-all procedure (i.e., counting both addends starting at 1, e.g., a 2 + 3 problem counting 1, 2, then 3, 4, 5) is followed by the counting-on max procedure (i.e., stating the smaller-valued addend, then counting a number of times equal to the value of the larger addend, e.g., 2, then 3, 4, 5) and the counting-on min procedure (i.e., stating the larger addend, then counting the smaller addend, e.g., 3, then 4, 5). The use of counting procedures develops memory representations of basic math facts, thereby facilitating direct retrieval of answers from memory (e.g., stating "five" without needing to count when asked to solve 2 + 3) (Raghubar & Barnes, 2017). Finnish children typically achieve strong accuracy in arithmetic with single-digit numbers during the first year of schooling (Polet & Koponen, 2012), which is required for developing fluency (Denckla, 2007; Juul, Poulsen, & Elbro, 2014).

Early numeracy skills, which are critically important for later mathematical development, involve the understanding and manipulation of both symbolic and non-symbolic numerical information, e.g., verbal counting, knowing number symbols, recognizing and manipulating quantities, discerning number patterns, and comparing numerical magnitudes (Raghubar & Barnes, 2017). The non-symbolic representation of numbers provides the semantic underpinning for Arabic numeral and number word representations (Dehaene & Cohen, 1995; Malone, Heron-Delaney, Burgoyne, & Hulme, 2019). According to Cirino et al. (2011) the association of early numeracy skills with mathematical

competence is stronger for precursors that are symbolic in content (also see, Schneider et al., 2017). Early symbolic number skills include learning the counting sequence and understanding the numerical meaning of number words (e.g., "three") and Arabic numerals (e.g., "3") (Raghubar & Barnes, 2017). In the development of arithmetic skills, the role of counting skills, e.g., the ability to recite a number-word sequence and acknowledge the position of a number word in this sequence (e.g., Raghubar & Barnes, 2017; Aunola, Leskinen, Lerkkanen, & Nurmi, 2004) and the ability to match Arabic numerals to their verbal labels (Göbel, Watson, Lervåg, & Hulme, 2014), is well-established.

On the basis of previous studies, both reading skills (Hulslander, Olson, Willcutt, & Wadsworth, 2010; Landerl & Wimmer, 2008; Parrila, Aunola, Leskinen, Nurmi, & Kirby, 2005) and arithmetic skills (Aunola et al., 2004; Bailey, Watts, Littlefield, & Geary , 2014; Watts, Duncan, Siegler, Davis-Kean, 2014) show moderate to high interindividual stability across school years from primary to lower secondary school. For example, a longitudinal study by Landerl and Wimmer (2008) found high stability in individual differences in reading fluency from Grade 1 to Grade 8. Similarly, achievement in math has been found to be highly stable from preschool through age 15 (Watts et al., 2014; also see Aunola et al., 2004).

1.2 The role of fluency in reading and arithmetic skills

The achievement of fluency, i.e., the ease and accuracy with which a skill is carried out (Locuniak & Jordan, 2008), is a central goal during early school years in both arithmetic calculation and reading (Koponen, Salmi, Eklund, & Aro, 2013). According to Koponen et al. (2013), subsequent acquisition of mathematics skills is compromised severely if basic calculation skills are weak, and weaknesses in reading skills can seriously impede the learning of most school subjects.

In mathematics, fluency in basic calculations is an important tool for solving most mathematical problems (Reeve & Waldecker, 2017), and calculation dysfluency has been shown to be a characteristic of children with math difficulties (Geary, 1993). For example, not knowing number facts reduces cognitive and attentional resources that are necessary for higher-level problem solving (Locuniak & Jordan, 2008; Pellegrino & Goldman, 1987). In reading, the development of fluency is a key link between word recognition and comprehension (Bashir & Hook, 2009; Hook & Haynes, 2008), and dysfluency, i.e., low speed, has been shown to be the hallmark of reading difficulties in both irregular and regular orthographies (Ziegler, Perry, Ma-Wyatt, Ladner, & Schulte-Körne, 2003). It has been suggested that slow word recognition may place demands on remembering what is read and, therefore, interfere with effective comprehension (Carlisle & Rice, 2002).

However, despite the importance of fluent reading and arithmetic calculation skills, explicit attention paid to fluency in reading and arithmetic

calculation—as well as their covariation—has been rare. Therefore, an understanding of the factors underlying fluency in reading and arithmetic calculation remains limited. To better understand the relationship between math and reading development, it seems relevant to focus on outcome measures that take into account both performance accuracy and speed. Consequently, in the present research, the terms *reading* and *arithmetic skills* are used to refer to fluency (combined measures of accuracy and speed) in reading and arithmetic.

1.3 Overlap between reading and arithmetic skills and stability across school years

An increasing number of studies suggests that substantial intercorrelations, i.e. , covariations, exist between reading and math skills among unselected populations during both primary school (Chen & Chalhoub-Deville, 2016; Davis et al., 2014; Koponen et al., 2007; Rutherford-Becker & Vanderwood, 2009) and lower secondary school (Chen & Chalhoub-Deville, 2016; Codding et al., 2015). Correlations vary in the moderate-to-high range up to 0.60 (Davis et al., 2014), regardless of gender, family socioeconomic status (SES), and race/ethnicity (Chen & Chalhoub-Deville, 2016). Furthermore, learning difficulties in one of the domains have been shown to increase the risk for difficulties in the other domain (Koponen et al., 2018; Landerl & Moll, 2010; Moll et al., 2014). According to Koponen et al. (2018), the prevalence of comorbid dysfluency difficulties varies from 27% to 46%. Despite the strong intercorrelations, previous studies focusing on overlap between reading and arithmetic skills mainly have been cross-sectional and focused on early school years. Consequently, knowledge is lacking regarding the extent to which reading and arithmetic skills show overlap (i.e., shared variance) from primary to lower secondary school, as well as, regarding the extent to which this overlap is time-invariant (i.e., shared over time) or time-specific (i.e., unique to a particular grade). To better understand both how the relation between reading and arithmetic develops or changes over time and the etiology of comorbid learning difficulties, longitudinal research is warranted.

It commonly is accepted that reading and arithmetic skills share similar developmental phases. At an initial stage, both reading and arithmetic skills are acquired via serial one-by-one processing: Reading is based on phonemic assembly of letter sounds, whereas arithmetic is based on counting number words in a sequence (Koponen et al., 2016; Siegler & Shrager, 1984). At later stages, a gradual shift occurs in processing and retrieving larger units in both domains, such as arithmetic facts in arithmetic and syllables or words in reading (see Koponen et al., 2016). As it has been suggested that reading and arithmetic skills are based on similar cognitive processes at different phases of skills development (Hecht et al., 2001; Koponen et al., 2013, 2016), it is likely

that a large part of the overlap in these skills is time-invariant. Studies showing that reading and math skills share significant genetic overlap also support this (Hart, Petrill, Thompson, & Plomin, 2009). According to the generalist genes hypothesis, the same set of genes partly affects diverse componential skills within both domains (Davis et al., 2014; Plomin & Kovas, 2005). However, due to the lack of longitudinal studies, it is not yet known whether the overlap between reading and arithmetic skills is equally strong at early (i.e., serial decoding/counting) and later stages (automatized phase relying on direct retrieval) of skills development. Part of the overlap also can be time-specific and related to these different phases in fluency development.

1.4 Cognitive correlates of the overlap between reading and arithmetic skills

Previous studies suggest that the overlap (i.e., shared variance) between reading and arithmetic skills (Cirino et al., 2018; Hecht et al., 2001; Koponen et al., 2007) and the comorbidity of reading and arithmetic difficulties (Cirino, Fuchs, Elias, Powell, & Schumacher, 2015; Peng & Fuchs, 2016; Willcutt et al., 2013) are partly related to their common cognitive background. Shared cognitive antecedents have included linguistic skills (Cirino et al., 2015; Hecht et al., 2001; Koponen et al., 2007, 2016; Simmons, Singleton, & Horne, 2008), basic number skills (Cirino et al., 2015; Koponen et al., 2007, 2016), and general cognitive abilities (Alloway & Alloway, 2010; Clair-Thompson & Gathercole, 2006; Hecht et al., 2001; Peng & Fuchs, 2016; Rohde & Thompson, 2007; Willcutt et al., 2013).

Recently, interest has been increasing in examining different linguistic and basic number skills' role in the overlap between reading and arithmetic. Extant studies suggest that phonological awareness, letter knowledge, RAN, and counting sequence knowledge also account for shared variance in reading and arithmetic skills (i.e., overall reading and arithmetic skill level) (Koponen et al., 2007; see also Hecht et al., 2001; Cirino et al., 2018). For example, Koponen et al. (2007) showed that the covariation between calculation and reading fluency in Grade 4 was predicted by RAN, counting sequence knowledge, and letter knowledge. Similarly, Cirino et al. (2018) reported that linguistic skills—including phonological awareness, RAN, and symbolic naming—accounted for a large amount (about 91%) of the overlap between reading and arithmetic fluency in Grade 1, whereas counting's role was less evident. These studies suggest that developing fluency both in reading and arithmetic relies on the abilities to form and retrieve visual-verbal associations from long-term memory, as well as process serial information (see also Koponen et al., 2013).

Mapping between visual symbols and their verbal labels is critical when learning to read (Hulme, Goetz, Gooch, Adams, & Snowling, 2007), as well as when learning arithmetic (Malone, Heron-Delaney, Burgoyne, & Hulme, 2019),

which may explain the role of letter knowledge and phonological awareness as predictors of shared variance between reading and arithmetic. According to Zhang et al. (2014), understanding mapping between letters in written words and phonemes in spoken language improves the ability to use and manipulate written symbols for numbers and operators in arithmetic. RAN and verbal counting's role in predicting shared variance between reading and arithmetic, in turn, may reflect the retrieval process (accessing long-term memory to retrieve phonological information) and the serial nature of this retrieval process needed in both domains for developing fluency (Koponen et al., 2019). For example, according to Koponen et al. (2007), fluent reading requires automatized retrieval of letter sounds to form associations between syllables or words and corresponding sound constructions. Similarly, in fluent calculation, accurate and fluent retrieval of the number-word sequence is required to form and strengthen the associations between problems and answers in long-term memory (Koponen et al., 2007). In addition, the ability to process multiple items in a sequence (Koponen et al., 2019) is needed in both domains, e.g., when solving arithmetic problems or identifying words.

Furthermore, general cognitive abilities—such as working memory (Hecht et al., 2001), attention, and nonverbal reasoning (Cirino et al., 2018)—also have been shown to account for shared variance between reading and arithmetic. Impairments specifically in working memory are common in children with reading and/or mathematical disabilities (De Weerdt, Desoete, & Roeyers, 2013). However, in previous studies, general cognitive abilities' role has been minor in explaining the shared variance of reading and arithmetic compared with linguistic and basic number skills. In addition to general cognitive abilities, parental education likely plays a role in the overlap between reading and arithmetic skills. It has been shown that family SES, as indexed by parental education level, is one of the best predictors of children's educational achievement (Davis-Kean, 2005; Eccles, 2005; Sharma & Jha, 2014). Family SES relates to a child's academic achievement directly through heritable traits (Kraphol & Plomin, 2016) and indirectly through parents' beliefs about achievement and stimulating behaviors (Davis-Kean, 2005; see also Eccles, 2005).

Overall, extant literature has suggested various cognitive antecedents for explaining the overlap between reading and arithmetic, as well as the comorbidity of learning difficulties in these domains. However, this overlap has not been examined yet over several grades from primary to lower secondary school. Consequently, knowledge is lacking regarding the extent to which known antecedents of reading and arithmetic skills (i.e., phonological awareness, RAN, letter knowledge, counting sequence knowledge), general cognitive abilities, and parental education level predict the time-invariant and time-specific portions of covariation between reading and arithmetic skills from Grade 1 to Grade 7.

1.5 Person-oriented approach on the cognitive antecedents of reading and arithmetic

Previous studies focusing on the cognitive antecedents of reading and arithmetic or the overlap between them mainly have applied a variable-oriented approach (Cirino et al., 2018; Hecht et al., 2001; Koponen et al., 2007, 2013). This approach provides valuable information about the unique contributions of different cognitive skills to reading and arithmetic development, but it also has some limitations. The main concern is a variable-oriented approach's assumption that the studied associations are the same for all children and, thus, are restricted to quantitative individual differences, thereby ignoring possible qualitative differences between children (Lanza & Cooper, 2016; Sterba & Bauer, 2010). Because children differ in their abilities, motivations, and preferences, and these characteristics interact while affecting their learning (Hickendorff et al., 2018), it is likely that the associations do not apply to all children in the same way (Bergman & Magnusson, 1997). Consequently, despite the strong intercorrelations (varying from .30 to .60) between reading and arithmetic found in previous studies, the correlation pattern may not be the same across the whole population. Person-oriented techniques allow for tracing back the observed heterogeneity in a population by identifying subgroups of individuals that show similar patterns of characteristics (Bergman & Magnusson, 1997; Hickendorff et al., 2018). Since variable-oriented approaches provide important information about the additive impacts of different linguistic and basic number skills on reading and arithmetic skills and their overlap, a person-oriented approach supplements a variable-oriented approach by providing a valuable tool with which to examine these cognitive antecedents' interactive effects.

Recently, the person-oriented approach has been applied to investigate separately the cognitive profiles related to reading (Ozernov-Palchik et al., 2017) and to arithmetic skills (Gray & Reeve, 2016; Hart et al., 2016). Based on these findings, subgroups of children with distinct profiles regarding the cognitive antecedents of reading and arithmetic have been identified, especially among children who are struggling. Furthermore, these children show different kinds of weaknesses in reading and arithmetic skills based on strengths and weaknesses in their cognitive profiles. For example, Ozernov-Palchik et al. (2017) suggested that children with a phonological awareness risk perform poorly in decoding, children with a RAN risk perform poorly in fluency, and children with both risks have the most severe reading problems. Similarly, Gray and Reeve (2016), found that math difficulties may result from different cognitive markers, but more research is needed to investigate both how the cognitive antecedents of reading and arithmetic skills are combined within individuals and how these different cognitive profiles predict overlap between reading and arithmetic across grade levels.

It has been shown in previous studies that the cognitive antecedents of reading and arithmetic, mainly linguistic and basic number skills, predict both shared and nonshared variance in subsequent reading and arithmetic skills (Cirino et al., 2018; see also Child et al., 2019). For example, Cirino et al. (2018) suggested that linguistic skills regarding phonological awareness and rapid automatized naming are more predictive of reading than math skills, whereas basic number skills, such as counting, are more predictive of math than reading skills due to domain-specific content knowledge. These cognitive antecedents also have been shown to account for most parts of the overlap between reading and arithmetic (Cirino et al., 2018; Hecht et al., 2001; Koponen et al., 2007). Consequently, it can be assumed that individual variations exist in a combination of these skills, as well as in the extent to which reading and arithmetic skills show overlap when students are in primary and lower secondary school.

By applying both variable- and person-oriented approaches, it is possible to characterize reading and arithmetic learning processes more fully in relation to each other. Aside from research on additive impacts regarding linguistic and basic number skills, new research is warranted on how combinations of these skills (i.e., different cognitive profiles), rather than the unique impact of different variables, play a role in subsequent skill development and overlap of reading and arithmetic. To complement current understanding, a person-oriented approach was applied, in addition to a variable-oriented approach, to specify associations of different cognitive antecedents with overlap between reading and arithmetic.

1.6 Theoretical background for explaining shared variance in reading and arithmetic

In previous literature, different explanations have been proposed for the shared variance between reading and arithmetic, mainly comorbidity of reading and arithmetic difficulties. Some studies suggest that learning difficulties in these two domains originate from unique cognitive deficits. For example, Landerl, Fussenegger, Moll, and Willburger (2009) showed that difficulties in mathematics result from deficits in the number module, and that difficulties in reading result from deficits in phonological processing. These domain-specific impairments are assumed to combine additively in children with comorbid learning difficulties in reading and arithmetic. However, it also has been shown that the phonological processing deficits of individuals with dyslexia impair mathematics aspects that rely on the manipulation of verbal codes (e.g., counting speed, number fact recall), whereas other mathematics aspects that are less reliant on verbal codes (e.g., estimation, subitizing) are unimpaired (for a review, see Simmons & Singleton, 2008).

Although it has been suggested that difficulties in reading and arithmetic originate from unique cognitive mechanisms, the underlying cognitive processes are not discrete (Ashkenazi & Silvermana, 2017). For example, both reading and arithmetic involve verbal working memory, cognitive control, and the representation and retrieval of symbolic information (Ashkenazi, Black, Abrams, Hoeft, & Menon, 2013). In line with this, other studies suggest that some weaknesses in cognitive functioning are associated with both reading and arithmetic difficulties, whereas other weaknesses are specific to one or the other of these difficulties (Peterson et al., 2017; Slot, van Viersen, de Bree, & Kroesbergen, 2016; Willcutt et al., 2013). For example, Slot et al., (2016) demonstrated that in addition to unique risk factors (number sense and visuospatial working memory in math; phonological awareness, and RAN in reading), reading and arithmetic difficulties shared a cognitive risk factor in phonological awareness.

However, it should be noted that much of the research related to the overlap between reading and arithmetic relies on the categorical classification of reading and arithmetic difficulties, as well as the variables that distinguish those groups from each other. It has been argued that these difficulties' achievement attributes are distributed normally (Branum-Martin, Fletcher, & Stuebing, 2013; Fletcher et al., 2012), and that the differences relate to severity, rather than qualitative distinctions. Understanding the attributes as correlated dimensions instead of independent categories (Fletcher et al., 2012) can add knowledge regarding the interrelationships between reading and arithmetic skills, as well as difficulties related to these skills.

1.7 Association of prematurity with overlap between reading and arithmetic

Prematurity has been shown to be associated negatively with learning outcomes at school (Dempsey et al., 2015; Keller-Margulis, Dempsey, & Llorens, 2011; Taylor et al., 2016), although some premature children perform within normal ranges (Kessenich, 2003). Previous studies have shown that, on average, very preterm children (i.e., with a gestational period of less than 32 weeks/birthweight less than 1,500 g) perform at lower levels compared with full-term children, particularly in math (Aarnoudse-Moens, Oosterlaan, Duivenvoorden, van Goudoever, & Weisglas-Kuperus, 2011; Pritchard et al., 2009), but also in reading (for a review, see Kovachy, Adams, Tamaresis, & Feldman, 2014). For example, a meta-analysis by Kovachy et al. (2014) found significant differences between very preterm and full-term children in both fundamental components of reading–decoding and comprehension. Taylor et al (2016), in turn, found that the differences between the groups are more pronounced in math computation than in reading at the beginning of school (age 7) (see also Pritchard et al., 2009). According to a meta-analysis by

Aarnoudse-Moens, Weisglas-Kuperus, Goudoever, and Oosterlaan (2009), very preterm children score 0.48 standard deviation (SD) lower in reading tests and 0.60 SD lower in mathematics tests than their full-term peers between ages 5 and 20.

In addition to reading and arithmetic skills, significant differences between very preterm and full-term children have been found in many cognitive antecedents of these skills, such as linguistic and basic number skills. For example, Schneider, Wolke, Schlagmuller, and Meyer (2004) found that very preterm children show lower levels of phonological awareness and letter knowledge compared with full-term peers. Differences between the groups also have been shown in RAN (Alanko et al., 2017; Saavalainen et al., 2006) and in skills related to number sense and counting sequence knowledge (Alanko et al., 2017; Guarini et al., 2014). Some studies have suggested that reading and arithmetic performance among very preterm children is linked with general cognitive abilities indexed by IQ (Schneider et al., 2004; see also Wolke, Samara, Bracewell, & Marlow, 2008). However, more specific skills, such as RAN, have been shown to predict very preterm children's underachievement in both domains after controlling for IQ (Wocadlo & Rieger, 2007).

Overall, previous literature suggests that on average, very preterm children have a higher risk of experiencing difficulties in both academic domains compared with full-term children at the beginning of school. The severity of impairment in cognitive functioning is related not only to the degree of maturity at birth (Anderson, 2014) but also to parental education and perinatal medical complications (Stålnacke, Lundequist, Böhm, Forssberg, & Smedler, 2015). In previous studies, differences between very preterm and full-term children in reading and math domains largely have been investigated separately, and knowledge is lacking regarding the extent to which these difficulties are related and share the same cognitive mechanisms. It has been demonstrated that co-occurring learning difficulties in reading and math domains are more severe and persistent over time than difficulties evident in only one domain (Jordan, Hanich, & Kaplan, 2003; see also Koponen et al., 2018). Therefore, investigating the extent to which the differences between very preterm and full-term children in reading and arithmetic skills result from domain-general vs. domain-specific variation, is vitally important from an educational perspective. Furthermore, identifying the cognitive mechanisms that underlie this academic underachievement in both domains is needed to diminish the achievement gap between preterm and full-term children, and to prevent co-occurring learning difficulties.

Since prematurity is associated with lower skill levels in both reading and arithmetic, it may reflect underlying adverse neurodevelopmental outcomes shared by reading and arithmetic that become evident when children reach school age (Aylward, 2005). This is supported further by findings showing that similar brain regions and structural networks are involved in performing both reading and arithmetic (De Smedt, Taylor, Archibald, & Ansari, 2010). According to Pennington (2006), multiple factors underlie

developmental learning difficulties, e.g., regarding reading and arithmetic skills (van Bergen, van der Leij, & de Jong, 2014), and some of these factors overlap at etiological, cognitive and neural levels. If lower performance levels in these two academic domains among preterm children result in more domain-general than domain-specific variation, reading and arithmetic skills are likely to share, partly, the same etiological factors that influence the development of relevant neural systems and cognitive processes (e.g. van Bergen, van der Leij, & de Jong, 2014).

1.8 Aims of the research

The main focus of this research was to examine the overlap between reading and arithmetic skills from primary to lower secondary school, including the underlying cognitive mechanisms of this overlap. Three studies were carried out, each approaching this broader aim from different aspect.

Study I examined the amount of shared variance (i.e., overlap) between reading and arithmetic skills at Grades 1 and 7 among an unselected population. In this study, the time-invariant and time-specific parts of the overlap were investigated separately, and the cognitive antecedents of these time-invariant and time-specific parts of the overlap were examined with regard to phonological awareness, letter knowledge, RAN, counting sequence knowledge, working memory, nonverbal reasoning, and parental education level.

In Study II, the variable-oriented approach applied in Study I was complemented using a person-oriented approach on the cognitive antecedents of reading and arithmetic skills among an unselected population. More specifically, the study aimed to identify subgroups of children demonstrating different cognitive profiles in kindergarten in terms of linguistic and basic number skills, that is, phonological awareness, letter knowledge, RAN, and counting sequence knowledge. Moreover, the study included an examination of the extent to which children with different cognitive profiles differ from each other in their subsequent (Grades 1 and 7) reading and arithmetic skills, including the overlap; in general cognitive abilities (nonverbal reasoning, working memory, short-term memory, inattention/hyperactivity); and in parental education level.

In Study III, prematurity's relation with the overlap between reading and arithmetic skills was examined at the beginning of school. In this study, the focus was on the difference between very preterm and full-term children in the overlapping part of reading and arithmetic skills. In addition, the extent to which the association of prematurity with the overlap is mediated through linguistic skills (letter knowledge, phonological awareness, and RAN), basic number skills (digit knowledge and counting sequence knowledge), and general cognitive abilities (performance IQ and verbal IQ) was examined after controlling for parental education and child gender.

2 METHODS

2.1 Participants and procedure

The research was part of the First Steps longitudinal age cohort study (Lerkkanen et al., 2006) and the Development and Functioning of Very Low Birth Weight Infants from Infancy to School Age (the PIPARI study) multidisciplinary project. The First Steps study followed a community sample of children born in 2000 from kindergarten to Grade 9. In the PIPARI study, very preterm and healthy full-term control children born in 2001–2004 at the Turku University Hospital were followed from infancy to Grade 1.

2.1.1 Studies I and II

The sample for Studies I and II consisted of children participating in the First Steps follow-up study from one rural municipality and three urban municipalities in Finland. These children comprised the whole age cohort from the rural municipality and from two of the three urban municipalities, and about half of the age cohort from the remaining urban municipality. They were followed from the kindergarten entry age (M = 74.0 ± 3.6 months) to the end of lower secondary school (age 15). All parents were asked for written consent for their child to participate. The sample was relatively representative of average family background characteristics in Finland (Official Statistics in Finland, 2017).

In Study I, a total of 1,335 children (47.1% girls) were chosen who had performance data available for reading and arithmetic skills both at Grade 1 and at Grade 7. The data concerning reading and arithmetic skills were collected during the spring semester (March/April) of Grades 1 and 7. Other measures, including phonological awareness, letter knowledge, RAN, and

counting were tested during the kindergarten year; working memory was tested at Grade 1; and nonverbal reasoning was tested at Grade 3. Researchers or students in psychology/education that had been trained accordingly carried out all tests. Information concerning the parental education level was gathered by questionnaire from parents at the beginning of the follow-up.

In Study II, 1,170 children were chosen for whom data were available for linguistic and basic number skills (phonological awareness, letter knowledge, RAN, and counting sequence knowledge) at kindergarten and for whom data were available concerning reading and arithmetic skills either at Grade 1 or at Grade 7, or both. In the study, the data from general cognitive abilities (working memory, short-term memory, inattention/hyperactivity, nonverbal reasoning) and parental education level were also included. The measurement points for reading and arithmetic skills, linguistic and basic number skills, general cognitive abilities, and parental education level were the same as in Study I. Teacher ratings of children's inattention/hyperactivity were collected at Grade 1.

2.1.2 Study III

The participants of Study III came from the PIPARI multidisciplinary project (Development and Functioning of Very Low Birth Weight Infants from Infancy to School Age) and consisted of 193 very preterm (43.0% girls) children and 175 (49.7% girls) full-term control children. The inclusion criteria for the preterm children were based on World Health Organization's International Classification of Diseases (ICD-10) definitions of very preterm birth (< 32 weeks of gestation) and very low birth weight (< 1500 g). Of these children, 153 were born weighing less than 1501 g and at less than 32 weeks of gestation, 15 met only the gestational age criterion, and 25 met only the birth weight criterion. The inclusion criteria for full-term children were a birth weight higher than –2 SD according to Finnish growth charts, a gestational age of 37 weeks or longer, and no neonatal care during the first week of life.

The data concerning reading and arithmetic skills, linguistic skill (phonological awareness, letter knowledge, RAN), and basic number skills (counting and digit knowledge) were collected by trained testers at school at the beginning of the first grade (August/September) when the children were either 6 or 7 years old. As an exception, data concerning the children's general cognitive abilities (verbal IQ and nonverbal IQ) were gathered at age 5 by the research unit at the university hospital. The mothers' level of education at the time of birth did not differ between very preterm and full-term children, but fathers with higher education were overrepresented in the full-term children's group. All parents were informed about the study and asked for their written consent.

2.2 Measures

Partly different sets of measures were used in the three studies. The main focus in each study was in the overlap between basic academic skills and cognitive correlates of the overlap. Children's reading and arithmetic skills, linguistic skills (phonological awareness, letter knowledge, RAN), and basic number skills (digit knowledge, counting sequence knowledge) were measured in all three studies, except for digit knowledge, which was measured only in Study III. In addition, the measure of parental education level was included in all studies. The measures of general cognitive abilities were included as control variables together with parental education level, and they varied in each study. Summary of the used variables, measurement points, and analysis methods for each study are presented in Table 1.

2.2.1 Reading and arithmetic skills

Reading skills. The Finnish adaptation of the Test of Silent Reading Efficiency and Comprehension (TOSREC; Wagner, Torgesen, Rashotte, & Pearson, 2009; Finnish version by Lerkkanen, Poikkeus, & Ketonen, 2008) was used as a measure of reading skills in Studies I and II. The test was administered in a group setting during the spring term (March/April) at Grades 1 and 7. At Grade 1, students were given three minutes to read silently 60 semantically simple sentences (e.g., "an apple is blue" or "candy is usually sweet") and then instructed to rate the sentences as correct or incorrect as accurately and rapidly as possible. At Grade 7, a sentence verification task of a standardized Finnish reading test for lower secondary school was used (YKÄ; Lerkkanen, Eklund, Löytynoja, Aro, & Poikkeus, 2018). This time, the students were given two minutes to read silently 70 sentences and were instructed to rate the sentences as correct or incorrect as accurately and rapidly as possible. The outcome score in both tasks was based on the number of correct answers given within the time limit. It has been shown that, on average, Finnish students can read whole sentences fluently by the end of Grade 1 (Lerkkanen, 2003). Cronbach's alpha reliabilities for the tests were .89 at Grade 1 and .94 at Grade 7.

In Study III, children's reading skills were assessed individually at the beginning of Grade 1 (August/September) with two different subtests. Word reading accuracy was assessed using a word list reading test (subtest of the ARMI, which is a tool for assessing reading and writing skills in Grade 1; Lerkkanen, Poikkeus, & Ketonen, 2006). In this test, two-syllable (seven words), three-syllable (two words), and five-syllable (one word) words were presented one at a time, and the child was asked to read them out loud without a time limit. Word reading fluency was assessed with a test containing a list of 90 words arranged into three columns in order of increasing difficulty (Lukilasse Graded Fluency Test; Häyrinen, Serenius-Sirve, & Korkman, 1999). The child

was asked to read as many words out loud as possible within a time limit of 45 seconds. For both tests, the score was based on the total number of words read out correctly. The sum score of the standardized word reading accuracy and word reading fluency was used as the measure of reading skills in Study III. Cronbach's alphas for the tests were 0.97 and 0.97, respectively.

Arithmetic skills. The Basic Arithmetic Test (Aunola & Räsänen, 2007) was used to assess children's arithmetic skills in all studies, that is, in Study I, II, and III. In Studies I and II, arithmetic skills were assessed in a group situation during the spring term (March/April) of Grades 1 and 7. In Study III, assessment took place during the fall term (August/September) of Grade 1. At Grade 1, the test consisted of 28 items altogether—14 items of addition (e.g., 2 + 1 = __; 3 + 4 + 6 = __), and 14 items of subtraction (e.g., 4 - 1 = __; 20 - 2 - 4 = __). At Grade 7, a total of 28 items were a mix of addition, subtraction, multiplication, and division tasks (e.g., 40 : 8 – 3 = __; __ – 18 = 45 – 12; 11 × 3.2 = __; 6 × 4 + 1 = __ -21). The participants were given three minutes to complete as many items as possible, and the sum score was based on the total number of correct items. Performance in the test requires both accuracy and speed (automatization of basic calculation routines). Due to the increasing difficulty of the items and the time limit, the test remains challenging even for older students. Cronbach's alpha reliabilities for arithmetic skills in Studies I and II were .70 at Grade 1 and .94 at Grade 7; for Study III, it was .85.

2.2.2 Linguistic and basic number skills

Phonological awareness. In Studies I and II, children's phonological awareness was tested during the fall of kindergarten by an initial phoneme identification task (Lerkkanen et al., 2006). This task contains 10 items in which the child was simultaneously shown four pictures of objects and told their names. The child was then asked to indicate which one of the pictures shows the object whose name starts with the requested phoneme (e.g., "At the beginning of which word do you hear ____?"). The score was the total number of correct items (maximum value of 10). In Study III, phonological awareness was assessed at the beginning of Grade 1 using a phoneme blending task. Three- to seven-letter words were presented to the participants phoneme by phoneme in a small group situation (Poskiparta, 1995). They were told to figure out the resulting word by choosing one of the alternative pictures matching the word on a sheet of paper. The test consists of one practice trial and nine test trials. The sum score was based on the number of correct items (maximum value of 9). Cronbach's alpha reliability of the test was .78 in Studies I and II, and .73 in Study III.

Letter knowledge. Letter knowledge was assessed individually using the Letter Knowledge Test (Lerkkanen et al., 2006) during the fall of kindergarten in Studies I and II, and at the beginning of Grade 1 in Study III. The test consists of all 29 uppercase letters in the Finnish alphabet arranged in random order in three rows. The child was shown one row at a time and asked to name the

letters. The sum score was based on the number of correct items (maximum value of 29). Cronbach's alpha reliability was .95 in Studies I and II, and .95 in Study III.

Rapid automatized naming. The standardized Finnish version by Ahonen, Tuovinen, and Leppäsaari (1999) of an object-naming task (Denckla & Rudel, 1976) was used to assess RAN during the spring of kindergarten in Studies I and II, and at the beginning of Grade 1 in Study III. This task consisted of five familiar objects replicated 10 times on a matrix in pseudorandom order. The child was asked to name all of them, as rapidly as possible, after asking first to name each of the five objects. The total matrix (five rows of 10) completion time in seconds was used as the RAN score. Documented errors and self-corrections were few, and they were not used in the analysis. According to the manual, the test-retest reliability coefficient ranged from 0.84 to 0.92 for all age groups (Wolf & Denckla, 2005).

Counting sequence knowledge. Counting sequence knowledge was assessed using the Number Sequences Test (forward and backward; Salonen et al., 1994) during the fall of kindergarten in Studies I and II, and at the beginning of Grade 1 in Study III. In Studies I and II, the test consisted of the following subtasks: (1) counting forward from 1 until given permission to stop at 31, (2) counting forward from 6 to 13, (3) counting backward from 12 until given permission to stop at 7, and (4) counting backward from 23 to 1. In Study III, partly different subtasks were used: (1) counting forward from 1 until given permission to stop at 51, (2) counting from 6 to 13, (3) counting from 18 to 25, (4) counting backward from 12 to 7, (5) counting backward from 23 to 1, (6) counting backward from 33 until given permission to stop at 17, and (7) counting 5 numbers backward from number 23. For each task, 2 points were given for the correct outcome, 1 point for completing the task with up to two errors, and 0 points if the child made more than two errors or failed to complete the task. The total maximum score for the test was 8 in Studies I and II, and 14 in Study III. Cronbach's alpha reliability for the test was .74 in Studies I and II, and .82 in Study III.

Digit knowledge. Digit knowledge was assessed in Study III at the beginning of Grade 1 using a test consisting of 12 visually presented 1- to 6–digit numbers in increasing numerical order—the smallest being 9 and the largest 627,003. The child was asked to name the numbers one at a time without a time limit; after two successive failures, the test was discontinued. Cronbach's alpha for the test was 0.82.

2.2.3 General cognitive abilities and parental education

Working memory and short-term memory. Working memory and short-term memory were assessed individually during the spring of Grade 1 in Studies I and II using the standard assessment procedure for the Wechsler Intelligence Scale for Children (WISC-III; Wechsler, 2012) digit span subtests. The student

was asked to repeat number digit spans read by the tester in the same order, both forward and backward. Test trials began with two-number digit spans and increased by one number in each section until the digit span had nine numbers (or eight numbers in number digit span backward). Each section contained two test trials with the same number digit span. The test was scored on a three-step scale: 2 points were given for repeating both number digit spans of the section correctly, and 1 point was given for repeating one of the number digit spans of the section correctly. If the student could not repeat either of the number digit spans of the section correctly, 0 points were given, and the test was discontinued. The maximum score was 16 points for number digit spans forward and 14 points for number digit spans backward. The maximum score for the test was 30 points. In Study II, two different variables were created because it has been suggested that digit span forward captures verbal short-term memory while digit span backward is an index of working memory (Alloway, Gathercole, & Pickering, 2006). According to the manual (Wechsler, 2012), Cronbach's alpha reliabilities for digit span subtests vary from .55 to .70 for different age groups.

Nonverbal reasoning. In Studies I and II, the shortened version of Raven's Colored Progressive Matrices (Raven, Court, & Raven, 1992) was used to assess the students' nonverbal reasoning during the spring of Grade 3 in classrooms. The test contains 18 items in which the student was asked to identify from six choices the missing element that completes a pattern. Total scores of correct items were calculated (maximum value of 18). The Guttman split-half reliability of the test was .66, and Cronbach's alpha reliability was .64.

In Study III, a short version of the Finnish translation of Wechsler Preschool and Primary Scale of Intelligence – Revised (WPPSI–R) was used to assess cognitive levels at the age of 5. Based on WPPSI–R, two sum scores were created: (1) The verbal IQ was estimated based on the following subtests of WPPSI–R: information, sentences, and arithmetic. (2) The performance IQ was estimated based on the following subtests: block design, geometric design, and picture completion subtests.

Inattention/hyperactivity. In Study II, teacher ratings of inattention and hyperactivity were collected at the end of Grade 1 using the inattention/hyperactivity subscale of the Strengths and Difficulties Questionnaire for 4- to 16 year olds (SDQ 4-16; Goodman, 1997). The questionnaire consists of five questions that are rated on a three-point scale (1 = not true, 2 = somewhat true, and 3 = true). Cronbach's alpha reliability for the inattention/hyperactivity subscale was .90.

Parental education level. In Studies I and II, the parents filled in and returned the questionnaires where they reported their vocational education on a seven-point scale (1 = no education beyond comprehensive school, 2 = vocational courses, 3 = vocational school degree, 4 = vocational college degree, 5 = polytechnic degree or bachelor's degree, 6 = master's degree, and 7 = licentiate or doctoral degree). The parental education score was the education score of the higher educated parent. In Study III, parents were asked about their

education in years by questionnaire with a three-point scale (1 = < 9 years, 2 = 9-12 years, 3 = > 12 years), and the parental education score was determined by the education score of the more educated parent.

TABLE 1 Summary of the variables and methods used in Studies I–III (IV = independent variables, DV = dependent variables)

Studies	Data	Variables		Statistical methods
Study I	First Steps study n = 1,335	IV	Phonological awareness (Kindergarten) Letter knowledge (Kindergarten) Rapid automatized naming (Kindergarten) Counting (Kindergarten) Working memory (Grade 1) Nonverbal reasoning (Grade 3)	Structural equation modelling
		DV	Reading (Grade1, Grade 7) Arithmetic (Grade 1, Grade 7)	
Study II	First Steps study n = 1,710	IV	Phonological awareness (Kindergarten) Letter knowledge (Kindergarten) Rapid automatized naming (Kindergarten) Counting (Kindergarten) Working memory (Grade1) Short-term memory (Grade 1) Inattention/hyperactivity (Grade 1) Nonverbal reasoning (Grade 3)	Latent profile analysis
		DV	Reading (Grade 1, Grade 7) Arithmetic (Grade 1, Grade 7)	
Study III	PIPARI study n = 368 (193 preterm and 175 full-term)	IV	Performance IQ (age of 5) Verbal IQ (age of 5) Letter knowledge (Grade 1, autumn) Phonological awareness (Grade 1, autumn) Rapid automatized naming (Grade 1, autumn) Counting (Grade 1, autumn) Digit knowledge (Grade 1, autumn)	Structural equation modelling
		DV	Reading (Grade 1, autumn) Arithmetic (Grade 1, autumn)	

3 OVERVIEW OF ORIGINAL STUDIES

3.1 Study I

The aim of Study I was to (1) investigate the extent to which reading and arithmetic skills overlap (i.e., show shared variance) at Grades 1 and 7 among an unselected population, and (2) to examine the extent to which this overlap is time-invariant (shared at two grades), on the one hand, and time-specific (unique to a particular grade), on the other. Two alternative hypotheses were proposed: (1a) As it has been suggested that the development of reading and arithmetic skills is based on similar cognitive processes at different grades (Hecht et al., 2001; Koponen et al., 2013, 2016), it was expected that a large part of the overlap between these two skills would be time-invariant. (1b) The alternative hypothesis was that part of the overlap between reading and arithmetic is time-specific, as the acquisition of both reading and arithmetic skills is known to include not only serial processing at the early stages but also the processing and retrieving of larger units later on, such as syllables or words in reading, and arithmetic facts in math (Koponen et al., 2016).

The second aim of Study I was to investigate the extent to which linguistic and basic number skills (phonological awareness, letter knowledge, RAN, and counting), general cognitive abilities (working memory, nonverbal reasoning), and parental education predict the time-invariant and time-specific parts of the overlap between reading and arithmetic skills at Grades 1 and 7. Based on the earlier literature, it was hypothesized that (2a) kindergarten pre-skills of reading and arithmetic (phonological awareness, letter knowledge, and counting) predict a time-specific overlap between reading and arithmetic skills in Grade 1 (Holopainen, Ahonen, & Lyytinen, 2001; Krajewski & Schneider, 2009; Silvén, Poskiparta, Niemi, & Voeten, 2007); (2b) more general cognitive processes (RAN, working memory, and nonverbal reasoning) predict the time-invariant part of the overlap.

The results of structural equation modeling (SEM) revealed first that reading and arithmetic skills shared 47% of their variance at Grade 1 and 33% at

Grade 7. The majority of this overlap between reading and arithmetic (about 30%) was time-invariant: the shared variance between reading and arithmetic was common for both Grade 1 and Grade 7. However, part of the covariation between reading and arithmetic was also time-specific: some pertaining only to Grade 1, and some only to Grade 7.

Second, the results showed that a time-invariant overlap between reading and arithmetic skills was predicted by RAN, counting sequence knowledge, letter knowledge, nonverbal reasoning, and working memory: the higher the level of these cognitive antecedents, the higher the overall performance level in reading and arithmetic across Grades 1–7. The time-specific overlap between reading and arithmetic skills at Grade 1 (i.e., level of performance shared by reading and arithmetic only at Grade 1) was predicted by important pre-skills, including counting sequence knowledge, letter knowledge, and phonological awareness: the higher these pre-skills in kindergarten, the higher the overall performance level in reading and arithmetic at Grade 1 in particular. The time-specific overlap between reading and arithmetic skills at Grade 7 (i.e., skill level shared by reading and arithmetic at Grade 7 that was not evident at Grade 1), in turn, was predicted by nonverbal reasoning and parental education level: the higher the level of reasoning skills and parental education, the higher the overall performance level of reading and arithmetic skills at Grade 7 independently of the level of these skills at Grade 1.

Overall, the results of this longitudinal study showed that a large proportion of covariation between reading and arithmetic was common both at primary (Grade 1) and at secondary school (Grade 7). These results suggest that reading and arithmetic skills are strongly related to each other, and this association is shared across grade levels. The results also suggest that the shared skill level of reading and arithmetic is fairly well established already in the beginning of school. Second, for the first time, the present study was able to differentiate the antecedents of time-invariant and time-specific parts of the covariation between reading and arithmetic. The results showed that early pre-skills, such as phonological awareness, played a particularly important role in the beginning of skill development, whereas the role of more general reasoning skills and parent's educational level are more crucial at the later phase of shared reading and arithmetic fluency development. The overlap across grade levels, in turn, was most strongly predicted by important indicators of fluency, such as RAN and counting sequence knowledge.

3.2 Study II

The aim of the Study II was, first, to investigate what kinds of distinct cognitive profiles regarding linguistic and counting skills can be identified among kindergarten-aged children. As previous studies suggest that there is high heterogeneity in cognitive profiles (i.e., subgroups of children representing differential relations between the cognitive antecedents) of reading (Ozernov-

Palchik et al., 2017) and arithmetic (Gray & Reeve, 2016; Hart et al., 2016), it was assumed that heterogeneity also exists for the combination of linguistic and counting skills. It was further assumed that both profiles typified by consistencies (e.g., high level of linguistic and counting skills) and profiles typified by discrepancies (e.g., high level of linguistic skills but low level of counting skills, and high level of counting skills but low level of linguistic skills) are identified (hypothesis 1).

The second aim of this study was to investigate how different cognitive profiles are associated with children's subsequent performance in reading and arithmetic at Grades 1 and 7. As previous studies suggest both shared and unique associations of linguistic and basic number skills with reading and arithmetic skills (Cirino et al., 2018; see also Child, Cirino, Fletcher, Willcutt, & Fuchs, 2019), it was assumed that children with high or low overall performance levels across phonological awareness, letter knowledge, RAN, and counting show more consistent skill levels for reading and arithmetic (being evident as either consistently high or low skill levels across reading and arithmetic) than do children with discrepant cognitive profiles (i.e., profiles with high linguistic and low counting skills or high counting skills and low linguistic skills).

First, latent profile analysis (LPA) was applied to identify homogeneous subgroups (i.e., profiles) of children showing similar response patterns across phonological awareness, letter knowledge, RAN, and counting sequence knowledge. Second, general cognitive abilities, parental education level, reading in Grade 1, arithmetic in Grade 1, reading in Grade 7, and arithmetic in Grade 7 were included in the model as auxiliary indicator variables, and differences between the latent profiles regarding these were tested using a chi-square test. Finally, the overlap of reading and arithmetic skills within profiles was investigated by comparing the 95% confidence intervals of the mean values within each group at Grades 1 and 7 separately.

By means of LPA, a total of four distinct cognitive profiles were found: (1) high linguistic and high counting skills (39%), (2) low linguistic and low counting skills (25%), (3) high counting skills in relation to linguistic skills (15%), and (4) low counting skills in relation to linguistic skills (20%). The majority of the children (64.6%) demonstrated overall either high or low linguistic and counting skills and, accordingly, either high or low levels of both reading and arithmetic skills in Grades 1 and 7. On the other hand, the results also showed that one-third of the children (35.4%) demonstrated discrepant linguistic and basic number skills and, accordingly, somewhat discrepant levels of reading and arithmetic skills in Grades 1 and 7. For all profiles, the children's performances across the measures of general cognitive abilities were in the average range. The results of Latent Profile Analysis (LPA) showed further that children characterized by high or low overall performance levels across linguistic and counting skills also showed high or low overall performance levels, respectively, in subsequent reading and arithmetic skills in Grades 1 and

7. Children showing discrepancy between linguistic and counting skills, in turn, showed somewhat discrepant subsequent levels of reading and arithmetic skills.

The results of this study suggest that there is individual variation in the combination of linguistic and basic number skills, and depending on these combinations, the developmental outcomes in reading and arithmetic, as well as the overlap between these skills, differ. Consequently, assessing the cognitive profiles regarding phonological awareness, letter knowledge, RAN, and counting sequence knowledge can provide additional information about the predictors of subsequent reading and arithmetic skill development and help to develop efficient means of support. Children showing early signs of risk in both academic domains are especially at risk for more stable and severe co-occurring difficulties in reading and arithmetic.

3.3 Study III

The aim of Study III was to investigate the extent to which prematurity (very preterm vs. full-term children) is associated with the overlap (i.e., common variance) of reading and arithmetic at the beginning of Grade 1. In previous studies, it has been shown than very preterm children demonstrate a lower skill level than full-term children both in reading and arithmetic (Aarnoudse-Moens et al., 2009; Pritchard et al., 2009; Taylor et al., 2016). Because these two academic skills have been shown to substantially overlap (Cirino et al., 2018; Korpipää et al., 2017), it was hypothesized that prematurity is negatively associated with the shared rather than the nonshared part of reading and arithmetic skills (hypothesis 1).

The second aim of Study III was to investigate the extent to which the association of prematurity with the overlap between reading and arithmetic is mediated by linguistic skills (letter knowledge, phonological awareness, and RAN), basic number skills (digit knowledge and counting sequence knowledge), and general cognitive abilities (nonverbal IQ and verbal IQ). Several studies have shown that very preterm children perform at lower levels than full-term children in these cognitive antecedents (Aarnoudse-Moens et al., 2011; Guarini et al., 2014; Wocadlo & Rieger, 2007). Therefore, the association of prematurity with the overlap between reading and arithmetic was assumed to be accounted for by the differences between very preterm and full-term children in linguistic skills, basic number skills, and general cognitive abilities (hypothesis 2).

First, the results of SEM showed that 41% of the variance in reading skills and 42% of that in arithmetic were explained by the latent common factor—overlap between reading and arithmetic—and thus, represented domain-general variation in these skills. The results also showed that prematurity was statistically significantly and negatively associated with this common variance of reading and arithmetic skills: very preterm children showed a lower skill level common for reading and arithmetic at the beginning of Grade 1 compared to their full-term peers. Moreover, prematurity was negatively related to the

domain-specific variance of arithmetic: very preterm children showed slightly lower arithmetic skills than full-term children independently of their reading skill levels.

Second, the results showed that the overlap between reading and arithmetic skills at Grade 1 was associated with letter knowledge, phonological awareness, RAN, counting sequence knowledge, and performance IQ; the association of prematurity with the overlap between reading and arithmetic was fully accounted for by these five antecedents of overlap. In other words, very preterm children showed lower letter knowledge, phonological awareness, RAN, counting sequence knowledge, and performance IQ than full-term children, and, consequently, they also demonstrated a lower skill level common for reading and arithmetic (i.e., domain-general part of the skill level) than full-term children. The association of prematurity with the domain-specific variation in arithmetic skills was mediated through digit knowledge and letter knowledge, the effects partly compensating each other: Very preterm children showed lower digit and letter knowledge than full-term children, but whereas digit knowledge was positively associated with domain-specific variation in arithmetic, letter knowledge demonstrated a negative association with it.

Overall, the results indicated that the differences between very preterm children and full-term children in reading and arithmetic skills are the result of the domain-general variation rather than the domain-specific variation of these skills. Consequently, premature children who are struggling in one domain should be closely monitored for difficulties in the other domain as well (see also Cirino et al., 2018). The results of the present study provide important insights for educators to support very preterm children's development of both reading and arithmetic skills early enough to diminish the achievement gap between these children and full-term children.

4 GENERAL DISCUSSION

This research aimed to complement the current understanding of the overlap between reading and arithmetic skills from primary to lower secondary school, as well as the underlying cognitive mechanisms of this overlap at different phases of skill development, by using both variable- and person-oriented approaches. More specifically, Study I examined the extent to which reading and arithmetic skills show overlap in Grades 1 and 7, as well as this overlap's time-invariance and time-specificity. Furthermore, the cognitive antecedents of the time-invariant and time-specific parts of the overlap were investigated. Study II investigated whether different cognitive profiles exist based on various linguistic and basic number skills evident among kindergarten-age children. Moreover, the study examined the extent to which different cognitive profiles predict subsequent reading and arithmetic skills in Grades 1 and 7, including these skills' overlap. Finally, in Study III, the role of prematurity in reading and arithmetic skills' overlap was investigated, as well as the extent to which the difference between preterm and full-term children in the overlapping part of reading and arithmetic is mediated by various cognitive antecedents.

4.1 Time-invariance and time-specificity of the overlap

This research's main purpose was to add knowledge of the cross-domain development of reading and arithmetic skills across grade levels using an unselected sample of reading and arithmetic skills from the beginning of primary school (Grade 1) to lower secondary school (Grade 7). Specifically, the research investigated the extent to which reading and arithmetic skills show overlap in Grades 1 and 7, and the extent to which this overlap is shared across these two grades. It was found that reading and arithmetic skills shared about 40%–50% of their variance in Grade 1 (Study I and Study III) and about 30–35% of their variance in Grade 7 (Study I). Most of this overlap (about 30%) was common to Grades 1 and 7 (Study I), representing overlap between reading and

arithmetic skills across Grades 1–7 (time-invariant overlap). Some of it also was specific to these grades and evident only in Grade 1 (14%) or in Grade 7 (3%) (time-specific overlap).

The finding that reading and arithmetic skills are related strongly in both Grade 1 and Grade 7 is consistent with previous findings. A growing body of evidence suggests that the covariation between these skills is substantial among an unselected population in primary school (Chen & Chalhoub-Deville, 2016; Davis et al., 2014; Hecht et al., 2001; Koponen et al., 2007; Rutherford-Becker & Vanderwood, 2009) and lower secondary school (Chen & Chalhoub-Deville, 2016; Codding et al., 2015). Furthermore, the finding that most of this overlap was common to both grades and shown across Grades 1–7 supports the previous studies that indicate a relatively high stability of individual differences in reading (de Jong &van der Leij, 2002; Hulslander et al., 2010; Landerl & Wimmer, 2008; Parrila et al., 2005) and arithmetic (Aunola et al., 2004; Bailey et al., 2014; Watts et al., 2014) across school years. However, in the present research, the overlap between reading and arithmetic skills was investigated longitudinally, and unlike in previous studies, the time-invariant and time-specific parts of the overlap were separated. This study's results add to previous literature by showing that the development of reading and arithmetic skills shares common cognitive processes from primary to lower secondary school. This conclusion is supported further by the findings that among most of the children in the study, reading and arithmetic skills, as well as the cognitive antecedents of these skills, are related strongly across grades (Study II), and that underachievement in these two domains is generalized, rather than specific, among preterm children (Study III).

The results showing that part of the overlap (i.e., shared variance) was time-specific for Grades 1 and 7 (i.e., evident only in Grade 1 or only in Grade 7) provide some evidence that the covariation between reading and arithmetic skills also can be related partly to certain phases of skill development. However, the proportion of this time-specific overlap was minor compared with the time-invariant overlap. Moreover, the higher amount of time-specific overlap discovered between reading and arithmetic in Grade 1 than in Grade 7 suggests that these skills have more in common at an early stage rather than in later stages of development, when both skills are based on serial one-by-one processing with a gradual shift for learning and retrieving larger units (i.e., syllables and words in reading, and arithmetic facts in math) (Koponen et al., 2016).

The substantial overlap between reading and arithmetic skills, as well as high invariance in the overlap found in the present research, suggests that reading and arithmetic skills develop in tandem across grade levels. Furthermore, individual differences in the shared level of skills seem to be well established by the end of the first year of formal schooling. However, it should be noted that the high invariance found in this study does not mean that children's reading and arithmetic skills are not developing. Although schooling

would not remove individual differences in skill levels, it does help improve all children's skills.

4.2 Cognitive antecedents of time-invariant and time-specific parts of the overlap

Another central goal of this research was to determine the cognitive antecedents that predict the cross-domain development of reading and arithmetic skills from primary to lower secondary school. In Study I, it was found that the time-invariant overlap across Grades 1–7 is predicted mainly by linguistic and basic skills regarding RAN and counting, as well as by letter knowledge, working memory, and nonverbal reasoning. The time-specific overlap in Grade 1, in turn, was predicted by phonological awareness, letter knowledge, and counting, whereas the time-specific overlap in Grade 7 was predicted by parental education level and nonverbal reasoning. In line with these findings, Study III's results showed that the overlap between reading and arithmetic skills, at the beginning of school, is predicted by kindergarten letter knowledge, phonological awareness, counting, and RAN, as well as performance IQ.

The results showing that the overlapping part of reading and arithmetic skills across grade levels is related most strongly to RAN and counting support earlier findings that suggest these two cognitive antecedents are the strongest predictors of both reading and arithmetic fluency in Grades 2 and 3 (Koponen et al., 2013, 2016), as well as their covariation in Grade 4 (Koponen et al., 2007). However, for the first time, it was found in the present research that both these skills also predict covariation in reading and arithmetic fluency over time. This finding emphasizes RAN and counting's role as early predictors of fluency in two important academic domains. RAN's predictive role suggests that the time-invariant part of the overlap between reading and arithmetic skills is not simply related to phonological awareness, but more specifically, to how quickly phonological representations can be accessed or how automatic visual-verbal associations are.

The findings also support previous studies that showed the importance of working memory (Alloway & Alloway, 2010; Gathercole et al., 2004) and nonverbal reasoning (Karbach, Gottschling, Spengler, Hegewald, & Spinath, 2013; Rohde & Thompson, 2007; Spinath, Spinath, Harlaar, & Plomin, 2006) in overall school achievement. These general cognitive abilities' role in explaining the overlap between reading and arithmetic skills over time was, after all, minor compared with the role of more specific linguistic and basic number skills. Study III's results also supported this idea by indicating that the overlap between reading and arithmetic at the beginning of school is predicted by linguistic and basic number skills, rather than by general cognitive abilities. The results are in line with previous findings suggesting that general cognitive abilities regarding phonological memory (Hecht et al., 2001), attention, and

nonverbal reasoning (Cirino et al., 2018) account for the overlap between reading and arithmetic, but to a lesser extent than linguistic and basic number skills.

The results concerning the cognitive antecedents of the time-specific overlap between reading and arithmetic in Grade 1 suggest that the cognitive factors behind the overlap partly differ depending on the developmental stage. This time-specific overlap in Grade 1 was found to be related to important indicators of early phases of skills development (i.e., phonological awareness, letter knowledge, and counting) in reading and arithmetic. Consequently, the overlap between these skills at the beginning of school also may be explained by the similarities in acquisition of alphabetic and numeric system principles. Awareness of a language's phonological structure has been shown to play an important role in the development of reading, particularly of basic word-decoding skills (e.g., Hogan, Catts, & Little, 2005; Holopainen et al., 2001; Silvén et al., 2007). In arithmetic, phonological awareness has been found to be associated with early quantity-number skills and, through those skills, with later arithmetic skills (Krajewski & Schneider, 2009). The strongest predictor of the overlap between reading and arithmetic skills in Grade 1, again, was counting ability, which seems to be a good predictor both for initial phases and more automatized phases of skill development in these domains.

Meanwhile, the results concerning the cognitive antecedents of the time-specific overlap between reading and arithmetic in Grade 7 suggest that parental education level and nonverbal reasoning play a role in overlap in later grades. These results are in line with previous findings that indicated the importance of parents' education level (Davis-Kean, 2005) and the child's nonverbal reasoning abilities (Karbach et al., 2013) in overall school achievement during early adolescence. It has been shown that the availability of learning opportunities, support, and resources accentuate individual differences in cognitive abilities (von Stumm & Plomin, 2015). Therefore, children with high initial intelligence and highly educated parents may engage in more reading- and math-related activities during their school years and show high overall performance levels in reading and arithmetic in later grades. It is also possible that high nonverbal reasoning abilities along with upper-level parental education, are advantageous in later grades, especially when reading and arithmetic demands are increasing.

Overall, the present research's findings suggest that reading and arithmetic skills share cognitive processes across grade levels from primary to lower secondary school. However, these cognitive processes vary to some extent, according to the phase of skills development (i.e., serial decoding/counting at the early stage vs. direct retrieval at later stage of skill development). Furthermore, the overlap between reading and arithmetic skills seems to be predicted by linguistic and basic number skills, rather than by general cognitive abilities. In line with previous findings (Cirino et al., 2018; see also Hecht et al., 2001; Koponen et al., 2007), it was found that this overlap is related to cognitive abilities that are linguistic in nature, even if they are

numerically focused (e.g., Cirino et al., 2018) and tap the ability to form and access associative relations (see Fuchs, Geary, Fuchs, Compton, & Hamlett , 2016).

4.3 Individual variations in cognitive profiles predicting both reading and arithmetic skills

The present study research also aimed to complement the variable-oriented approach with the person-oriented approach while investigating individual differences in cognitive profiles, predicting both reading and arithmetic skills later in school. These profiles comprised cognitive antecedents (phonological awareness, letter knowledge, RAN, counting sequence knowledge) found in Studies I and III to predict most strongly the shared variance of reading and arithmetic skills. In Study II, four distinct cognitive profiles—(1) high linguistic and high counting skills, (2) low linguistic and low counting skills, (3) high counting skills in relation to linguistic skills, and (4) low counting skills in relation to linguistic skills—emerged that differentially predicted reading and arithmetic skills, as well as their overlap in Grades 1 and 7. Most of the children (64.6%) showed high or low levels across linguistic and basic number skills and, accordingly, high or low levels of both reading and arithmetic skills across Grades 1–7. Some children (35.4%) showed discrepant levels of linguistic and counting skills and, accordingly, somewhat discrepant levels of reading and arithmetic skills across Grades 1–7. Referring to the list of profiles at the beginning of this paragraph, children with profiles 1 or 2 showed overlap between reading and arithmetic skills in Grades 1 and 7, children with profile 3 showed overlap only in Grade 7, and children with profile 4 showed overlap only in Grade 1.

First, the results concerning the cognitive profiles of high or low overall performance levels across linguistic and basic number skills confirm previous findings that showed fluency in both reading and arithmetic builds on abilities to form and retrieve phonological representations from visually presented symbols, such as letters and digits, as well as the ability to process serial information (Koponen et al., 2007, 2016). It also has been shown that the central manifestation of learning difficulties in both academic domains—reading (Fuchs, Fuchs, Hosp, & Jenkins, 2001) and math (Geary, 2004)—relates to lack of fluency. The present research's results support the idea that learning difficulties' attributes are dimensional, representing a correlated continua of severity (Branum-Martin et al., 2013). Furthermore, these findings, together with the results from Study I and Study III, suggest that linguistic skills and basic number skills regarding phonological awareness, letter knowledge, RAN, and counting have additive impacts on reading and arithmetic skills; i.e., the higher the level of all these cognitive antecedents, the higher the overall performance level of reading and arithmetic across Grades 1–7.

The results from the present research also suggest that although reading and arithmetic skills as well as the cognitive antecedents of these skills, vary together for most of the children, there are subgroups of children who show, to some extent, differing outcomes. Children with high counting skills in relation to linguistic skills (profile 3) performed higher in arithmetic than in reading in Grade 1, but they showed overlap between reading and arithmetic skills in Grade 7. Children with low counting skills in relation to linguistic skills (profile 4), in turn, performed higher in reading than in arithmetic in Grade 7, but they showed overlap between the skills in Grade 1. These results may be explained by the fact that linguistic and basic number skills also predict nonshared variance in reading and arithmetic due to domain-specific content knowledge (Chu, van Marle, & Geary, 2016), with linguistic skills being more predictive of reading than math, and basic number skills being more predictive of math than reading (Cirino et al., 2018).

In line with this, children with profile 3 who had weaknesses in phonological awareness and letter knowledge are likely to have difficulties mainly in the development of basic word-decoding skills (Hogan et al., 2005; Hulme, Boyer-Crane, Carroll, Duff, & Snowling, 2012). However, after children have acquired all the needed subskills to learn to read (Hulme & Snowling, 2013), a rapid increase occurs in their reading performance and a decrease in interindividual variation (Leppänen, Niemi, Aunola, & Nurmi, 2004). Therefore, the difference between reading and arithmetic skills is not anymore evident in later grades. On the other hand, children with profile 4 who had weaknesses in counting may experience increasing difficulties in arithmetic, in particular, as counting skill has been shown to predict strongly the development of fluency, as well as exert its influence in higher grades (Koponen et al., 2016). Furthermore, unlike in reading skills, individual differences in arithmetic skills tend to increase over time (Aunola et al., 2004), when these results also may reflect different developmental trajectories of reading and arithmetic skills during school years.

Moreover, children with high counting skills in relation to linguistic skills, performed lower in arithmetic across grades than did children with high linguistic and high basic number skills. This confirms earlier findings showing that weaknesses in linguistic skills impair aspects of mathematics that rely on the manipulation of verbal codes (e.g., counting speed and number fact recall) (for a review, see Simmons & Singleton, 2008). However, children with low counting skills in relation to linguistic skills performed low across grades in arithmetic despite average linguistic skills. In Grade 7, they performed the lowest in arithmetic, together with those with low linguistic and low counting skills. It is possible that the difficulties in arithmetic stem from weaknesses in number-specific skills, rather than from weaknesses in representing and accessing semantic information (Locuniac & Jordan, 2008) in this group of children. In addition, more general cognitive abilities are likely to play a role in reading and arithmetic performance, as well as in overlap between the skills, as was found in Study I. For all profiles, children performed on an average range

across the measures of working memory, short-term memory, attention, and nonverbal reasoning.

Overall, this study's results suggest that individual variations exist in cognitive profiles comprising shared predictors of reading and arithmetic. Due to the different patterns of performance across linguistic and basic number skills that have both shared and unique influences on reading and arithmetic skills (Cirino et al., 2018), the outcomes also differ. The overlap across grades is related to covariation of these cognitive antecedents, whereas the discrepancy between linguistic and basic number skills is related to somewhat differing levels of reading and arithmetic skills later in school, supporting Pennington's (2006) multiple-deficit framework.

4.4 Prematurity's role in the overlap between reading and arithmetic skills

In addition to different cognitive antecedents, this research aimed to investigate prematurity's relation with the overlap between reading and arithmetic skills at the beginning of school (Study III). Specifically, the research investigated the extent to which very preterm children's lower performance level, compared with full-term children in reading and arithmetic, is related to domain-general variation, rather than domain-specific variation (Study III). The results showed that prematurity was associated negatively with domain-general variation (i.e., overlap between reading and arithmetic), rather than domain-specific variation, in reading and arithmetic skills: very preterm children showed a lower skill level common to reading and arithmetic than full-term children. Moreover, the results from the present research demonstrated that prematurity's negative association with the overlap between reading and arithmetic is accounted for particularly by linguistic and basic number skills regarding letter knowledge, phonological awareness, RAN, and counting sequence knowledge, which were found to predict the overlap in Study I.

The finding that prematurity is associated negatively with the overlap between reading and arithmetic skills supports previous findings that suggested very preterm children tend to perform at lower levels than full-term children both in reading (Kovachy et al., 2014) and arithmetic (Taylor, Espy, & Anderson, 2009). However, the results from the present research add to this previous literature by showing that these risks for underachievement in both academic domains are, in large part, related to each other and share a common cognitive background. Despite the finding that prematurity showed a unique association with arithmetic independent of the level of reading skills, difficulties in mathematical development among very preterm children seem to have, in part, a linguistic basis. This finding is in line with studies that have underscored the importance of reading-related skills in mathematical

development (Krajewski & Schneider, 2009; Zhang et al., 2014) and supports a similar pattern of findings by Hannula-Sormunen et al. (2017).

The results showed that linguistic and basic number skills, rather than general cognitive abilities, accounted for by the difference between very preterm and full-term children in the overlap between reading and arithmetic in Grade 1, support the findings that the academic difficulties are related more to specific than general cognitive abilities (Wocadlo & Rieger, 2007). The results suggest that the most powerful mediators were phonological awareness and counting sequence knowledge, which were found in Study I to be the strongest predictors of the overlap between reading and arithmetic in the early phase of skills development (Korpipää et al., 2017), during which, both skills are based on serial one-by-one processing (i.e., serial decoding in reading and counting-based strategies in arithmetic; see Koponen et al., 2016). However, group differences also were mediated through RAN, which has been found to be related to the development of fluency both in reading and arithmetic together with counting (i.e., direct retrieval of larger units following practice or retrieving arithmetical facts; Koponen et al., 2013, 2016). Furthermore, RAN has been found to be related to the overlap between these skills across grade levels (Study I).

Overall, the findings suggest that the differences between very preterm children and full-term children in reading and arithmetic skills are mainly the result of the domain-general variation of these skills, i.e., variation shared by reading and arithmetic. This can reflect subtle neurodevelopmental deficiencies that underlie weaknesses in cognitive antecedents of reading and arithmetic, and become more obvious at preschool age when children face broader academic demands (Aylward, 2014). Moreover, preterm children's weaknesses in cognitive antecedents that were shown in Study I to predict the overlap between reading and arithmetic at early and later phases of skills development suggest that prematurity may place children at risk for overlapping difficulties in reading and arithmetic that are more severe and stable over time (Jordan et al., 2003; Koponen et al., 2018). The results concerning the negative association of prematurity with the overlap between reading and arithmetic skills further indicate that the factors underlying reading and arithmetic development overlap at many levels, including etiological factors (see Pennington, 2006)

4.5 Limitations and future directions

Although the present research includes some strengths such as the use of longitudinal data and large, population-based data sets — limitations also exist that should be considered before generalizing this research's findings. First, the predictor variables regarding cognitive antecedents in Studies I and II were measured partly at different time points. Whereas phonological awareness, letter knowledge, RAN, and counting sequence knowledge were assessed in kindergarten, working memory, short-term memory, and

inattention/hyperactivity were assessed in Grade 1. Information from nonverbal reasoning, in turn, was available only in Grade 3. Furthermore, the measures of phonological awareness, letter knowledge, and counting were from kindergarten fall, and RAN measures were from kindergarten spring. The measures at the beginning of kindergarten also could function as an indicator of how well prepared children were for school tasks before they started school. After formal instruction and practice at school, the variance related to early training (and nontraining) diminish; thus, it does not exert a long-lasting impact. Thus, having nonverbal reasoning measured in Grade 3 can make it difficult to see how this ability is related to the overlap between reading and arithmetic in Grade 1. However, nonverbal reasoning ability has been shown to be a very stable individual ability (Schneider, Niklas, & Schmiedeler, 2014).

Second, the measures of working memory, short-term memory, and inattention/hyperactivity in Study I and Study II were available only from a subsample. In the absence of relevant data, these three measures were not included in Study III. Moreover, a limited working memory measure with a digit span subtest of WISC-III was used in Studies I and II.

Third, no information was gathered in either of the data sets concerning executive functioning and processing speed, although both previously have been shown to play a role in reading (Bull, Espy, & Wiebe, 2008; Catts, Gillispie, Leonard, Kail, & Miller, 2002) and arithmetic (Bull et al., 2008; Swanson & Beebe-Frankenberger, 2004) development. In future studies, a wider set of control measures should be included when investigating the cognitive antecedents of the overlap between reading and arithmetic skills to gain a deeper understanding of the cognitive mechanisms involved.

Fourth, basic number skills in Studies I and II included only a measure of procedural counting in terms of counting sequence knowledge, which taps the ability to form and access associative relations (see Fuchs et al., 2016). In future studies, conceptual counting and other basic number skills, such as number concept (mapping between symbolic number words and numbers with quantities) and symbolic magnitude comparisons, should be included when investigating the cognitive profiles of reading and arithmetic skills to determine whether low performance mainly in arithmetic derives from weaknesses in number-specific skills.

Fifth, in Study III, reading and arithmetic skills were skewed to low values because participating children were school beginners. Therefore, it is possible that variations in children's reading and arithmetic skills diminish after formal and systematic reading and arithmetic instruction starts in Grade 1. Measures of Grade 1 spring would be more reliable when investigating the differences between preterm and full-term children in terms of the overlap between reading and arithmetic skills.

Finally, the Finnish language's transparent orthography should be taken into account when generalizing these findings to other languages. Due to the highly consistent grapheme–phoneme correspondence structure, decoding in Finnish requires less advanced phonological processing skills than in more

opaque orthographies, such as English. Moreover, regarding orthography's transparency, the variance in reading skills derives mainly from fluency, not accuracy, even though reading efficiency (reading words accurately within a time limit) was used as an outcome measure. Due to the transparency of Finnish orthography, in which grapheme–phoneme correspondences are equally regular for spelling as they are for reading, spelling was not investigated. In future studies in languages with less transparent orthographies, spelling should be included as a separate outcome variable.

4.6 Ethical issues

The present research was carried out in the context of two broader research projects: The First Steps longitudinal age cohort study (Lerkkanen, Niemi, et al., 2006), and the multidisciplinary Development and Functioning of Very Low Birth Weight Infants from Infancy to School Age (PIPARI) project. Thus, the data collections and data sets that were used already were gathered before the studies on this research were carried out. The Hospital District of Southwest Finland's Ethics Review Committee approved the PIPARI study protocol, and the University of Jyväskylä's Ethical Committee approved the First Steps study protocol. The parents of all participating children were informed about the study and provided written consent. Only anonymized data were used, without any identification information available for the author of the present research. Moreover, after analysis and publication, all data sets and data-related information were deleted from the author's files.

4.7 Practical implications

In the present research, the development of reading and arithmetic skills was investigated in terms of overlap (i.e., covariation between reading and arithmetic), which made it possible to investigate the extent to which these two academic skills develop in relation to each other and share the same underlying cognitive mechanisms. The results from this research add to previous literature by showing that reading and arithmetic skills are strongly related during both primary and lower secondary school, and that most of this overlap exists across grade levels due to the partly shared cognitive processes during different phases of skills development. The overlap between reading and arithmetic across grade levels mainly was predicted by fluency indicators in both domains, such as counting and RAN. These findings also suggest that the shared skill level of reading and arithmetic is well established already at the beginning of a school career; thus, skills development in those children, who might develop fluency problems in these two academic domains, should be followed up, both in reading and arithmetic. RAN and counting can be used as diagnostic tools to

detect those children before school age. Furthermore, a need exists to support the development of fluency, in particular, in reading and math domains, which has received less attention in intervention research.

Unlike in previous studies, the cognitive antecedents of the time-invariant and time-specific parts of the overlap between reading and arithmetic skills were investigated separately. The results concerning the time-specific overlap between reading and arithmetic showed that this overlap is, in part, also related to certain phases of skills development. Cognitive antecedents, such as phonological awareness, played a particularly important role at an early phase, whereas parents' education levels and more general reasoning skills were significant at a later phase of fluency development in both domains. This finding suggests that intensive, preventive support for children who show impairment in phonological processing could be an efficient way to support the early phases of skills development in reading and arithmetic. However, skill levels in later grades is likely to require a more general type of support, such as interventions aimed at increasing students' motivation and engagement.

The results suggest further that individual differences exist in cognitive profiles regarding linguistic and basic number skills, and due to these different individual profiles, the outcomes and overlapping in reading and arithmetic skills also differ. Among most of the children (64%), linguistic and basic number skills were related strongly, which was evident as the children showed either high or low performance levels across all these skills. This covariation of linguistic and basic number skills predicted overlapping either high or low overall performance levels in reading and arithmetic skills during primary and lower secondary school. However, among some of the children (about 35%), linguistic and basic number skills were less related, and the discrepant patterns of linguistic and basic number skills predicted somewhat discrepant levels of subsequent reading and arithmetic skills as well. Therefore, assessing cognitive profiles according to linguistic and basic number skills provides additional information about the need for support during different phases of skills development. Furthermore, recognizing children who show signs of weaknesses across cognitive antecedents is important in preventing more severe and stable comorbid learning difficulties in these domains.

Finally, focusing on prematurity's relation with the overlap between reading and arithmetic made it possible to examine to what extent the previously found group differences between very preterm and full-term children in reading and arithmetic skills are domain-general rather than domain-specific. The results indicated that these differences in skill levels between the groups mainly are the result of the domain-general variation of reading and arithmetic skills. An important implication is that premature children who are struggling in one domain should be monitored closely for difficulties in other domain as well (see also Cirino et al., 2018). The results of the present research provide important insights for educators to support very preterm children's development of both reading and arithmetic skills early enough to diminish the achievement gap between these children and full-term

children. As it was found in the present research that the shared level of these skills is well established by the first year of school, more attention to training linguistic and basic number skills among very preterm children is necessary during their kindergarten year. Such an intensive follow-up might prove valuable in later grades.

4.8 Concluding remarks

This research focused on the cross-domain development of reading and arithmetic skills from primary to lower secondary school, as well as this overlap's underlying cognitive mechanisms. Overall, the results suggest that reading and arithmetic skills show substantial overlap across grade levels from primary to lower secondary school, and this overlap is due to the partly shared cognitive background in developing fluency. Linguistic and basic number skills related to forming and retrieving associative relations were found to be highly predictive of performance in both reading and arithmetic. Among most of the children, these foundations vary together, suggesting that substantial overlap exists not only in reading and arithmetic, but also in these skills' cognitive antecedents. The findings that prematurity was related mainly to generalized weaknesses in these two domains further support the overlapping nature of skills development in reading and arithmetic. Therefore, close monitoring and support are needed in both academic domains among children who show early signs of risk for difficulties in one domain.

YHTEENVETO (SUMMARY)

Luku- ja laskutaidon kehityksen päällekkäisyys alakoulusta yläkouluun ja taustalla vaikuttavat kognitiiviset mekanismit

Luku- ja laskutaito ovat keskeisiä koulussa opittavia taitoja (Durand, Hulme, Larkin, & Snowling, 2005), jotka muodostavat perustan myöhemmälle oppimiselle (Duncan ym., 2007; Rabiner, Godwin, & Dodge, 2016). Ongelmat näillä alueilla näkyvät erityisesti sujuvuuden kehityksessä eli nopean ja tarkan tekstin lukemisen tai peruslaskutoimitusten hallinnassa (Geary, 1993; Ziegler et al., 2003). Sujuvuuden kehityksen tiedetään etenevän molemmilla alueilla samankaltaisten vaiheiden kautta (Koponen ym., 2016). Sekä lukeminen että laskeminen perustuvat taidon kehityksen alkuvaiheessa yksittäisten kirjaimien ja numeroiden sarjalliseen prosessointiin. Taitojen automatisoitumisen myötä siirrytään vähitellen prosessoimaan suurempia yksiköitä, kuten tavuja ja sanoja lukemisessa ja aritmeettisia faktoja laskemisessa. Aikaisemmissa tutkimuksissa luku- ja laskutaidon välillä on havaittu melko voimakas yhteys (Davis ym., 2014; Chen & Chalhoub-Deville, 2016) ja näiden taitojen kehitykseen liittyvien ongelmien yhteisesiintymisen (ts. päällekkäisyyden) tiedetään olevan varsin yleistä (Koponen ym., 2018; Landerl & Moll, 2010). Lisäksi tiedetään, että esiopetusvuoden alkuvalmiudet, kuten fonologinen tietoisuus, kirjaintuntemus, nopean nimeämisen taidot ja lukujonotaidot sekä yleisemmät tiedonkäsittelytaidot ennustavat sekä luku- että laskutaidon kehitystä kouluiässä (Cirino ym., 2018; Hecht ym., 2001; Koponen ym., 2007). Tietoa siitä, miten pysyvää luku- ja laskutaidon kehityksen yhteys on läpi kouluvuosien, ja missä määrin näillä taidoilla on yhteinen tiedonkäsittelytausta kehityksen eri vaiheissa, on kuitenkin vähän. Tämän tutkimuksen tavoitteena oli tarkastella luku- ja laskutaidon kehityksen päällekkäisyyttä valikoimattomassa otoksessa peruskoulun 1. luokalta 7. luokalle sekä kehityksen päällekkäisyyteen yhteydessä olevia tekijöitä sekä muuttuja- että henkilökeskeisellä lähestymistavalla. Lisäksi tavoitteena oli tarkastella keskosuuden muodostamaa riskiä luku- ja laskutaidon yhteisen taitotason kehityksessä koulun alussa.

Ensimmäinen osatutkimus perustui laaja-alaiseen Jyväskylän yliopiston Alkuportaat -seurantatutkimukseen, jossa samojen lasten kehitystä on seurattu esikouluiästä alkaen yläkouluikään. Tähän osatutkimukseen valikoitui 1,335 lasta, joiden luku- ja laskutaidon päällekkäisyyttä tarkasteltiin 1. luokalta 7. luokalle. Tavoitteena oli selvittää, miten suuri osa luku- ja laskutaidoissa esiintyvästä vaihtelusta on näille taidoille yhteistä (lukemisen ja laskemisen yhteinen taitotaso), ja miten suuri osa tästä yhteisvaihtelusta ilmenee yli ajan 1. luokalta 7. luokalle ja miten suuri osa puolestaan on kehitysvaiheesta riippuvainen eli ilmenee vain 1. tai 7. luokalla. Tavoitteena oli myös selvittää miten ja mitkä alkuvalmiudet (fonologinen tietoisuus, kirjaintuntemus, nopeannimeämisen taidot, lukujonotaidot) ja yleisemmät tiedonkäsittelytaidot (työmuisti, ei-kielellinen päättelykyky) sekä vanhempien koulutustaso ennustavat yhtäältä luku- ja laskutaidolle yhteistä kehitysvaiheesta

riippumatonta taitotasoa 1. ja 7. luokalla sekä toisaalta tietylle kehitysvaiheelle ominaista luku- ja laskutaidon jakamaa taitotasoa. Tulokset osoittivat, että n. 40-50 % luku- ja laskutaidon vaihtelusta on näille taidoille yhteistä 1. luokalla ja n. 30-35% 7. luokalla. Tulokset myös osoittivat, että n. 30% luku- ja laskutaidon yhteisvaihtelusta on näille kehitysvaiheille yhteistä eli ilmenee yli ajan 1. luokalta 7. luokalle. Noin 14% yhteisvaihtelusta esiintyi ainoastaan 1. luokalla ja 3% ainoastaan 7. luokalla. Läpi kouluvuosien ilmenevä luku- ja laskutaidon yhteisvaihtelu (yhteinen taitotaso) oli kaikkein voimakkaimmin yhteydessä esikouluiän alkuvalmiuksiin (nopean nimeämisen taidot, lukujonotaidot, kirjaintuntemus) mutta myös työmuistiin ja ei-kielelliseen päättelykykyyn. Yhteisvaihtelu, joka esiintyi ainoastaan 1. luokalla, oli voimakkaimmin yhteydessä taitojen kehityksen varhaisvaiheen ennustajiin (fonologinen tietoisuus, kirjaintuntemus ja lukujonotaidot), kun taas yhteisvaihtelu, joka esiintyi ainoastaan 7. luokalla, oli yhteydessä ei-kielelliseen päättelykykyyn ja vanhempien koulutustasoon.

Toinen osatutkimus perustui samaan Alkuportaat-seurantatutkimukseen kuin ensimmäinen osatutkimus ja siihen valikoitui tutkittujen muuttujien perustella 1,710 lasta. Tässä tutkimuksessa tavoitteena oli tarkastella luku- ja laskutaidon alkuvalmiuksien muodostamia taitoprofiileja, joiden havaittiin voimakkaimmin ennustavan ensimmäisessä osatutkimuksessa luku- ja laskutaidon päällekkäisyyttä kouluiässä (fonologinen tietoisuus, kirjaintuntemus, nopean nimeämisen taidot, lukujonotaidot). Tavoitteena oli myös tarkastella miten nämä erilaiset profiilit ovat yhteydessä luku- ja laskutaidon kehitykseen sekä näiden taitojen yhteisvaihteluun 1. ja 7. luokilla. Tämän tutkimuksen tulokset osoittivat, että valtaosalla lapsista (n.65%) luku- ja laskutaidon alkuvalmiudet vaihtelivat voimakkaasti yhdessä esikouluiässä ja tämä ennusti korkeaa tai matalaa taitotasoa sekä luku- että laskutaidossa ja näiden taitojen voimakasta yhteisvaihtelua läpi kouluvuosien. Osalla lapsista (n. 35%) sekä esikouluiän luku- ja laskutaitojen alkuvalmiudet että kouluiän luku- ja laskutaidot olivat eri tasoilla ja yhteisvaihtelu oli vähäisempää. Näillä lapsilla heikkoudet olivat enemmän lukemisen tai laskemisen alueilla, mutta luku- ja laskutaidon yhteinen taitotaso oli korkeampi kuin niillä lapsilla, joilla ilmeni ongelmia molemmilla aluilla ja matalampi kuin niillä lapsilla, joilla taitotaso oli korkea molemmilla alueilla.

Kolmannen osatutkimuksen tavoitteena oli tarkastella, missä määrin ennenaikaisina syntyneiden lasten täysiaikaisina syntyneitä lapsia keskimääräistä alhaisemmat taidot sekä lukemisen että laskemisen alueilla (Aarnoudse-Moens et al., 2009) liittyvät näille taidoille yhteiseen taitotasoon ja tiedonkäsittelytaustaan. Tutkimus perustui Turun yliopistollisen keskussairaalan PIPARI -seurantatutkimukseen, jossa ennenaikaisina (n=193) ja täysiaikaisina (n=175) syntyneiden lasten kehitystä on seurattu syntymästä kouluikään. Tässä tutkimuksessa tavoitteena oli selvittää keskosuuden muodostamaa riskiä luku- ja laskutaidon jakamaan taitotasoon koulun alussa sekä näiden yhteyksien välittymistä erilaisten alkuvalmiuksien (fonologinen tietoisuus, nopean nimeämisen taidot, kirjaintuntemus, lukujonotaidot,

numeroiden nimeäminen) ja yleisempien tiedonkäsittelytaitojen (kielellinen ja ei-kielellinen päättelykyky) kautta vanhempien koulutuksen ja lapsen sukupuolen huomioinnin jälkeen. Tulokset osoittivat, että keskosuus muodostaa riskin lähinnä luku- ja laskutaidon yhteisen taitotason kehitykseen erityisesti erilaisten alkuvalmiuksien (fonologinen tietoisuus, kirjaintuntemus, nopean nimeämisen taidot ja lukujonotaidot), mutta myös yleisempien tiedonkäsittelytaitojen (ei-kielellinen päättelykyky) kautta. Lisäksi tutkimuksessa havaittiin, että keskosuus ennusti myös lukutaidosta riippumatonta laskutaidon tasoa, joka oli ennenaikaisilla lapsilla täysiaikaisina syntyneitä lapsia alhaisempi.

Kaiken kaikkiaan tutkimuksen tulokset osoittivat, että merkittävä osa luku- ja laskutaidon kehityksestä on päällekkäistä alakoulusta yläkouluun ja tämä selittyy osin sillä, että näillä taidoilla on osittain sama tiedonkäsittelytausta kehityksen eri vaiheissa. Lisäksi tulokset osoittivat, että luku- ja laskutaidon päällekkäisyys on voimakkaampaa taidon kehityksen alkuvaiheessa kuin myöhäisemmässä vaiheessa: tämän voidaan ajatella johtuvan varhaisten kehitysvaiheiden samankaltaisuudesta. Erityisesti alkuvalmiudet, jotka ovat voimakkaasti yhteydessä luku- ja laskutaidon automatisoitumiseen, ennustavat esikouluiässä lukemisen ja laskemisen yhteistä taitotasoa läpi kouluvuosien. Erilaiset alkuvalmiuksien taitoprofiilit ennakoivat kuitenkin eri tavoin luku- ja laskutaidon kehitystä suhteessa toisiinsa peruskoulun aikana. Tulokset myös osoittivat, että keskosuus muodostaa riskin yleistyneille, sekä luku- että laskutaidon alueilla ilmeneville kehitysviiveille näiden taitojen yhteistä tasoa ennustavien alkuvalmiuksien kautta. Tämä viittaa luku- ja laskutaidon varhaisten kehityksellisten prosessien osittaiseen päällekkäisyyteen. Tulokset tukevat ajatusta, että ennenaikaisina syntyneiden lasten täysiaikaisina syntyneitä lapsia heikommilla taidoilla erityisesti matematiikassa, on osin kielellinen tausta. Luku- ja laskutaidon kehityksen yhteydestä johtuen on tärkeää kiinnittää huomiota molempiin taitoalueisiin erityisesti niiden lasten kohdalla, joilla ilmenee ongelmia oppimisessa toisella näistä alueista. Heikkoudet kaikissa lukemisen ja laskemisen alkuvalmiuksissa ennakoivat päällekkäisiä ongelmia näillä alueilla läpi kouluvuosien. Näiden lasten tunnistaminen on tärkeää jo esikouluiässä, koska luku- ja laskutaidon yhteisen taitotason havaittiin olevan suhteellisen pysyvä 1. luokalta 7. luokalle. Tutkimus myös osoittaa tarpeen kehittää erityisesti luku- ja laskutaidon sujuvuutta tukevia interventioita lukemiselle ja laskemiselle yhteisen taitotason parantamiseksi ja päällekkäisten oppimisvaikeuksien ennaltaehkäisemiseksi.

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ORIGINAL PAPERS

I

COVARIATION BETWEEN READING AND ARITHMETIC SKILLS FROM GRADE 1 TO GRADE 7

by

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Empirical study

Covariation between reading and arithmetic skills from Grade 1 to Grade 7 ☆

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ABSTRACT

This study examined the extent to which reading and arithmetic skills show covariation at Grade 1 and at Grade 7, to what extent this covariation is time-invariant or time-specific, and to what extent different antecedents will predict these time-invariant and time-specific portions of the covariation. The reading and arithmetic skills of a total of 1335 Finnish children were assessed at the end of Grade 1 and then again at the end of Grade 7. Phonological awareness, letter knowledge, rapid automatized naming (RAN), counting, and parental education levels were measured in kindergarten; working memory at Grade 1 and nonverbal reasoning at Grade 3. The results showed that reading and arithmetic had a substantial amount of covariation at grades 1 and 7, and that most of the covariation between these grades was time-invariant and could be predicted by RAN, counting, letter knowledge, working memory, and nonverbal reasoning. The time-specific portion of the covariation between reading and arithmetic in Grade 1 was predicted by phonological awareness, letter knowledge, and counting; while time-specific covariation in Grade 7 was predicted by parental education level and nonverbal reasoning.

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1. Introduction

Research on the development of different components of reading and math skills has traditionally focused on each skill domain separately. During the last ten years, however, there has been increasing interest in examining the covariation between reading and math (Koponen, Aunola, Ahonen, & Nurmi, 2007) and their joint antecedents (e.g., Durand, Hulme, Larkin, & Snowling, 2005; Koponen, Salmi, Eklund, & Aro, 2013; Koponen et al., 2016). Similarly, the coexistence of reading and math difficulties (Landerl & Moll, 2010; Moll, Kunze, Neuhoff, Bruder, & Schulte-Körne, 2014) and the possible shared and unique cognitive backgrounds to these difficulties have been investigated (Landerl, Fussenegger, Moll, & Willburger, 2009; Slot, van Viersen, de Bree, & Kroesbergen, 2016). Although previous studies have confirmed the association between reading and math skills among both population-based (Davis et al., 2014; Koponen et al., 2007; Rutherford-Becker & Vanderwood, 2009) and clinical samples (Landerl & Moll, 2010; Moll et al., 2014), several fundamental questions still remain unclear. First, because most of the earlier studies have been cross-sectional, little is known about the extent to which the covariation between reading and math skills is based on similar processes across time or whether this covariation is specific to certain grade levels (i.e., varies according to the phase of skill development). Second, there are conflicting views concerning the cognitive antecedents of covariation between reading and math skills. On the one hand, it has been suggested that reading and math skills partially share underlying cognitive processes (Hecht, Torgesen, Wagner, & Rashotte, 2001; Koponen et al., 2013, 2016). On the other, reading and math difficulties have been seen to result from two different cognitive core problems, that is, problems in phonological processing and in number sense, respectively (Landerl et al., 2009). To shed more light on these questions, longitudinal research on the time-invariance and time-specifity of the shared variation between reading and math is needed – as well as the key cognitive antecedents of this variation. The present study thus aims to

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examine the extent to which reading and arithmetic skills show shared variation at Grade 1 and Grade 7; to what extent this shared variation is time-invariant or time-specific; and to what extent parental education, general cognitive abilities, and pre-skills in both subjects predict the time-invariant and time-specific portions of covariation between reading and arithmetic skills across grades 1 and 7.

1.1. Covariation of reading and arithmetic skills

A growing body of research has shown that there are substantial intercorrelations (i.e., covariation) between reading and math skills among unselected populations during the primary (Chen & Chalhoub-Deville, 2016; Davis et al., 2014; Koponen et al., 2007; Rutherford-Becker & Vanderwood, 2009) and lower secondary school years (Chen & Chalhoub-Deville, 2016; Codding, Petscher, & Truckenmiller, 2015). Correlations in the moderate to high range, of up to 0.60 (Davis et al., 2014), have been observed for all grades examined, regardless of gender, family socioeconomic status (SES), and race/ethnicity (Chen & Chalhoub-Deville, 2016). Difficulties in one academic domain have also been found to clearly increase the risk of difficulties in the other in studies specifically looking at their co-occurrence (Jordan, Wylie, & Mulhern, 2010; Landerl & Moll, 2010).

In previous research focusing on the comorbidity of math and reading difficulties, or on the covariation of reading and math skills, various kinds of operationalization of these skills have been used: some studies focusing on accuracy and some others on speed, for example. With respect to reading, Share (2008) suggested that the irregular orthography of the English language has led to an emphasis on the accuracy of oral reading as a measure of reading skill, at the expense of silent reading, reading speed, and comprehension. However, in most alphabetic orthographies, accuracy of reading is generally achieved rather rapidly, after which the individual variation is mostly only observable in reading fluency – that is, combined measures of accuracy and speed (e.g., Seymour, Aro, & Erskine, 2003). Speed problems have been shown to be characteristic of problems in reading development in both irregular and regular orthographies (Ziegler, Perry, Ma-Wyatt, Ladner, & Schulte-Körne, 2003). Equally, the speed at which math problems are solved has proved indicative of problems in the development of different components of math skills – especially in arithmetic skills (Geary, 1993). Thus, in order to better understand the relation between math and reading development, it seems relevant to focus on outcome measures which take into account both the accuracy and speed of performance. Consequently, the terms 'reading and arithmetic skills' are used in the present study to refer to fluency in them (accuracy and speed combined). Because these skills are better conceived as continuous rather than discrete variables (Branum-Martin, Fletcher, & Stuebing, 2012), a dimensional approach will be used to examine the covariation between reading and arithmetic skills among an unselected population.

1.2. Interindividual stability of reading and arithmetic skills

Both reading skills (Hulslander, Olson, Willcutt, & Wadsworth, 2010; Landerl & Wimmer, 2008; Parrila, Aunola, Leskinen, Nurmi, & Kirby, 2005) and arithmetic skills (Aunola, Leskinen, Lerkkanen, & Nurmi, 2004; Bailey, Watts, Littlefield, & Geary, 2014; Watts, Duncan, Siegler, & Davis-Kean, 2014) have been found to show moderate to high interindividual stability across school years, suggesting that a substantial portion of skill variation is time-invariant. For example, in the longitudinal study by Landerl and Wimmer (2008), the stability of individual differences in reading fluency (in a regular orthography) was observed to be high from Grade 1 to Grade 8. Similarly, Watts et al. (2014) found high stability in mathematical achievement across school grades even if the variance increased (see also, Aunola et al., 2004). Overall, these studies indicate that an individual's relative skill-level in reading and arithmetic might be established in the early years of school and remain rather invariant after that.

1.3. Time-invariance and time-specificity in the covariation of reading and arithmetic skills across school grades

Although much is known about the inter-individual stability of reading and arithmetic skills across school grades, less is known about whether the covariation of these skills is time-invariant (i.e., shared over time) or time-specific (i.e., unique for different grades). Similarly, although previous research has shown a substantial amount of covariation between reading and arithmetic skills among unselected populations during the primary (Chen & Chalhoub-Deville, 2016; Koponen et al., 2007) and lower secondary (Chen & Chalhoub-Deville, 2016; Codding et al., 2015) school years, little is known about whether this covariation is common over different grades or, alternatively, whether it is unique for a particular grade only. The present study thus examined the extent to which reading and arithmetic skills show shared variation at grades 1 and 7, and whether it was time-invariant or time-specific to them. To do this, the covariation between reading and arithmetic skills at grades 1 and 7 was divided into three parts: the time-invariant part common to both grades 1 and 7, and time-specific parts typical only to either Grade 1 or Grade 7.

It is commonly accepted that, when children start school, both reading and arithmetic skills are acquired via serial processing: reading is based on phonemic assembly, whereas arithmetic is based counting-based calculation strategies (Koponen et al., 2016). After this initial stage, there is a gradual shift towards the processing and retrieving of larger units, such as syllables or words in reading, and arithmetic facts in math. As reading and arithmetic fluency become automatized (Koponen et al., 2007, 2016), however, it is possible that the covariation between reading and arithmetic is not constant; rather it varies according to the different phase of skill development (i.e., serial decoding/counting at the early stage of skill development vs. automatized phase relying strongly on direct retrieval at later stage of skill development). Another possibility is that reading and arithmetic skills have a persistent relationship across grade levels as suggested by Chen and Chalhoub-Deville (2016). Studies showing that there is a significant genetic overlap in reading and math skills (Hart, Petrill, Thompson, & Plomin, 2009) also support this.

1.4. Antecedents of covariation between reading and arithmetic skills

It has been suggested that the covariation of reading and arithmetic skills (Hecht et al., 2001; Koponen et al., 2007), as well as the comorbidity of related difficulties (Cirino, Fuchs, Elias, Powell, & Schumacher, 2015; Peng & Fuchs, 2016; Willcutt et al., 2013), are partly due to same cognitive processes being involved in the development of both domains. In previous studies, suggested cognitive predictors for both have included linguistic skills (Hecht et al., 2001; Koponen et al., 2007, 2016; Simmons, Singleton, & Horne, 2008), basic number skills (Koponen et al., 2007, 2016), and general cognitive abilities (Alloway & Alloway, 2010; Clair-Thompson & Gathercole, 2006; Gathercole, Pickering, Knight, & Stegmann, 2004; Rohde & Thompson, 2007).

Empirical research in reading and arithmetic has supported the notion that many linguistic skills are related to both academic domains. For example, phonological awareness, i.e., the ability to analyze the sound structure of oral language, has been shown to be a strong predictor of both reading (de Jong & van der Leij, 1999, 2002; Leppänen, Aunola, Niemi, & Nurmi, 2008) and

arithmetic skills (De Smedt, Taylor, Archibald, & Ansari, 2010; Hecht et al., 2001; Simmons et al., 2008) especially in the early phases of skill development. There are, however, some studies where this association has not been found with respect to arithmetic skills (Durand et al., 2005; Passolunghi & Lanfranchi, 2012). The double-deficit hypothesis presented by Wolf and Bowers (1999) proposes that problems with phonological processing and naming speed are separable sources of dysfunction. This has been confirmed in children with reading difficulty or comorbid reading and arithmetic difficulty (Heikkilä, Torppa, Aro, Närhi, & Ahonen, 2016). In line with this suggestion, rapid automatized naming (RAN), i.e., the ability to name sequentially presented familiar symbols (e.g., objects, colors, letters, or digits), has been shown to be an important indicator of fluency not only in reading (Kirby, Georgiou, Martinussen, & Parrila, 2010), but also in arithmetic (Koponen et al., 2013, 2016). Koponen et al. (2016) found too that RAN was a strong predictor of both reading and arithmetic fluency development, even after controlling for a number of other underlying skills, such as phonological awareness and memory. During primary school, letter knowledge – as a basis for understanding the alphabetic principle – has also been shown to be a powerful predictor of both reading (Leppänen et al., 2008; Lerkkanen, Rasku-Puttonen, Aunola, & Nurmi, 2004) and arithmetic fluency development (Zhang et al., 2014). According to Koponen et al. (2007) the ability to learn and retrieve the phonological representations of visual symbols could be a process needed both in learning letters and number words, and thus it could be a common prerequisite for learning to both read and calculate. Up to now, only a few studies have examined the predictors of covariation in reading and arithmetic (Hecht et al., 2001; Koponen et al., 2007); and these have found that all three linguistic skills – phonological awareness, RAN and letter knowledge – are positively related to covariation in reading and calculation from grades 2 to 5 (Hecht et al., 2001; Koponen et al., 2007).

In addition to linguistic skills, basic number skills might also be associated with the covariation of reading and arithmetic skills. Previous findings from separate studies on reading and arithmetic suggest, for example, that the ability to count number words (forwards, backwards, and in steps) at age six and seven predicts the later development in primary school of both arithmetic (Aunola et al., 2004; Zhang et al., 2014) and reading skills (Koponen et al., 2013). Studies on the covariation of reading and arithmetic have also shown that a shared skill level in reading and calculation fluency at Grade 4 is strongly predicted by the counting ability shown at kindergarten (Koponen et al., 2007). One possible explanation for the relationship between counting and fluency in both reading and arithmetic is the ability to grasp rules describing the relations between elements repeatedly within a sequence (Koponen et al., 2013, 2016). In most alphabetic orthographies grapheme-phoneme correspondences are regular and predictable. For early reading, this means that the pronunciation of written words is achieved reliably by serial assembly of phonemic representations of single graphemes. Thus, at the early stages of development of both reading and arithmetic, letters and numbers are processed one by one [i.e., A-U-T-O (car); 1, 2, 3, 4, . . .] after which processing becomes more automatized following practice (i.e., recognizing syllables AU-TO and whole words AUTO or skip counting 5, 10, 15, and fact retrieval).

Besides linguistic and basic number skills, more general cognitive learning abilities have been identified as potential predictors of covariation in reading and arithmetic. A study by Alloway and Alloway (2010), for example, showed that children's working memory at age five predicted their academic attainment in both domains six years later (after controlling for IQ). Working memory, that is the ability to retain information in the correct order while processing it, requires control of attention, retrieval of information from long-term memory and temporary storage of verbal and visuospatial information (Baddeley, 2000). The phonological aspects of working memory (Alloway & Alloway, 2010; Gathercole et al., 2004; Stevenson, Bergwerff, Heiser, & Resing, 2014) and central executive ability (Clair-Thompson & Gathercole, 2006) have been found to be closely associated with both reading and math skills. Nonverbal reasoning is also a good predictor of school achievement in both academic domains (Karbach, Gottschling, Spengler, Hegewald, & Spinath, 2013; Rohde & Thompson, 2007; Spinath, Spinath, Harlaar, & Plomin, 2006). Of these general cognitive skills, limitations in working memory is the most typical among children with reading and math (including arithmetic) difficulties (Cirino et al., 2015; Moll, Göbel, Gooch, Landerl, & Snowling, 2016; Peng & Fuchs, 2016; Willcutt et al., 2013).

Parental education may also play a role in the covariation of reading and arithmetic skills, as it has been shown to be one of the best predictors of children's educational achievement (Davis-Kean, 2005; Eccles, 2005; Sharma & Jha, 2014). For example, in a study by Larson, Shirley, Bergen, Olson, and Halfon (2015), family SES (i.e., a composite of parents' education, occupational status, and household income) explained over half of the individual differences in early reading and math skills. It has been shown that SES directly relates to a child's academic achievement; not only through heritable traits (Kraphol & Plomin, 2016), but also indirectly through the parents' beliefs about achievement and stimulating behaviors (Davis-Kean, 2005; see also Eccles, 2005).

Although different antecedents have been suggested for the covariation between reading and arithmetic skills, this covariation has rarely been examined over several grades. Consequently, little is known about the antecedents of the time-invariant and time-specific portions of that covariation across school grades. The second aim here is thus to examine the extent to which the known antecedents of reading and arithmetic skills (i.e., phonological awareness, RAN, letter knowledge, counting); general cognitive abilities (nonverbal reasoning, working memory); and parental education predict the time-invariant and time-specific portions of covariation between reading and arithmetic skills from grades 1 to 7.

1.5. Research questions

The present study examined the following research questions:

(1) Given that reading and arithmetic skills show covariation (shared variance) at grades 1 and 7, to what extent is this covariation time-invariant (shared at two grades), and to what extent is it time-specific (unique to a particular grade)?

Two alternative hypotheses were proposed: (1a) Because it has been suggested that both reading and arithmetic skills are based on similar cognitive processes at different grades (Hecht et al., 2001; Koponen et al., 2013, 2016), we expected that a large part of the covariation between these two skills would be time-invariant. (1b) Our alternative hypothesis was that part of the covariation between reading and arithmetic is time-specific, as the acquisition of both reading and arithmetic skills is known to include not only serial processing at the early stages (Koponen et al., 2016), but also the processing and retrieving of larger units later on, such as syllables or words in reading, and arithmetic facts in math. Covariation thus represents the association here between reading and arithmetic skills, which we were then differentiated into time-invariant and time-specific parts.

(2) To what extent do reading and arithmetic pre-skills, general cognitive abilities, and parental education in kindergarten predict the time-invariant and time-specific portions of covariation between reading and arithmetic skills at grades 1 and 7?

Our two hypotheses to this research question were that: (2a) kindergarten pre-skills of reading and arithmetic (phonological awareness, letter knowledge, and counting) would predict time-specific covariation between reading and arithmetic skills in Grade 1 (Holopainen, Ahonen, & Lyytinen, 2001; Krajewski & Schneider, 2009; Silvén, Poskiparta, Niemi, & Voeten, 2007); and that (2b) more general cognitive processes (rapid automatized naming, working memory, and nonverbal reasoning) would predict the time-invariant part of the covariation between these skills.

2. Method

2.1. Participants and procedure

This study is part of an extensive longitudinal age cohort study (Lerkkanen, Niemi, et al., 2006), which follows up a community sample of children (n = 1880) from one rural and three urban municipalities in Finland from kindergarten entry (age $M = 74.0 \pm 3.6$ months) to the end of lower secondary (age 15). All of the age cohort in the rural and two of the urban municipalities, plus about a half of the age cohort from the remaining urban municipality were used in this study. Parents were asked for written consent for their child to participate. Most of the children (80%) came from nuclear families, 10% from single parent families, 8% from blended families, and 2% from families where the parents were divorced and the child lived in two homes.

There was a total of 1335 children (47.1% girls) participating in the present study that had performance data available for reading and arithmetic in both grades 1 and 7. These children showed a higher skill-level in reading ($M = 18.73$, $SD = 7.80$) and arithmetic ($M = 11.01$, $SD = 3.94$) at Grade 1 than those in the larger population of 1880 who participated only at Grade 1 ($M = 16.76$, $SD = 8.38$, $t\ (2030) = -5.27$, $p < 0.001$ for reading; and $M = 9.59$, $SD = 4.17$, $t\ (2049) = -7.61$, $p < 0.001$ for arithmetic). Similarly, children who participated at both grades showed a higher skill-level of reading ($M = 33.64$, $SD = 7.29$) and arithmetic ($M = 13.93$, $SD = 3.71$) at Grade 7 than those in the larger population who participated only at Grade 7 ($M = 31.56$, $SD = 7.57$, $t\ (1762) = -5.08$, $p < 0.001$ for reading and $M = 12.97$, $SD = 3.83$, $t\ (1743) = -4.56$, $p < 0.001$ for arithmetic). The children were either 7 years old on entering school, or they turned 7 during the first term of Grade 1 ($M = 85.77$ months old, $SD = 3.44$ months). Among their parents, 27.4% of mothers had a Master's degree or higher, 32.5% a Bachelor's or vocational college degree, 25.3% a vocational school degree, and 5.7% had no education beyond lower secondary school. Meanwhile, 22.5% of the children's fathers had a Master's degree or higher, 30.7% a Bachelor's or vocational college degree, 29.8% a vocational school degree, and 7.6% had no education beyond lower secondary. This is relatively representative of average family background characteristics in Finland (Official Statistics of Finland (OSF): Educational structure of population [e-publication], 2013).

The Finnish basic compulsory education is from grades 1 to 6 at primary, and from grades 7 to 9 at lower secondary. Children start primary at age seven, and before this there is a year of kindergarten for 6-year-olds, to consolidate the pre-skills required for reading and arithmetic, which are then formally taught from Grade 1 onwards. The data concerning reading and arithmetic skills was collected from a group setting in the March/April of grades 1 and 7. Phonological awareness, letter knowledge, RAN, and counting were tested individually during the kindergarten year, while working memory was tested at Grade 1, and nonverbal reasoning at Grade 3. All tests were carried out by researchers or students in psychology/education that had been trained accordingly.

2.2. Measurements

2.2.1. Reading

In March/April of Grade 1, a Finnish adaptation of TOSREC (the Test of Silent Reading Efficiency and Comprehension; Wagner, Torgesen, Rashotte, & Pearson, 2009) was used as a sentence verification task to measure reading fluency. This Finnish version (Lerkkanen & Poikkeus, 2008) is very similar to measures used in previous studies examining the comorbidity of fluency problems in reading and arithmetic (see Landerl & Moll, 2010). It required students to read silently 60 semantically simple sentences (such as "an apple is blue"; or "candy is usually sweet"), and decide whether the sentences were true or not. The score was based on the number of correct responses made within three minutes (min./max. = 0/60). According to Lerkkanen (2003), it has been confirmed that, on average, Finnish students can read whole sentences by the December of Grade 1.

At Grade 7, another Finnish version of the TOSREC was used (Lerkkanen, Löytynoja, Poikkeus, Aro, & Eklund, 2016). This time it consisted of reading 70 sentences silently and deciding whether they were true or not within two minutes (i.e., "*Monday is a season*", "*An irreversible damage is easy to repair*"). The sum score (min./max. = 0/70) was based on the number of items they had got correct. The Cronbach's alpha reliabilities for the test were 0.89 at Grade 1 and 0.94 at Grade 7.

2.2.2. Arithmetic skills

Students' arithmetic skills were assessed using the Basic Arithmetic Test (Aunola & Räsänen, 2007) in March/April of grades 1 and 7. Performance in the test requires both accuracy and speed (automatization of basic calculation routines). At Grade 1, the test consisted of completing 14 addition items (e.g., $2 + 1 = \_\_$, $3 + 4 + 6 = \_\_$), and 14 subtraction items (e.g., $4 - 1 = \_\_$, $20 - 2 - 4 = \_\_$). At Grade 7 the test also consisted of 28 items in total, but they were a mix of addition, subtraction, multiplication and division tasks (e.g., $40: 8 - 3 = \_\_$, $\_\_ - 18 = 45 - 12$, 11×3, $2 = \_\_$, $6 \times 4 + 1 = \_\_ - 21$). Students were given three minutes to complete as many items as possible, and this time limit, combined the increasing difficulty of items towards the end meant the test was challenging even for the older students. The total number of correct items at grades 1 and 7 was then calculated to provide a sum score (maximum value of 28). The Cronbach's alpha reliabilities for arithmetic skills were 0.70 at Grade 1 and 0.94 at Grade 7.

2.2.3. Phonological awareness

Phonological awareness was assessed individually during the fall of kindergarten using an initial phoneme identification task containing 10 items (Lerkkanen, Poikkeus, & Ketonen, 2006). For each item (phoneme), the student was shown the pictures of four objects at the same time and told their names. The student was then asked to indicate which of the pictures began with the same phoneme (e.g., "*At the beginning of which word do you hear ____?*"). The score was the total number of correct items (maximum value of 10). The Cronbach's alpha reliability was 0.78.

2.2.4. Letter knowledge

Letter knowledge was assessed individually during the fall of kindergarten using the Letter Knowledge Test (Lerkkanen, Poikkeus, et al., 2006), consisting of all 29 uppercase letters in the Finnish alphabet arranged along three rows in a random order. The student was shown one row at a time and asked to name the letters. The sum score was based on the number of correct items (maximum value of 29). The Cronbach's alpha reliability for the test was 0.95.

2.2.5. Rapid automatized naming (RAN)

The rapid naming of objects was assessed in March/April of kindergarten using a standard procedure (see Denckla & Rudel, 1974) in which the student was asked to name, as rapidly as possible, a series of five familiar visual stimuli replicated 10 times on a matrix in random order. Documented errors and self-corrections were few and they were not used in the analysis. The completion time in seconds of the total matrix (five rows of 10) was used as the score. According to the manual, the test-retest reliability coefficients ranged from 0.84 to 0.92 for all age groups (Wolf & Denckla, 2005).

2.2.6. Counting sequence knowledge

Counting sequence knowledge was assessed individually during the fall of kindergarten using the Number Sequences Test (Salonen et al., 1994). This consists of four tasks in which the student is asked to count out loud (i) forwards from 1 to 31; (ii) forwards from 6 to 13; (iii) backwards from 12 to 7; and (iv) backwards from 23 to 1. For each of the four tasks, two points were given for completing it without a mistake; one point for up to two mistakes; and zero for any more than that, or if the task could not be completed. The total maximum score for the test was therefore 8, and the Cronbach's alpha reliability for the test was 0.74.

2.2.7. Working memory

Working memory was assessed individually in March/April of Grade 1 using the WISC-III (Wechsler, 1991) digit span subtest. The student was asked to repeat an identical string of digits after the tester, and then again so that there were two identical spans per section. The span was then increased by one in each section, so that eventually there were 8 forward, and 7 backward digit spans. Two points were given for repeating both spans correctly, 1 for only one, and 0 for none, whereupon the test was discontinued. The maximum possible score was therefore 16 points for forward digit spans and 14 for backward, giving a total of 30. According to the manual, the average reliability for all age groups was 0.75 (Wechsler, 1991).

2.2.8. Nonverbal reasoning

The shortened version of Raven's Colored Progressive Matrices (Raven, Court, & Raven, 1992) was used to assess the students' nonverbal reasoning in March/April of Grade 3. The test contains 18 items, in each of which the student was asked to identify the missing element to complete a pattern (from 6 choices). One point was scored for each correctly answered item, so that the maximum total score was 18. Guttman's split-half reliability for the test was found to be 0.66 and Cronbach's alpha reliability 0.64.

2.2.9. Parental education level

A total of 1214 mothers (90.7%) and 1212 fathers (90.6%) filled in and returned the questionnaires reporting on their education level using a 7-point scale (1 = *no education beyond secondary school*, 2 = *vocational courses*, 3 = *vocational school degree*, 4 = *vocational college degree*, 5 = *polytechnic degree or bachelor's degree*, 6 = *master's degree*, and 7 = *licentiate or doctoral degree*). Parental education score was then determined by education score of the most highly educated parent.

2.3. Analysis strategy

The research questions were examined using structural equation modeling (SEM). The SEM models were conducted through two steps. First, we constructed a model in which reading and arithmetic skills were modeled with three latent factors at grades 1 and 7 (times 1 and 2 respectively). The first factor modeled the covariation (shared variance) of reading and arithmetic skills across time, i.e., *time-invariant covariation* (see Fig. 1); for which

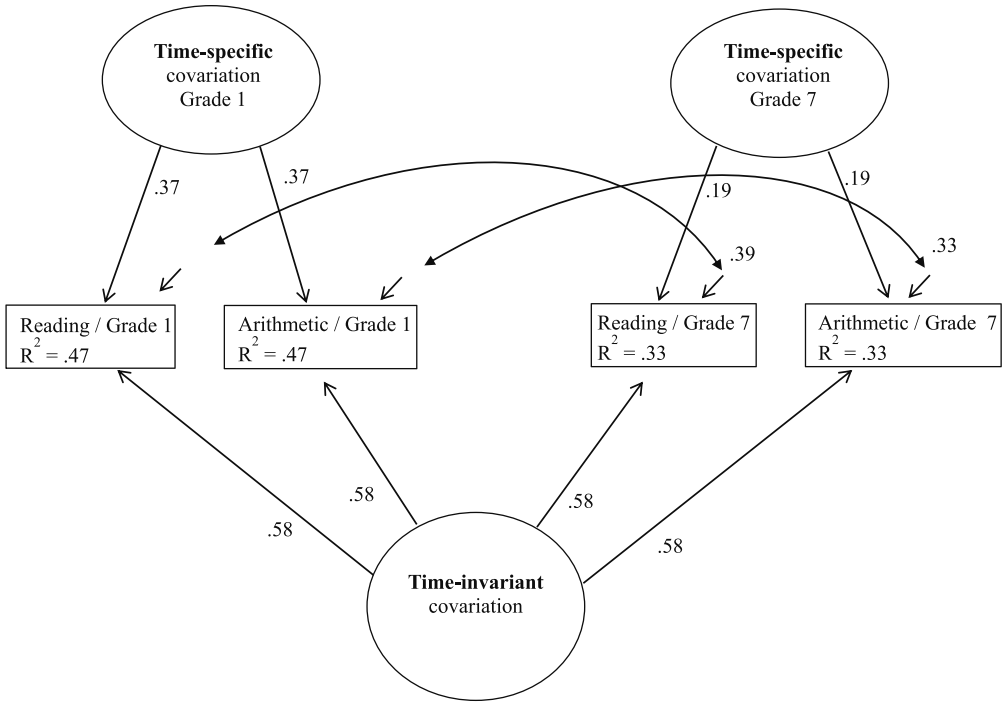

Fig. 1. Time-invariant and time-specific parts of covariation between reading and arithmetic skills from Grade 1 (Time 1) to Grade 7 (Time 2).

the loadings of indicators (i.e., standardized reading and arithmetic skills at time 1, and at time 2) were estimated as equal. Meanwhile, the second latent factor described the *time-specific covariation* of reading and arithmetic at time 1 (that was no longer evident at time 2). This latent factor had two indicators—reading and arithmetic skills at time 1—for which loadings were estimated as equal. Finally, the third latent factor described the *time-specific covariation* of reading and arithmetic at time 2 (that was not evident at time 1). This latent factor consisted of two indicators—reading and arithmetic skills at time 2—for which loadings were estimated as equal. In the model, the residual of the observed reading skills at time 1 was allowed to correlate with the residual of the same at time 2, and the residual of the observed arithmetic skills at time 1 was allowed to correlate with the residual of the same at time 2.

The second step in the analysis was to predict the time-invariant covariation in the level of skills shared by reading and arithmetic at both times 1 and 2 by adding the antecedent variables to the previous model. Then, we examined the model fit and modification indices to see whether the paths from antecedents should be estimated also to time-specific covariation factors between reading and arithmetic skills at times 1 and 2. Large modification indices (over the value of 10) were taken to suggest that the fit would improve if the paths from predictor variable to latent time-specific covariation factor was added to the model (Fig. 2).

All of the statistical analyses were performed using Mplus statistical software and the standard missing-at-random (MAR) approach – which supposes that any data missing would be at random (Muthén & Muthén, 1998–2010). The parameters of the models were estimated using full information maximum likelihood (FIML) estimation with standard errors that are robust to non-normality (MLR estimator; Muthén & Muthén, 1998–2010). This method allowed us to use all of the observations in the dataset to estimate the parameters of the models.

With both a nonsignificant χ^2-test value and comparative fit index (*CFI*) of greater than 0.95; and a root mean square error of approximation (*RMSEA*) of lower than 0.06, the model seemed to fit the data well (Muthén & Muthén, 1998–2010). Several fit indices were used since, as Bollen and Long (1993) have suggested, they provide different information about the model fit (RMSEA might measure absolute fit, but CFI and TLI measure relative fit). The correlations, means (*M*), and standard deviations (*SD*) of study variables are shown in Table 1.

3. Results

As we have seen, to examine the first research question of how much covariation between reading and arithmetic skills is shared between grades 1 and 7 (time-invariant), and how much is unique to each grade (time-specific), we modeled the latent factors for time-invariance and time-specificity. The fit of the model was: χ^2 (3) = 7.59, p = 0.06; *CFI* = 1.00; *RMSEA* = 0.03. The model is shown in Fig. 1.

Fig. 1 shows that reading and arithmetic skills shared 47% of their variance at Grade 1 and 33% at Grade 7. The results showed further that the majority of this covariation between reading and

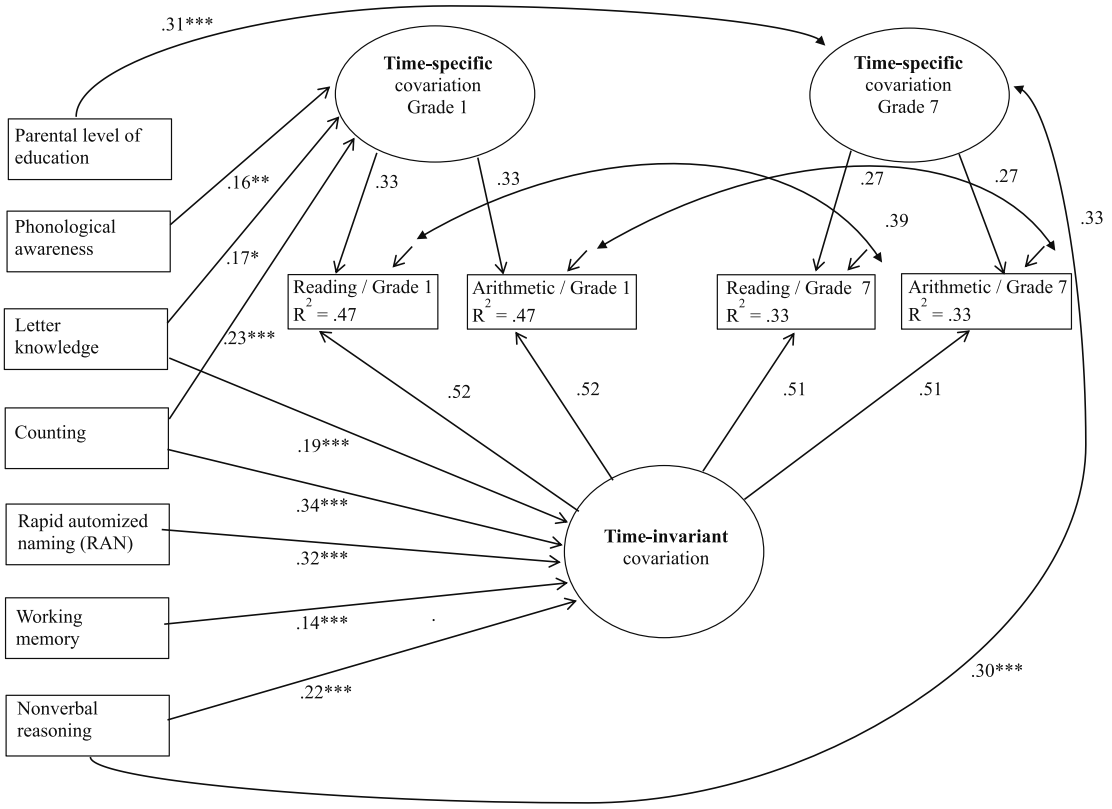

Fig. 2. Predictors of the time-invariant and time-specific parts of covariation between reading and arithmetic skills (Standardized Estimates). *Note.* $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

Table 1
Correlations, means (M), and standard deviations (SD) of the study variables.

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.
1. Reading skills Time 1	1.00										
2. Arithmetic skills Time 1	0.44***	1.00									
3. Reading skills Time 2	0.54***	0.27***	1.00								
4. Arithmetic skills Time 2	0.35***	0.51***	0.36***	1.00							
5. Phonological awareness	0.39***	0.19***	0.23***	0.21***	1.00						
6. Letter knowledge	0.47***	0.31***	0.30***	0.30***	0.56***	1.00					
7. Rapid automized naming	−0.35***	−0.24***	−0.30***	−0.25***	−0.24***	−0.29***	1.00				
8. Counting	0.41***	0.44***	0.27***	0.40***	0.38***	0.57***	−0.25***	1.00			
9. Working memory	0.35***	0.20***	0.28***	0.20***	0.23***	0.21***	−0.10	0.31***	1.00		
10. Nonverbal reasoning	0.20***	0.19***	0.23***	0.27***	0.20***	0.18***	−0.18***	0.20***	0.21***	1.00	
11. Parental level of education	0.13***	0.12***	0.13***	0.22***	0.19***	0.21***	−0.13***	0.18***	0.03	0.11***	1.00
M	18.73	11.01	33.64	13.93	7.66	18.02	69.36	4.80	9.13	16.78	4.58
SD	7.80	3.94	7.29	3.71	2.30	8.63	16.45	2.77	1.89	1.60	1.46

Note 1. Time 1 = March/April of Grade 1, Time 2 = March/April of Grade 7.
Note 2. $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.
Note 3. Rapid automatized naming was scored as reaction time (low scores meaning high performance and high score meaning low performance).

arithmetic was time-invariant: the shared variance between reading and arithmetic was common for both times 1 and 2. However, part of the covariation between reading and arithmetic was also time-specific: some pertaining only to time 1, and some of it only to time 2.

To answer the second research question of how phonological awareness, letter knowledge, RAN, counting, working memory, nonverbal reasoning, and parental education would predict time-invariant and time-specific covariation between reading and arithmetic skills at grades 1 and 7, they were first added to the model to predict the time-invariant portion of covariation. The fit of the model was: χ^2 (26) = 206.35, $p < 0.001$; *CFI* = 0.93; *RMSEA* = 0.05. However, the inspection of modification indices suggested that the fit would improve if the paths were estimated (i) from letter knowledge, phonological awareness, and counting to time-specific covariation at time 1; and (ii) from nonverbal reasoning and parental education level to time-specific covariation at time 2. After these modifications, the model fitted the data well (χ^2 (21) = 137.67, $p = < 0.001$; *CFI* = 0.95; *RMSEA* = 0.05), and no more modification indices were over 10. This final model is shown directly below in Fig. 2.

To begin with, the results showed that *time-invariant* covariation between reading and arithmetic was predicted by *letter knowledge*, *counting*, *RAN*, *working memory*, and *nonverbal reasoning*; the higher these predictor variables were, the higher the levels of both reading and arithmetic in grades 1 and 7. Secondly, *time-specific* covariation between reading and arithmetic at Grade 1 (time 1) was predicted by *letter knowledge*, *phonological awareness*, and *counting* in kindergarten; the higher these three antecedent variables were, the higher the levels of both reading and arithmetic in Grade 1 (i.e., skill level shared by reading and arithmetic at Grade 1 that is no longer evident at Grade 7). Finally, *time-specific* covariation between reading and arithmetic in Grade 7 (time 2) was predicted by *nonverbal reasoning* and the *level of parental education;* the higher these two antecedent variables were, the higher the levels of both reading and arithmetic in Grade 7 (i.e., skill level shared by reading and arithmetic at Grade 7 that was not evident at Grade 1).

4. Discussion

The present study was an attempt to complement current understanding of the cross-domain development of reading and arithmetic skills using an unselected population from the beginning of primary school (Grade 1) to lower secondary school (Grade 7), and to define the antecedents of this development. The results showed that reading and arithmetic skills shared about half of their variance at Grade 1 and one third of their variance at Grade 7. It was also clear that a large proportion of this covariation was common (time-invariant) to both grades 1 and 7. Moreover, this time-invariant part of the shared variation between reading and arithmetic was found to be predicted by RAN and counting, as well as by early letter knowledge, working memory, and nonverbal reasoning. Time-specific part of the shared skill level of reading and arithmetic evident at Grade 1 was predicted by phonological awareness, letter knowledge, and counting. Time-specific part of the shared skill level at Grade 7, in turn, was predicted by parental education level and nonverbal reasoning.

4.1. Covariation between reading and arithmetic from primary to lower secondary school

The first aim of the present study was to investigate to what extent there is covariation between reading and arithmetic skills in Grade 1 and Grade 7 in an unselected population, and to what extent this covariation is invariant (shared across the two grades) from primary school (Grade 1) to lower secondary school (Grade 7). The results showed that reading and arithmetic skills were associated both at grades 1 and 7. Overall, this result is consistent with previous studies that also indicate substantial covariation between reading and math skills among an unselected population in primary (Chen & Chalhoub-Deville, 2016; Davis et al., 2014; Hecht et al., 2001; Koponen et al., 2007; Rutherford-Becker & Vanderwood, 2009) and lower secondary school (Chen & Chalhoub-Deville, 2016; Codding et al., 2015), suggesting that reading and arithmetic skills develop in tandem across grade levels.

The results of the present study further showed, in line with our hypothesis (1a), that the majority of covariation in reading and arithmetic skills was common to both grades 1 and 7 (i.e., time-invariant). This confirms previous findings indicating relatively high stability of individual differences both in reading (de Jong & van der Leij, 2002; Hulslander et al., 2010; Landerl & Wimmer, 2008; Parrila et al., 2005) and in arithmetic (Aunola et al., 2004; Bailey et al., 2014; Watts et al., 2014) across the school years. Our results also suggest that the development of reading and arithmetic seem to share common processes *across* the different developmental phases. Considering the importance of early reading and arithmetic skills for later academic performance (Duncan et al., 2007), these findings raise the question as to whether individual differences in the shared level of these skills are established already at the beginning of school. At this point, however, it should be noted that high invariance in the skill level shared by reading and arithmetic does not mean that children's reading and arithmetic skills are not developing; even if school does not seem to

remove individual differences in skill levels, it clearly helps in improving all children's skills.

The large proportion of shared variance between reading and arithmetic from Grade 1 to Grade 7 may be explained by the fact that these skills are related to each other at many levels. For example, the 'generalist genes' hypothesis suggests that the same set of genes affect a diverse number of skills that are required in both domains (Davis et al., 2014; Plomin & Kovas, 2005). Due to the rather high heritability of reading and math skills (Davis et al., 2014; Kraphol et al., 2014), it is likely that this genetic overlap is one reason for our results. It has been found that there is also an overlap in cognitive processes between reading and arithmetic skills (Hecht et al., 2001; Koponen et al., 2016; Simmons et al., 2008), that can be found in studies on the comorbidity of related difficulties too (Cirino et al., 2015; Peng & Fuchs, 2016; Willcutt et al., 2013). If difficulties in reading and math are indeed caused by the same underlying cognitive factors that enable the learning of these skills (Kovas & Plomin, 2007), then the high covariation found in the entire distribution of the unselected population used in this present study would seem to confirm this.

Furthermore, in line with hypothesis 1 b, part of the covariation between reading and arithmetic was found to be time-specific (i.e., typical only to Grade 1 or Grade 7). This finding provides some evidence for a notion that the covariation between reading and arithmetic can be partly related to certain phases of skill development, such as serial decoding/counting or automatized phase with direct retrieval of larger units. Moreover, association between reading and arithmetic fluency was slightly stronger in Grade 1 than in Grade 7, suggesting that reading and arithmetic skills have more in common in the early phases of skill development.

4.2. Antecedents of time-invariant and time-specific covariation from grades 1 to 7

The second aim of the present study was to investigate the extent to which linguistic and basic number skills, general cognitive abilities, and parental education level predict time-invariant and time-specific covariation between reading and arithmetic from Grade 1 to Grade 7. Our results showed that the invariant part of the covariation was predicted by various reading and arithmetic pre-skills (letter knowledge, RAN, counting) and by general cognitive abilities (working memory, nonverbal reasoning). The higher the level of these pre-skills and general cognitive abilities, the higher the level of skills shared by reading and arithmetic across grade levels.

The strongest predictors of the time-invariant level of skills shared by reading and arithmetic from Grade 1 to Grade 7 were RAN and counting, which previous studies have also found to predict both reading and arithmetic fluency at Grades 2 and 3 (Koponen et al., 2013, 2016), as well as their covariation at Grade 4 (Koponen et al., 2007). For the first time, however, the present study showed that both of these skills also predict the covariation of reading and arithmetic fluency over time. This finding emphasizes the role of RAN and counting as early predictors of fluency in two important academic domains. The predictive role of RAN suggests that the time-invariant part of skills used in both arithmetic and reading is not simply related to phonological awareness, but more specifically, to how quickly phonological representations can be accessed, or how automatic visual-verbal associations are.

In addition, the results are consistent with studies indicating the importance of working memory (Alloway & Alloway, 2010; Gathercole et al., 2004) and nonverbal reasoning (Karbach et al., 2013; Rohde & Thompson, 2007; Spinath et al., 2006) in overall school achievement. Of the general cognitive abilities, working memory was a stronger predictor of the level of skills shared by reading and arithmetic across grade levels than nonverbal reasoning. Alloway and Alloway (2010) also found verbal working memory, at the start of formal education, to be a better predictor than IQ of subsequent success in reading and arithmetic.

The results also showed, in line with our hypothesis (2a), that time-specific skill level shared by reading and arithmetic at Grade 1 (i.e., covariation evident in Grade 1 but not Grade 7) were predicted by phonological awareness, letter knowledge, and counting: the higher the level of these pre-skills in kindergarten, the higher the shared skill level of reading and arithmetic at Grade 1. These results may be explained by the similarity in acquisition of the alphabetic and numeral system principles at the beginning of school. This confirms previous research showing that phonological awareness (Simmons et al., 2008), letter knowledge (Koponen et al., 2007), and counting (Koponen et al., 2016) are important precursors of both reading and arithmetic skills. Awareness of the phonological structure of a language has also been shown to have an important role in the development of reading, particularly of basic word-decoding skills (e.g., Hogan, Catts, & Little, 2005; Holopainen et al., 2001; Silvén et al., 2007). In arithmetic, phonological awareness has been found to be associated with early quantity-number skills and, through those skills, to later arithmetic skills. Interestingly, Krajewski and Schneider (2009), found that phonological awareness did not directly contribute to either the prediction of higher order quantity-number skills or later arithmetic competencies but only did so indirectly, via early quantity-number skills. The strongest predictor of covariation between reading and arithmetic skills at Grade 1 was again counting ability, which seems to be a good predictor both for initial phases as well as more automatized phases of skill development in reading and arithmetic. The results regarding phonological awareness, letter knowledge, and counting being predictors of time-specific covariation at Grade 1 might also be explained by the fact that these pre-skills were all measured at the beginning of kindergarten, thus indicating how well prepared children were for school tasks before they started school. After formal instruction and practice at school, it would seem safe to assume that the variance related to early training (and non-training) will diminish over time.

Meanwhile, time-specific skill level shared by reading and arithmetic at Grade 7 (i.e., covariation that was evident in Grade 7 but not in Grade 1) was found to be predicted by the level of parental education and nonverbal reasoning: the higher the level of parental education and nonverbal reasoning, the higher the shared skill level of reading and arithmetic in Grade 7, independent of the level of these skills at Grade 1. The results of time-specific covariation at Grade 7 are in line with studies indicating the importance of the parents' education level (Davis-Kean, 2005) and the child's nonverbal reasoning abilities (Karbach et al., 2013) in overall school achievement during early adolescence. A study by von Stumm and Plomin (2015), for example, showed that the development of children's intelligence from infancy to adolescence was significantly associated with family SES. Since differences in the availability of learning opportunities, support and resources are also thought to accentuate individual differences in cognitive ability (von Stumm & Plomin, 2015), it is possible that children with high initial intelligence engage more in reading and math related activities than children with low initial intelligence due to both family environment (Davis-Kean, 2005) and their individual cognitive abilities (Trzaskowski et al., 2014). In the long-term, this engagement may then lead to higher overall performance in both reading and arithmetic skills, regardless of the level of these skills at Grade 1– thus explaining our results for the predictors of covariation in reading and arithmetic skills specific to Grade 7 only.

4.3. Limitations

There are at least seven limitations that should be taken into account before we can generalize any further about the findings

of the present study. First, the predictor variables were measured at different points in time: counting, phonological awareness, and letter knowledge were measured at the fall of kindergarten, whereas RAN was measured the following spring. General cognitive abilities were also measured at different points in time: working memory in spring of Grade 1 and nonverbal reasoning in spring of Grade 3. Second, limited working memory measure with the digit span subtest of WISC-III was used. Although the digit span subtest of WISC-III has been shown to be highly reliable as a test for working memory across a range of age groups (Wechsler, 1991), no information concerning the reliability of the test for the present sample was available. Third, we did not have the necessary data to include executive functioning as a predictor variable of covariation in reading and arithmetic skills. Fourth, although the level of parental education was included as a predictor variable, it was not possible to separate genetic from environmental influences.

Fifth, when generalizing these findings across languages, the transparent orthography of the Finnish language should be taken into account. Due to the simple and symmetrically regular phoneme-grapheme connection structure of Finnish, decoding requires less advanced phonological processing skills than do more opaque orthographies, such as English. Moreover, with regards to the transparency of orthography, the variance in reading skills derives mainly from fluency and not accuracy, even though reading efficiency (reading words accurately within a time limit) was used as an outcome measure. Sixth, due to the relative transparency of grapheme–phoneme correspondence being equally regular for spelling as it is for reading in Finnish, spelling was not investigated. In future studies in languages with less transparent orthographies, spelling should be included as a separate outcome variable. Finally, the amount of covariation between reading and arithmetic skills might well be dependent on the individual skill levels of the students, so this should be examined in future studies.

4.4. Conclusion

Overall, the results of the present longitudinal study showed that most of the covariation between reading and arithmetic was common to grades 1 and 7. This suggests that reading and arithmetic skills are strongly related to each other, and the association is shared across grade levels. Our results also suggest that the shared skill level of reading and arithmetic is already fairly well established at the beginning of school.

These results have at least two practical implications. Firstly, there is a substantial amount of time-invariant covariation between reading and arithmetic across the school years, and the cognitive predictors of this time-invariance suggest that these skills have the same underpinnings at different phases of skill development. As development in both reading and math requires fluency in basic skills, early identification of those children who might develop fluency problems is important already at kindergarten. Rapid serial naming and counting are easy to assess before children enter school, and can be used as diagnostic tools to detect children at risk of developing fluency difficulties in both reading and arithmetic. The high invariance in covariation between the two domains also underlines the need to develop effective tools for supporting fluency development in math and reading skills, which has received less attention in intervention research.

Secondly, unlike many other studies, we were able to differentiate the antecedents of time-invariant and time-specific covariation in reading and arithmetic skills. The results concerning time-specific covariation showed that early pre-skills, such as phonological awareness, played a particularly important role at the start of skill development, whereas the educational level of parents and more general reasoning skills were significant at a later phase of shared reading and arithmetic fluency development. This finding suggests that intensive preventive support for those children who show impairment in phonological processing could be an efficient way to support the early phases of skill development in reading and arithmetic. However, the skill level in later grades is likely to require a more general type of support such as interventions aimed to increase students' motivation and engagement.

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II

EARLY COGNITIVE PROFILES PREDICTING READING AND ARITHMETIC SKILLS IN GRADES 1 AND 7

by

Heidi Korpipää, Kristina Moll, Kaisa Aunola, Asko Tolvanen, Tuire Koponen, Mikko Aro, & Marja-Kristiina Lerkkanen, 2020

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Early cognitive profiles predicting reading and arithmetic skills in grades 1 and 7

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Person-oriented approach

ABSTRACT

The aim of this study was to investigate cognitive profiles composed of skills predicting the overlap between reading and arithmetic in kindergarten (phonological awareness, letter knowledge, rapid automatized naming, and counting sequence knowledge) and the relation of these profiles to reading and arithmetic skills at Grades 1 and 7. A total of four distinct cognitive profiles were identified in an unselected sample of 1,710 children aged 5–6 years: (1) high linguistic and high counting skills (39.2%), (2) low linguistic and low counting skills (25.4%), (3) high counting skills in relation to linguistic skills (15.3%), and (4) low counting skills in relation to linguistic skills (20.1%). Among most of the children (about 65%), the linguistic and counting skills varied together. Children characterized by high or low overall performance levels across linguistic and counting skills also showed, predictably, high or low overall performance levels in subsequent reading and arithmetic skills in Grades 1 and 7. Children characterized by a discrepancy between linguistic and counting skills (about 35% of the children) in turn showed somewhat discrepant subsequent levels of reading and arithmetic skills. The results point towards individual variation (i.e., heterogeneity) in cognitive profiles that predict both reading and arithmetic skills in Grades 1 and 7. Based on these findings, the linguistic and basic number skills predict differently the overlap between reading and arithmetic in Grades 1 and 7 depending on cognitive profile. The weaknesses across linguistic and counting skills are a greater risk for persistent overlapping difficulties in reading and arithmetic than weaknesses in only one of the learning domains. For difficulties in arithmetic skill development, however, weaknesses in only counting skills present an equal risk compared to weaknesses evident across linguistic and counting skills.

1. Introduction

Reading and arithmetic skills show substantial overlap across grade levels from primary to lower secondary school (Korpipää et al., 2017), and difficulties in one of the learning domains increases the risk for difficulties in the other domain (Landerl & Moll, 2010). The overlap of performance in these two domains has been suggested to be at least partly related to the shared cognitive factors of reading and arithmetic skill development (Cirino, Child, & Macdonald, 2018; Hecht, Torgesen, Wagner, & Rashotte, 2001; Koponen, Aunola, Ahonen, & Nurmi, 2007). However, the previous studies have mainly used a variable-oriented approach (i.e., linear techniques) and focused on the separate, unique impacts of different linguistic and basic number skills when explaining the overlap between reading and arithmetic. Because a variable-oriented approach applies a single model to the whole sample to estimate a single set of parameters (Mäkikangas et al., 2018), the possible interindividual differences (i.e., heterogeneity) in patterns of performance across the studied variables underlying the overlap have thus far been ignored. Whereas a variable-oriented method examines associations between different variables, a person-oriented approach examines individual differences in these associations (Hickendorff, Edelsbrunner, McMullen, & Schneider, 2018; Laursen & Hoff, 2006) and, thus, makes

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it possible to investigate not only whether there are subgroups of individuals showing different profiles of cognitive antecedents but also whether these different profiles end up with similar or different subsequent performance outcomes. If qualitatively different subgroups exist within a population, they are not accurately represented by the general model provided by variable-oriented approach (Hickendorff et al., 2018). Therefore, a person-oriented approach was used in the present study for identifying individual differences in cognitive profiles composed of shared predictors of reading and arithmetic skills (i.e., phonological awareness, letter knowledge, rapid automatized naming, and counting sequence knowledge) and finding out the typicality of different profiles (i.e., the proportion of the sample that shows a particular pattern). Furthermore, differences between the profiles in reading and arithmetic skills at Grades 1 and 7 were investigated. The aim was to complement the current understanding of the cognitive mechanisms—and possible heterogeneity in these mechanisms—that underlie both reading and arithmetic skill development, and, in this way, to provide insights on individualized ways to support the development of the overall performance level of these skills.

1.1. Cognitive antecedents predicting the overlap between reading and arithmetic skills

Previous studies that have investigated the role of different cognitive antecedents in the overlap (i.e., covariation) between reading and arithmetic skills suggest that this overlap is predicted more by linguistic and basic number skills than by general cognitive abilities (Cirino et al., 2018; Hecht et al., 2001; Koponen et al., 2007; Korpipää et al., 2017, 2019). According to Korpipää et al. (2017), phonological awareness (i.e., awareness of the phonological structure of a language), letter knowledge, rapid automatized naming (i.e., the ability to rapidly name familiar visual stimuli, such as letters, digits, colors, and objects), and counting sequence knowledge (i.e., reciting number words forwards, backwards, and in steps) are all independent predictors of the overlap between reading and arithmetic skills after controlling for working memory, nonverbal reasoning, and parental education level (see also Koponen et al., 2007; Korpipää et al., 2019). Also, Cirino et al. (2018) reported that linguistic and basic number skills, including phonological awareness, rapid automatized naming, and symbolic naming (number identification) accounted for a large amount (about 91%) of the overlap between reading and arithmetic fluency in Grade 1, whereas the role of counting sequence knowledge was less evident. In their study, a wide range of basic number skills was used for predicting the overlap (procedural and conceptual counting knowledge, symbolic comparison and symbolic naming), but letter knowledge was not included which may explain the role of symbolic number naming as a predictor of shared variance between reading and arithmetic fluency. In line with these findings, Hecht et al. (2001) found that the overlap of reading and arithmetic skills was almost completely accounted for by phonological awareness, rapid automatized naming, and phonological memory from Grade 2 to 5; however, counting sequence knowledge was not included in their study.

The study by Korpipää et al. (2017) showed further that phonological awareness and letter knowledge are related to the overlap between reading and arithmetic skills mainly at an early phase of skill development (Grade 1), when both reading and arithmetic skills are based on serial one-by-one processing of letter sounds and number words. It has been suggested that understanding the mapping between the letters in written words and the phonemes in spoken language improves the ability to use and manipulate written symbols for numbers and operators in arithmetic (Zhang et al., 2014). Counting sequence knowledge, in turn, was strongly related to both early (Grade1) and later (Grade 7) phases of skill development. In a study by Korpipää et al. (2017), counting sequence knowledge and rapid automatized naming were found to be the strongest predictors of the overlap between reading and arithmetic skills across grade levels from primary to lower secondary school. It has been shown that these two abilities are related to developing fluency in both domains and reflect the ease of forming and retrieving visual-verbal associations from long-term memory (Fuchs, Geary, Fuchs, Compton, & Hamlett, 2016; Koponen, Salmi, Eklund, & Aro, 2013). However, linguistic and basic number skills also account for nonshared variance in reading and arithmetic skills due to the domain-specific content knowledge. For example, linguistic skills regarding phonological awareness and rapid automatized naming are more predictive of reading than of computation, and basic number skills, such as counting knowledge, are more predictive of computation than of reading (Cirino et al., 2018; see also Child, Cirino, Fletcher, Willcutt, & Fuchs, 2019).

In addition to linguistic and basic number skills, the development of reading and arithmetic skills (Bull, Espy, & Wiebe, 2008; Davis-Kean, 2005), as well as the overlap between these skills (Korpipää et al., 2017), have been shown to be predicted by more general cognitive abilities, such as working memory, attentional resources and parental education level. In previous studies, preschool measures of verbal short-term memory, working memory, and executive functioning skills have been found to predict academic achievement in reading and math throughout the early school years (Bull et al., 2008; see also Alloway & Alloway, 2010). Furthermore, phonological memory has been shown to contribute to the overlap between reading and arithmetic skills across Grades 1 and 7, along with nonverbal reasoning but to a lesser extent than linguistic and basic number skills (Korpipää et al., 2017, see also Hecht et al., 2001). Recent studies have demonstrated, however, that the associations of general cognitive abilities with the overlap between reading and arithmetic are mainly indirect via core predictors, such as linguistic and basic number skills, rather than direct (Koponen et al., 2019). Similarly, the role of parental education level (Koponen et al., 2019; Korpipää et al., 2017) has been shown to be minor in explaining the shared variance of reading and arithmetic.

1.2. A person-oriented approach to the cognitive antecedents of reading and arithmetic skills

Previous studies focusing on the cognitive antecedents of reading and arithmetic skills have typically applied a variable-oriented approach, mainly focusing on the associations of antecedent variables with reading and arithmetic or with the overlap between reading and arithmetic (Cirino et al., 2018; Hecht et al., 2001; Korpipää et al., 2017; Koponen et al., 2007, 2013). Although this approach provides valuable information about the unique contribution of different cognitive skills to reading and arithmetic development, it also has some limitations. The main limitation is that a variable-oriented approach assumes the studied associations to be the same for all children. Thus, the basic assumption is the homogeneity of a population. In contrast, the more rarely applied person-oriented approach is based on the assumption that the population can be heterogeneous with respect to the studied phenomena (Laursen & Hoff, 2006). This approach enables identifying subgroups of children with different cognitive profiles and examining whether these children develop either similarly or differently in their reading and arithmetic skills. Although previous studies have shown that linguistic and basic number skills correlate rather strongly with observed intercorrelations varying from 0.30 to 0.60 (Korpipää et al., 2017, 2019), the correlation pattern may not be the same across the whole population. Whereas variable-oriented approaches provide important information about the additive impacts (i.e., the unique linear associations of different independent variables after controlling for the impacts of other independent variables) of different linguistic and basic number skills on reading and arithmetic skills and their overlap, a person-oriented approach provides a valuable tool to examine the possible interactive effects of these antecedent cognitive skills. Based on variable oriented approaches, for example, high levels of linguistic skills with low levels of basic number skills lead to the same performance outcome in terms of overlap between reading and arithmetic

than low levels of linguistic skills with high basic number skills or, for example, average levels of both linguistic and basic number skills. Consequently, person-oriented approaches can improve our understanding of individual differences in the patterns of how linguistic and basic number skills operate together in predicting reading and arithmetic skills and their overlap across grade levels.

Studies applying a person-oriented approach separately for reading (Ozernov-Palchik et al., 2017) and arithmetic (Gray & Reeve, 2016; Hart et al., 2016) have identified distinct cognitive profiles that predict the development of these skills, specifically in children who are struggling. For example, Ozernov-Palchik et al. (2017) found six different profiles in kindergarten regarding nonverbal reasoning, phonological awareness, verbal short-term memory, rapid automatized naming, and letter sound knowledge. According to their findings, difficulties in reading may derive from different cognitive profiles, including weaknesses either in phonological awareness or in rapid automatized naming or both. Similarly, Hart et al. (2016) found that difficulties in arithmetic fluency at age 12 resulted from different cognitive profiles regarding math achievement, numerosity, and anxiety rather than only one profile.

Overall, these previous studies suggest that there are subgroups of children representing differential relations regarding the cognitive antecedents associated with performance in reading and arithmetic. The limitation of these previous studies examining heterogeneity in cognitive profiles of reading and arithmetic skills is, however, that they have included mainly domain-specific predictors (i.e., cognitive antecedents of reading *or* arithmetic). Furthermore, longitudinal studies regarding the role of different cognitive profiles in predicting subsequent reading and arithmetic skills, as well as the overlap between these skills, are rare. Unlike previous studies, the present study simultaneously examines the relations among linguistic *and* basic number skills, which have been shown to have both shared and unique influences on reading and arithmetic skills (Cirino et al., 2018; see also Child et al., 2019). The aim was to find out how different patterns of performance across these cognitive antecedents are associated with performance levels in reading and arithmetic and overlap between these skills later on in school. Specifically, the focus of this study was on cognitive profiles predicting the overlap between reading and arithmetic skills rather than each skill separately at different stages of development. As linguistic and basic number skills regarding phonological awareness, letter knowledge, rapid automatized naming, and counting sequence knowledge have been shown to be the strongest independent predictors of the overlap between reading and arithmetic skills (Korpipää et al., 2017, 2019), the cognitive profiles were examined in terms of these measures. By applying a person-oriented approach, the present study has the potential to specify the associations of these cognitive antecedents with the overlap between reading and arithmetic skills and thus provide knowledge important for developing efficient means of support.

1.3. The aim of the present study

The present study examined the following research questions:

(1) What kinds of distinct cognitive profiles with regard to linguistic and counting skills (i.e., shared predictors of reading and arithmetic) can be identified in kindergarten? As previous studies suggest that there is high heterogeneity in cognitive profiles (i.e., subgroups of children representing differential relations between the cognitive antecedents) of reading (Ozernov-Palchik et al., 2017) and arithmetic (Gray & Reeve, 2016; Hart et al., 2016), it is assumed that heterogeneity also exists for the combination of linguistic and basic number skills. Furthermore, we assumed that both profiles typified by consistencies (i.e., high level or low level of both linguistic and counting skills) and profiles typified by discrepancies (i.e., high level of linguistic skills but low level of counting skills, and high level of counting skills but low level of linguistic skills) can be identified (Hypothesis 1).

Given that the general cognitive abilities together with parental education level form the foundation for developing knowledge needed for learning both reading and arithmetic (Alloway & Alloway, 2010; Bull et al., 2008; Davis-Kean, 2005; Korpipää et al., 2017), differences between the profiles regarding working memory, short-term memory, nonverbal reasoning, inattention/hyperactivity, and parental education level were also investigated.

(2) To what extent do the identified cognitive profiles predict subsequent reading and arithmetic skills, and overlap between these skills, at Grades 1 and 7? As previous studies suggest both shared and unique associations of linguistic and basic number skills with reading and arithmetic skills (Cirino et al., 2018; see also Child et al., 2019), it is assumed that children characterized by high or low overall performance levels across phonological awareness, letter knowledge, rapid automatized naming, and counting sequence knowledge will show more consistent skill levels of reading and arithmetic (being evident as either consistently high or low skill levels across reading and arithmetic) than children characterized by discrepant cognitive profiles (i.e., profiles with high linguistic skills and low counting skills, or, alternatively, high counting skills and low linguistic skills). More specifically, children typified by high overall performance levels across linguistic and counting skills are assumed to show high skill levels across both reading and arithmetic, whereas children typified by low overall performance levels across linguistic and counting skills are assumed to show low skill levels across both reading and arithmetic (Hypothesis 2). Furthermore, it is assumed that children typified by high linguistic skills but low counting skills perform higher in reading than in arithmetic, whereas those typified by high counting skills but low linguistic skills will show the opposite pattern of results (Hypothesis 3). Because previous studies investigating the shared cognitive antecedents of reading and arithmetic have applied a variable-oriented approach, it is not, however, possible to set more solid predictions for the levels of reading and arithmetic skills among those showing discrepant profiles.

2. Method

2.1. Participants

The study is part of an extensive longitudinal age cohort study (Lerkkanen, Poikkeus, & Ketonen, 2006–2016), which follows up a community sample of children (n = 1,880) from one rural and three urban municipalities in Finland from kindergarten entry (age M = 74.0 months ± 3.6 months) to the end of Grade 9 (age 15). The children comprised the whole age cohort from the rural and from two of the three urban municipalities, and about half of the age cohort from the remaining urban municipality. All parents were asked for written consent for their child to participate.

The present study included all children for whom data were available for reading and arithmetic skills at the end of Grades 1 and/or 7, as well as for their linguistic and basic number skills (phonological awareness, letter knowledge, rapid automatized naming, counting sequence knowledge) in kindergarten. This resulted in a total sample size of 1,710 children (52.2% boys, 47.8% girls). The children were five to six years of age upon entering kindergarten in the Fall (M = 73.95 months, SD = 3.49 months). Of the children's mothers, 26.1% had a Master's degree or higher, 30.8% a Bachelor's degree or vocational college degree, 28.5% a vocational school degree, and 6.8% had taken vocational courses or had no education beyond lower secondary school. Of the children's fathers, 20.8% had a Master's degree or higher, 33.1% a Bachelor's degree or vocational college degree, 35.0% a

vocational school degree, and 8.5% had taken vocational courses or had no education beyond lower secondary school. This was relatively representative of the average family background characteristics in Finland (Official Statistics of Finland (OSF): Educational structure of population [e-publication], 2017). Additional background information regarding working memory, short-term memory and inattention/hyperactivity was available for a subsample of 480 to 584 children participating in individual test situations and receiving teacher ratings in Grade 1.

In Finland, the basic compulsory education consists of Grades 1 to 6 in primary school, followed by Grades 7 to 9 in lower secondary school. Before the start of primary school in the year the child turns 7 years old, there is an obligatory year of kindergarten for 6-year-olds. With regard to academic skills, the preschool curriculum supports pre-literacy and pre-numeracy skills, but formal and systematic reading and arithmetic instruction starts in Grade 1. The data concerning linguistic and basic number skills (phonological awareness, letter knowledge, rapid automatized naming, counting sequence knowledge) were assessed individually during the last year of kindergarten, and the data on reading and arithmetic skills were assessed in group settings during the Spring term (March/April) of Grades 1 and 7. General cognitive abilities, including working memory and short-term memory, were assessed individually in Grade 1, and nonverbal reasoning in Grade 3. All tests were carried out by trained researchers or students of psychology/education.

2.2. Measurements

2.2.1. Cognitive variables in kindergarten

2.2.1.1. Phonological awareness. Phonological awareness was assessed individually by using an initial phoneme identification task (Lerkkanen et al., 2006). The task contained ten items (phonemes) for which students were shown the pictures of four objects at the same time and told their names. After this, the children were asked to indicate the picture that began with the phoneme requested. (e.g., "At the beginning of which word do you hear ___?"). The score was based on the total number of correct items (maximum = 10). Cronbach's alpha reliability based on the current sample was.78.

2.2.1.2. Letter knowledge. The Letter Knowledge Test (Lerkkanen et al., 2006) included all 29 uppercase letters of the Finnish alphabet arranged along three rows in a random order. Each child was asked to name the letters one row at a time, and the sum score was the number of correct items (maximum = 29). Cronbach's alpha reliability based on the current sample was 0.95.

2.2.1.3. Rapid automatized naming (RAN). Rapid automatized naming was assessed using the standardized Finnish version, by Ahonen, Tuovinen, and Leppäsaari (1999), of an object naming task (Denckla & Rudel, 1974). Each child was asked to name, as rapidly as possible, a series of five familiar visual stimuli replicated 10 times on a matrix in fixed, pseudorandom order. Documented errors and self-corrections were few, and they were not included in the analysis. The score was the time (in seconds) children needed to complete the total matrix (five rows of 10 items). According to the manual, the test–retest reliability coefficients ranged from 0.84 to 0.92 for all age groups (Zhang et al., 2005).

2.2.1.4. Counting sequence knowledge. In the Number Sequences Test (Salonen et al., 1994), each child was asked to count aloud forward and backward as instructed: (1) counting forward from number 1 (counting was stopped after 31); (2) counting forward from number 6 to 13; (3) counting backward from number 12 (counting was stopped after 7); and (4) counting backward from number 23 to 1. For each of the four tasks, two points were given for the correct outcome, one point for completing the task with up to two errors, and zero points if the student made more than two errors or failed to complete the task (maximum score = 8). Cronbach's alpha reliability based on the current sample was 0.74.

2.2.2. Outcome variables for Grades 1 and 7

2.2.2.1. Reading skills. On average, Finnish students can fluently read whole sentences by the end of Grade 1 (Lerkkanen, 2003). The Test of Silent Reading Efficiency and Comprehension (TOSREC; Wagner, Torgesen, Rashotte, & Pearson, 2009; Finnish version by Lerkkanen, Poikkeus, & Ketonen, 2008) was used to assess silent reading efficiency at the end of Grade 1. In this sentence verification task respondents were given three minutes to read 60 sentences (e.g., "*Strawberries are blue"*) and instructed to rate the sentences as correct or incorrect as accurately and rapidly as they can. At the end of Grade 7, a sentence verification task from a standardized Finnish reading test for lower secondary school was used (YKÄ; Lerkkanen, Eklund, Löytynoja, Aro, & Poikkeus, 2018). Participants were given two minutes to read 70 sentences and instructed to rate the sentences as correct or incorrect as accurately and rapidly as they can. The outcome score for all tasks was the number of correct answers given within the time limit. Both tests had the same aim and used the same instructions but featured different items and a different number of items. Correlations between different tests were very similar to the stability correlates within tests, suggesting that the same skill was assessed despite changes in test items. Similar measures have been used in previous studies examining the comorbidity of fluency problems in reading and arithmetic (see Landerl & Moll, 2010). The Cronbach's alpha reliabilities for the test in the current sample were 0.89 at Grade 1 and 0.94 at Grade 7.

2.2.2.2. Arithmetic skills. The Basic Arithmetic test (Aunola & Räsänen, 2007) was used to assess students' arithmetic skills at the end of Grades 1 and 7. The students were asked to complete as many items as possible within a three-minute time limit. In Grade 1, the test consisted of 14 additions (e.g., $2 + 1 = \_?; 3 + 4 + 6 = \_?$) and 14 subtractions (e.g., $4 - 1 = \_?; 20 - 2 - 4 = \_?$). In Grade 7, the test consisted of a mix of addition, subtraction, multiplication and division tasks (e.g., $40 : 8 - 3 = \_?; \_ - 18 = 45 - 12?; 11 \times 3.2 = \_?; 6 \times 4 + 1 = \_ - 21?$). In total, 28 items increasing in difficulty were presented. In terms of performance, the test requires both accuracy and speed (automatization of basic calculation routines). The sum score represents the total number of correct items and was calculated separately for each grade (maximum = 28). The Cronbach's alpha reliabilities for arithmetic skills in the current sample were 0.70 at Grade 1 and 0.94 at Grade 7.

2.2.3. Background variables

2.2.3.1. Working memory and short-term memory. Working memory and short-term memory were assessed individually at the end of Grade 1, using the Digit Span subtest of the WISC-III (Wechsler, 1991). There are two parts in this test: *digits forward* and *digits backward*. As it has been suggested that Digit Span Forward captures verbal short-term memory while Digit Span Backward is an index of working memory, two different variables were created (Alloway, Gathercole, & Pickering, 2006). The maximum score for the working memory measure was 14 points. In the short-term memory measure, the maximum score was 16 points. According to the manual (Wechsler, 2012), the Cronbach's alpha reliabilities for Digit Span subtests vary from 0.55 to 0.70 for different age groups.

2.2.3.2. Nonverbal reasoning. The students' nonverbal reasoning was tested at the end of Grade 3 in classrooms using the shortened version of the Raven's Colored Progressive Matrices test (Raven, Court, & Raven, 1992). The maximum score was 18. In the current sample, the Guttman split-half reliability of the test was 0.66 and Cronbach's alpha reliability 0.64.

2.2.3.3. Parental education level. Of the students' parents, 1,574 mothers (92.1%) and 1,569 fathers (91.8%) filled in the

Table 1
Correlations, means, and standard deviations of the study variables in a sample of 1710 children.

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.
1. Reading skills T1	1.00												
2. Arithmetic skills T1	0.46***	1.00											
3. Reading skills T2	0.54***	0.27***	1.00										
4. Arithmetic skills T2	0.36***	0.52***	0.36***	1.00									
5. Phonological awareness	0.40***	0.24***	0.22***	0.21***	1.00								
6. Letter knowledge	0.49***	0.35***	0.30***	0.30***	0.56***	1.00							
7. Rapid automatized naming	−0.36***	−0.29***	−0.29***	−0.24***	−0.26***	−0.34***	1.00						
8. Counting sequence knowledge.	0.43***	0.47***	0.27***	0.40***	0.41***	0.59***	−0.28***	1.00					
9. Short-term memory	0.24***	0.17***	0.25***	0.12*	0.24***	0.21***	−0.19***	0.23***	1.00				
10. Working memory	0.31***	0.28***	0.18**	0.22***	0.24***	0.23***	−0.15***	0.32***	0.27***	1.00			
11. Inattention / hyperactivity	−0.04	−0.01	−0.09	0.02	−0.07	−0.34***	0.12*	−0.03	−0.06	−0.10*	1.00		
12. Nonverbal reasoning	0.21***	0.22***	0.22***	0.28***	0.23***	0.20***	−0.20***	0.21***	0.20***	0.25***	−0.19***	1.00	
13. Parental education level	0.14***	0.14***	0.13***	0.21***	0.21***	0.24***	−0.13***	0.16***	0.05	0.06	−0.05	0.11***	1.00
M	18.32	10.60	33.59	13.88	7.54	17.32	69.79	4.53	5.84	3.04	9.34	16.65	4.47
SD	8.03	4.09	7.41	3.80	2.40	8.89	16.98	2.81	1.32	1.15	1.48	1.73	1.49

Note. T1 = March/April of Grade 1, T2 = March/April of Grade 7. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.
Rapid automatized naming was scored as reaction time (low scores representing high performance and high scores representing low performance).

questionnaires reporting their vocational education on a 7-point scale (1 = *no education beyond comprehensive school,* 2 = *vocational courses,* 3 = *vocational school degree,* 4 = *vocational college degree,* 5 = *polytechnic degree or Bachelor's degree,* 6 = *Master's degree,* and 7 = *licentiate or doctoral degree*). The education level of the parent with a higher education was used as an indicator of parental education level.

2.2.3.4. Inattention/hyperactivity. Teacher-ratings of inattention and hyperactivity were collected at the end of Grade 1, using the inattention/hyperactivity subscale of the Strengths and Difficulties Questionnaire for 4–16-year-olds (SDQ 4–16; Goodman, 1997). The questionnaire consists of five questions that are rated on a 3-point scale (1 = *not true,* 2 = *somewhat true,* and 3 = *true*). Cronbach's alpha reliability for the inattention/hyperactivity subscale was 0.90.

2.3. Analysis strategy

First, latent profile analysis (LPA) was used for identifying homogeneous subgroups (i.e., profiles) of children that show similar response patterns in variables related to linguistic and basic number skills (phonological awareness, letter knowledge, rapid automatized naming, and counting sequence knowledge). The goal of LPA is to identify the fewest number of latent profiles that adequately explain the unobserved heterogeneity of the relationships between indicators within a population (Orri et al., 2007). Estimation was performed step-by-step, starting with a one-class solution and continuing to estimate the parameters for two-, three-, and further k-class solutions. To ensure the validity of each class solution, several different starting values were used for the parameters (see Muthén & Muthén, 1998–2011).

The following statistical criteria were used to evaluate the fit of the model in order to find the optimal number of latent profiles regarding linguistic and basic number skills: (a) log likelihood (Log L); (b) Akaike's information criterion (AIC); (c) the sample-size adjusted Bayesian information criterion (aBIC); (d) the Vuong-Lo-Mendel-Rubin test (VLMR); (e) the Lo-Mendel-Rubin test (LMR); (f) the parametric bootstrapped likelihood ratio test (BLRT; Muthén & Muthén, 1998–2007); (g) the reliability of classification by entropy; and (h) average latent class posterior probabilities (AvePP; Muthén & Muthén, 1998–2007). The lower the absolute value of the Log L, AIC, and aBIC, the better the model fit. The likelihood ratio tests (VLMR, LMR, and BLRT) compare solutions with different numbers of latent profiles. A low p value ($p < .05$) suggests that a solution with k latent profiles fits the data better than a solution with k-1 profiles. The entropy and AvePP indices assess the statistical quality of the classification (i.e., how well the model classifies individuals into subgroups), with possible values ranging from 0 to 1. As a rule of thumb, values > 0.70 indicate that the found solution is interpretable using the mean trajectories (Nagin, 2005).

Second, in order to examine potential differences between the domain-general cognitive profiles and parental education, we included working memory, short-term memory, nonverbal reasoning, inattention/hyperactivity, and parental education level into the previous model as auxiliary indicator variables in line with the auxiliary measurement-error-weighted method (BCH; Muthén & Asparouhov, 2015). This method enables the testing of differences between the latent groups in some external variables (so-called auxiliary variables) with a Chi-square test, without letting these external variables affect the formation of the latent profiles. Finally, to examine the extent to which the identified cognitive profiles predict subsequent reading and arithmetic skills in Grades 1 and 7, reading in Grade 1, arithmetic in Grade 1, reading in Grade 7, and arithmetic in Grade 7 were included in the model as auxiliary indicator variables, and differences between the latent profiles on these were tested using a Chi-square test. In this context, the overlap of the levels of reading and arithmetic skills within groups was investigated by comparing the 95% confidence intervals of the mean values of reading and arithmetic skills within each group, both for Grade 1 and Grade 7 separately.

When considering the magnitude of the studied effects, mean differences between the subgroups of children showing different latent profiles divided by the standard deviation of the whole sample were used as indicators of effect size. Mean differences over 0.80 were considered large, mean differences between 0.50 and 0.80 were considered medium, and values between 0.20 and 0.50 were considered small (Cohen, 1992).

All analyses were performed using the Mplus statistical software program (Version 7.0) and the standard missing-at-random (MAR) approach, which supposes that any data missing would be missing at random (Muthén & Muthén, 1998–2010). The parameters of the models were estimated using full information maximum likelihood (FIML) estimation with standard errors robust to non-normality (MLR estimator; Muthén & Muthén, 1998–2010). Means *(M)*, standard deviations *(SD)*, and the correlations between all variables are shown in Table 1.

3. Results

3.1. Cognitive profiles based on linguistic and basic number skills

First, we aimed to identify the cognitive profiles with regard to linguistic and basic number skills (phonological awareness, letter knowledge, rapid automatized naming, and counting sequence

Table 2
Comparison of the latent profile analysis solutions with one to seven classes (selected solution in bold).

Classes	Log L	AIC	aBIC	VLMR *(p)*	LMR *(p)*	BLRT *(p)*	Entropy	AvePP	*n*
1	−9680.902		19377.803	19395.942					1710
2	−8834.622	17695.244	17724.720	0.0000	0.0000	0.0000	0.82	0.94–0.95	735/ 975
3	−8654.747	17345.494	17386.307	0.0000	0.0000	0.0000	0.84	0.88–0.95	463/531/716
4	**−8518.578**	**17083.156**	**17135.305**	**0.0000**	**0.0000**	**0.0000**	**0.83**	**0.82–0.95**	**671/434/262/343**
5	−8434.284	16924.567	16988.053	0.0771	0.0813	0.0000	0.85	0.82–0.95	426/20/261/332/671
6	−8383.752	16833.505	16908.328	0.0031	0.0036	0.0000	0.82	0.81–0.94	21/142/298/315/663/271
7	−8318.643	16713.287	16799.447	0.3191	0.3274	0.0000	0.83	0.79–0.94	21/157/211/238/311/129/643

Note. Log L = log-likelihood value; AIC = Akaike's information criterion; aBIC = adjusted Bayesian information criterion; VLMR = Vuong-Lo-Mendell-Rubin likelihood ratio test; LMR = Lo-Mendell-Rubin adjusted likelihood test; BLRT = Bootstrapped likelihood ratio test; AvePP = Average Latent Class Posterior Probabilities.

knowledge) assessed in kindergarten using LPA. The model fit indices and class sizes of the one- to seven-class solutions are shown in Table 2. A comparison of the statistical fit information suggested that the four-class solution was the best for further analysis. Although the fit indices regarding the absolute Log L, AIC, and aBIC decreased even after the four-class solution, the changes in values beyond the four-class solution were only small, suggesting that the improvement of the fit was not remarkable. Furthermore, most of the likelihood ratio tests (VLMR, LMR) indicated that the four-class solution fit the data better than the five-class solution. Finally, the class sizes were taken into account. The solutions with more than four classes included a class consisting of only 20–21 individuals, which makes it difficult to generalize the findings. The statistical quality of the classification based on entropy and AvePP values was acceptable concerning all class solutions, from 1 to 7.

The standardized means and estimated class probabilities for the selected four-class solution are listed in Table 3. The four identified latent profiles are shown in Fig. 1: (1) high linguistic and high counting skills, (2) low linguistic and low counting skills, (3) high counting skills in relation to linguistic skills, and (4) low counting skills in relation to linguistic skills. The given labels were based on the relation between linguistic and counting skills within profiles. Accordingly, the “high linguistic and high counting skills” children were performing above average in phonological awareness, letter knowledge, rapid automatized naming, and also counting, whereas the “low linguistic and low counting skills” children were performing below average across these skills. Children in the “high counting skills in relation to linguistic skills” and “low counting skills in relation to linguistic skills” profiles showed a discrepancy between linguistic and counting skills. The children with “high counting skills in relation to linguistic skills” performed at or below the average level in phonological awareness, letter knowledge, and rapid automatized naming but above average in counting. Children with “low counting skills in relation to linguistic skills,” on the other hand, performed at the average level across linguistic skills but below average in counting.

The effect sizes (i.e., group differences in standardized values of criteria variables; see standardized mean values in Table 3) of group differences in criteria variables varied from small to large. When comparing profiles showing either consistent high or consistent low skill level—that is, profiles 1 and 2—the effect sizes were large (> 0.80) across all criteria variables. Regarding the differences between the two more discrepant profiles, that is, profiles 3 and 4, the effect sizes were large (> 0.80) for counting and letter knowledge, and small (> 0.20) for the other variables. Regarding the differences between profiles 1 and 4, as well as the differences between profiles 2 and 3, the effect size was large (> 0.80) for counting and from small (> 0.20) to medium (> 0.50) for the other variables. The effect sizes between profiles 1 and 3 and between profiles 2 and 4 were large (> 0.80) for phonological awareness and letter knowledge and from small to medium (< 0.80) for the other variables.

Next, the differences between the four cognitive profiles in general cognitive variables—that is, nonverbal reasoning ($\chi^2(3) = 75.00$, $p < .001$), short-term memory ($\chi^2(3) = 25.54$, $p < .001$), working memory ($\chi^2(3) = 23.64$, $p < .001$), and inattention/hyperactivity ($\chi^2(3) = 1.46$, $p > .05$), as well as in parental education level ($\chi^2(3) = 84.07$, $p < .001$)—were investigated. Statistically significant group differences were found in all of the external variables with effect sizes ranging from small to medium, except for inattention/hyperactivity, in which the variable group differences were not evident. The differences between the profile groups in these variables are shown in Table 4 and Fig. 2. Children characterized by high linguistic and high counting skills (Profile 1) and those characterized by high counting skills in relation to linguistic skills (Profile 3) performed significantly better in short-term memory and working memory than the children in the other two groups. Regarding nonverbal reasoning, children showing high linguistic and high counting skills (Profile 1) performed significantly better, and children showing low linguistic and low counting skills (Profile 2) performed significantly poorer than the other groups, whereas the children belonging to the other two profiles performed at the average level and did not differ from each other. The level of parental education was significantly highest among children characterized

Table 3
The results of the four-class solution: standardized means (M), standard errors (S.E.), and average posterior probabilities (AvePP) for each latent cognitive profile regarding linguistic and basic number skills.

Cognitive profiles				
	1 *M (S.E.)*	2 *M (S.E.)*	3 *M (S.E.)*	4 *M (S.E.)*
Phonological awareness	0.63 (0.03)[a]	−0.78 (0.06)[b]	−0.35 (0.07)[c]	0.03 (0.07)[d]
Letter knowledge	0.92 (0.02)[a]	−1.24 (0.04)[b]	−0.62 (0.06)[c]	0.25 (0.06)[d]
Counting sequence knowledge	0.84 (0.03)[a]	−1.16 (0.03)[b]	0.59 (0.05)[c]	−0.70 (0.06)[d]
Rapid automatized naming	0.38 (0.03)[a]	−0.50 (0.06)[b]	−0.17 (0.08)[c]	0.01 (0.06)[c]
AvePP	0.95	0.93	0.86	0.82

Note. 1 = High linguistic and high counting skills; 2 = Low linguistic and low counting skills; 3 = High counting skills in relation to linguistic skills; 4 = Low counting skills in relation to linguistic skills; AvePP = Average Latent Class Posterior Probabilities.
Subscripts: Means with the same subscript do not differ significantly from each other.

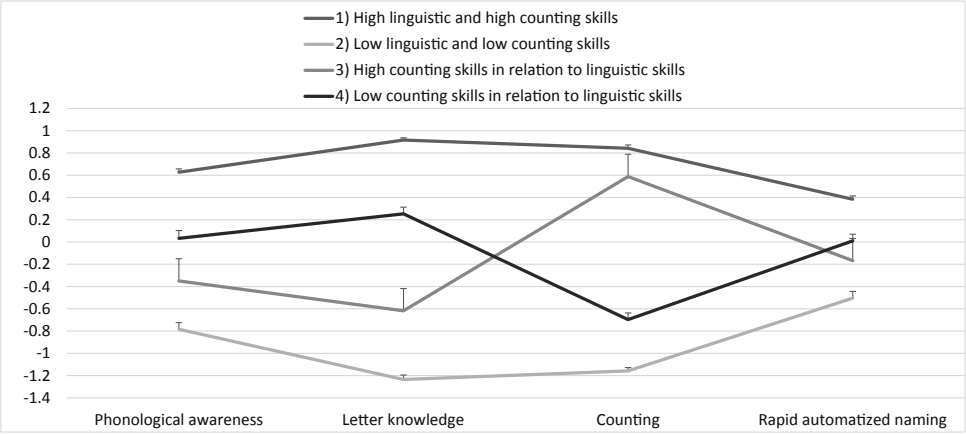

Fig. 1. Cognitive profiles based on linguistic and basic number skills. Lines represent different patterns of performance across phonological awareness, letter knowledge, rapid automatized naming, and counting sequence knowledge (i.e., cognitive profiles).

by high linguistic and high counting skills (Profile 1) and lowest among children characterized by low linguistic and low counting skills (Profile 2) together with children showing high counting skills in relation to linguistic skills (Profile 3).

3.2. The association between cognitive profiles and reading and arithmetic skills in Grades 1 and 7

Next, we analyzed to what extent the identified cognitive profiles are associated with children's subsequent reading and arithmetic skills in Grades 1 and 7. The results showed statistically significant group differences between the latent cognitive profiles in reading and arithmetic skills both in Grade 1 [$\chi^2(3) = 567.68, p < .001$ for reading; $\chi^2(3) = 402.64, p < .001$ for arithmetic] and Grade 7 [$\chi^2(3) = 123.42, p < .001$ for reading; $\chi^2(3) = 212.87, p < .001$ for arithmetic]. The differences between the profile groups are shown in Table 5 and Fig. 3.

The results showed that, both in Grades 1 and 7, children characterized by high linguistic and high counting skills (Profile 1) performed significantly highest, whereas children characterized by low linguistic and low counting skills (Profile 2) performed significantly lowest both in reading and arithmetic. The 95% confidence intervals revealed further that, in the case of profile 1, performance in reading and in arithmetic were on the same level (i.e., demonstrated overlap) in Grade 1 (CI [0.53, 0.69] for reading, CI [0.43, 0.59] for arithmetic) and in Grade 7 (CI [0.26, 0.46] for reading, CI [0.37, 0.53] for arithmetic). Similarly, in the case of profile 2, performance in reading and in arithmetic were on the same level in Grade 1 (CI [–0.78, –0.62] for reading, CI [–0.67, –0.51] for arithmetic) and in Grade 7 (CI [–0.64, –0.36] for reading, CI [–0.69, –0.41] for arithmetic). Overall, these results suggest that in the case of profiles showing either consistent high or low levels of linguistic and counting skills—that is, profiles 1 (high linguistic and high counting skills) and 2 (low linguistic and low counting skills)—reading and arithmetic skills were on the same level, demonstrating overlap from primary to lower secondary school.

The other two profiles—high counting skills in relation to linguistic skills (Profile 3) and low counting skills in relation to linguistic skills (Profile 4)—were associated with somewhat discrepant reading and arithmetic performances in Grades 1 and 7, and the overlap between reading and arithmetic skills was less evident. Children characterized by high counting skills in relation to linguistic skills (Profile 3) performed in between the ones with "high linguistic and high counting skills" and those with "low linguistic and low counting skills" in reading and arithmetic across both grades. Furthermore, they scored significantly higher in arithmetic (CI [0.01, 0.29]) than in reading (CI [–0.32, –0.08]) in Grade 1, but they showed overlap between reading (CI [–0.34, –0.06]) and arithmetic (CI [–0.12, 0.20]) skills in Grade 7. Children characterized by low counting skills in relation to linguistic skills (Profile 4) in turn performed similarly in between the children with "high linguistic and high counting skills" and those with "low linguistic and low counting skills" in reading at Grades 1 and 7. In arithmetic, they performed at a level between the children with "high counting skills in relation to linguistic skills" and those with "low linguistic and low counting skills" in Grade 1, and they performed lowest together with those with "low linguistic and low counting skills" in Grade 7. In Grade 1, their skills in arithmetic (CI [–0.50, –0.30]) and in

Table 4
Means (M) and standard errors (S.E.) of the children's general cognitive abilities and parental education level in each cognitive profile, and statistically significant differences between the four patterns.

Cognitive profiles				
	1 *M (S.E.)*	2 *M (S.E.)*	3 *M (S.E.)*	4 *M (S.E.)*
Short-term memory	0.38 (0.09)^{a}	−0.20 (0.09)^{b}	0.35 (0.15)^{ac}	0.02 (0.12)^{bc}
Working memory	0.41 (0.09)^{a}	−0.09 (0.10)^{b}	0.43 (0.17)^{a}	−0.17 (0.12)^{b}
Inattention /hyperactivity	−0.01 (0.09)^{a}	−0.04 (0.12)^{a}	0.06 (0.23)^{a}	−0.22 (0.15)^{a}
Nonverbal reasoning	0.25 (0.03)^{a}	−0.34 (0.07)^{b}	0.03 (0.07)^{c}	−0.11 (0.07)^{c}
Parental education level	0.27 (0.04)^{a}	−0.30 (0.05)^{b}	−0.22 (0.07)^{b}	−0.00 (0.07)^{c}

Note. 1 = High linguistic and high counting skills; 2 = Low linguistic and low counting skills; 3 = High counting skills in relation to linguistic skills; 4 = Low counting skills in relation to linguistic skills. Subscripts: Means with the same subscript do not differ significantly from each other.

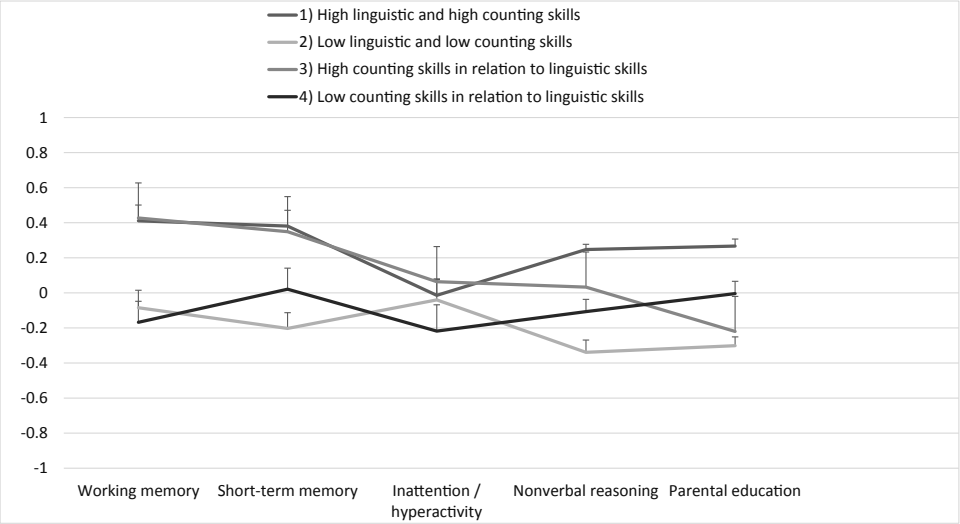

Fig. 2. Differences between the cognitive profiles in control variables. Lines represent differences between the profiles in general cognitive abilities and parental education.

reading (CI [–0.32, –0.08]) were on the same level, indicating overlap between these skills. However, in Grade 7, their skills in reading (CI [–0.21, 0.07]) were at a higher level than their skills in arithmetic (CI [–0.57, –0.29]), demonstrating a discrepancy rather than an overlap between reading and arithmetic.

The effect sizes (i.e., group differences in standardized values of dependent variables; see standardized mean values in Table 5) between the two consistent profiles, that is, profiles 1 and 2, were large (> 0.80) across all dependent variables (reading Grade 1, arithmetic Grade 1, reading Grade 7, arithmetic Grade 7). The two discrepant profiles—that is, profiles 3 and 4—differed from each other only in arithmetic: the effect size ranging from small (> .20) (Grade 7) to medium (> .50) (Grade 1). Differences between the profiles 1 and 4 were large (> .80) in arithmetic (Grade 1 and 7) and from small (> .20) (Grade 7) to large (> .80) (Grade 1) in reading, and differences between the profiles 1 and 3 were from medium (> .50) (Grade 7) to large (> .80) (Grade 1) in reading and small (> .20) in arithmetic (Grade 1 and 7). Finally, differences between the profiles 2 and 3 varied from small (> .20) (reading Grade 7) to medium (> .50) (reading Grade 1 and arithmetic Grade 1 and Grade 7), and differences between the profiles 2 and 4 varied from small (> .20) (arithmetic Grade 1 and reading Grade 7) to medium (> .50) (reading Grade 1).

4. Discussion

In the present study, we applied a person-oriented approach in order to improve our understanding of the cognitive antecedents related to the overlap between reading and arithmetic skills from primary to lower secondary school. Specifically, we investigated the extent to which different patterns of performance across linguistic and basic number skills predict the overall performance level in reading and arithmetic. Subgroups of children showing distinct cognitive profiles in kindergarten with regard to phonological awareness, letter knowledge, rapid automatized naming, and counting sequence knowledge were identified. Furthermore, the relations of these cognitive profiles to reading and arithmetic skills assessed at Grades 1 and 7 were examined. Four distinct cognitive profiles emerged: (1) high linguistic and high counting skills, (2) low linguistic and low counting skills, (3) high counting skills in relation to linguistic skills, and (4) low counting skills in relation to linguistic skills. These profiles differentially predicted subsequent reading and arithmetic development as well as the overlap between the two academic skills at Grades 1 and 7.

First, the results showed that the majority of the children (about 65%) demonstrated overall either high or low linguistic and counting skills, and, accordingly, either high or low levels in both reading and arithmetic skills, tested in Grades 1 and 7. These two profiles thus demonstrated overlap not only between early linguistic and basic number skills but also between reading and arithmetic skills across school

Table 5
Means (M) and standard errors (S.E.) of the children's reading and arithmetic skills in grades 1 and 7 for latent cognitive profiles and statistically significant differences between the patterns.

Cognitive profiles				
	1 *M (S.E.)*	2 *M (S.E.)*	3 *M (S.E.)*	4 *M (S.E.)*
Reading skills, Grade 1	0.61 (0.04)^{a}	−0.70 (0.04)^{b}	−0.20 (0.06)^{c}	−0.20 (0.06)^{c}
Arithmetic skills, Grade 1	0.51 (0.04)^{a}	−0.59 (0.04)^{b}	0.15 (0.07)^{c}	−0.40 (0.05)^{d}
Reading skills, Grade 7	0.36 (0.05)^{a}	−0.50 (0.07)^{b}	−0.20 (0.07)^{c}	−0.07 (0.07)^{c}
Arithmetic skills, Grade 7	0.45 (0.04)^{a}	−0.55 (0.07)^{b}	0.04 (0.08)^{c}	−0.43 (0.07)^{b}

Note. 1 = High linguistic and high counting skills; 2 = Low linguistic and low counting skills; 3 = High counting skills in relation to linguistic skills; 4 = Low counting skills in relation to linguistic skills. Subscripts: Means with the same subscript do not differ significantly from each other.

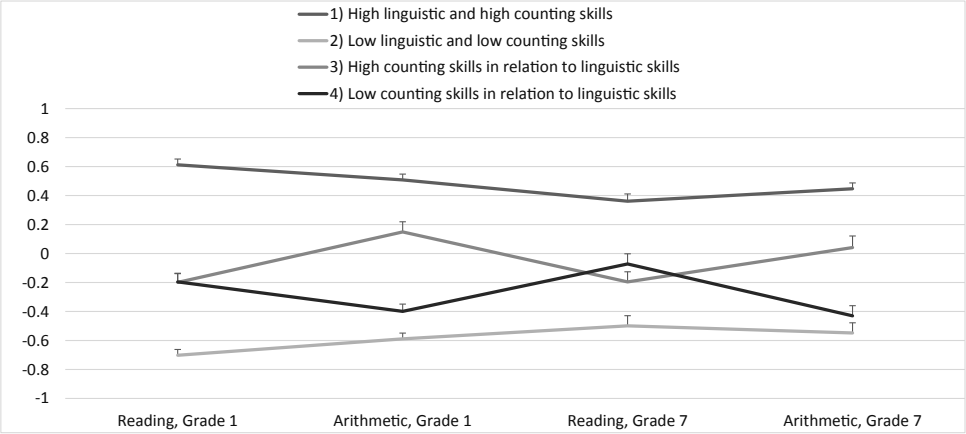

Fig. 3. Differences between the cognitive profiles in reading and arithmetic skills in Grades 1 and 7. Lines represent outcomes in reading and arithmetic skills in Grades 1 and 7 by different cognitive profiles.

grades. The differences between these two profiles in the levels of subsequent reading and arithmetic skills were notable. Taking into account the fact that the studied linguistic and basic number skills have previously been shown to have additive impacts (i.e., an increase in each independent variable adds independently to the predicted value) on the overlap of reading and arithmetic skills in studies using a variable-oriented approach (Korpipää et al., 2017, 2019), it is not surprising that children demonstrating high levels in all of these cognitive antecedents also show high skill levels in both reading and arithmetic, whereas children with low levels in all of these cognitive antecedents show the lowest performance levels in reading and arithmetic. In previous research, fluency in both reading and arithmetic has been shown to build on the ability to form and retrieve phonological representations corresponding to visually presented symbols, such as letters and digits, as well as on the ability to process serial information (Koponen et al., 2007, 2016). Furthermore, the central manifestation of both difficulties in reading (Fuchs, Fuchs, Hosp, & Jenkins, 2001) and math (Geary, 2004) relates to a lack of fluency. As such, these two cognitive profiles represent the high and low end of reading and arithmetic skills, supporting the idea that the attributes of learning difficulties in reading and math are dimensional and represent a correlated continua of severity (Branum-Martin, Fletcher, & Stuebing, 2013).

On the other hand, the results of the present study also showed that one-third of the sample (35.4%) demonstrated discrepant linguistic and basic number skills and, accordingly, somewhat discrepant levels of reading and arithmetic skills in Grades 1 and 7. The first discrepant group comprised children with high counting skills in relation to linguistic skills. As expected, children with this profile performed higher in arithmetic than in reading in Grade 1. Interestingly, in Grade 7, these differences between reading and arithmetic skills were somewhat less evident. This result may reflect a slower development of reading skills in the early phase of skill development in this group of children. As a result, the reading skills of children with high counting skills in relation to linguistic skills were not, during the transition stage to primary school, at the same level. The awareness of letters and sounds has been shown to be particularly important in the development of basic word decoding skills (Hogan, Catts, & Little, 2005; Hulme, Bowyer-Crane, Carroll, Duff, & Snowling, 2012), whereas rapid automated naming is a predictor of later growth in reading fluency (Lervåg & Hulme, 2009; see also Landerl et al., 2019). However, once children have acquired all the needed subskills to learn to read (Hulme & Snowling, 2013), there is a rapid increase in their reading performance and decrease in interindividual variation (Leppänen, Niemi, Aunola, & Nurmi, 2004). In line with this, phonological awareness and letter-sound knowledge have been shown to predict the overlap between reading and arithmetic mainly in the early phase of skill development (Korpipää et al., 2017). The strengths in cognitive antecedents that are strongly related to developing fluency in both domains, such as rapid automatized naming and counting sequence knowledge (Koponen et al., 2013; 2016), are likely to explain the overlap between reading and arithmetic especially in Grade 7.

The other discrepant group included children with low counting skills in relation to linguistic skills. Children with this profile showed an overlap between reading and arithmetic skills in Grade 1, but they performed higher in reading than in arithmetic in Grade 7. This pattern may also be due to different developmental trajectories of reading and arithmetic skills: whereas individual differences in reading ability decrease across school years (Leppänen et al., 2004; Parrila, Aunola, Leskinen, & Nurmi, 2005), differences in arithmetic ability rather increase (Aunola, Leskinen, Lerkkanen, & Nurmi, 2004). Kindergarten counting has been shown to be the strongest predictor of this cumulative development of arithmetic skills (Aunola et al., 2004; Zhang et al., 2014). Counting is related to developing memory representations of arithmetic facts and more mature strategies of retrieving these facts from long-term memory (Geary, 2004; Siegler & Shranger, 1984). Consequently, counting sequence knowledge continues to exert its influence on arithmetic ability until higher grades (Koponen et al., 2016). Following this line of reasoning, poor basic number skills in kindergarten may lead the child to lag behind his or her peers, particularly concerning arithmetic ability. Furthermore, children in this group had more strengths regarding the shared cognitive antecedents of reading and arithmetic skills at an early rather than later phase of skill development, such as phonological awareness and letter knowledge (Korpipää et al., 2017). It is likely that the overlap between reading and arithmetic is therefore more evident in Grade 1 than in Grade 7.

In the present study, children who showed high counting skills in relation to linguistic skills performed lower in arithmetic across the grades than did the children who showed high linguistic and high counting skills (the effect was, however, small). This result can be interpreted to stem from the children's weaknesses in linguistic skills. It has been shown that weaknesses in linguistic skills have a negative impact on developing arithmetic skills (Geary, 1993; Jordan, Hanich, & Kaplan, 2003; Simmons & Singleton, 2008), and this negative effect seems to be independent of the effect of counting skills. Children showing low counting skills in relation to linguistic skills, in turn, performed low in arithmetic in Grades 1 and 7 despite their average linguistic skills. It is likely that, in this profile, low arithmetic skills derive mainly from weaknesses in number-specific skills rather than

from weaknesses in representing and accessing semantic information (Locuniak & Jordan, 2008). However, further research is needed to clarify the issue. Overall, having strengths in one of the skill domains seems to be somewhat advantageous (effect sizes ranging from small to medium) over having weaknesses in both domains. Particularly, a high level of counting skills may function as a compensator for poor letter knowledge and phonological awareness. It has been previously reported that deficits in both domains can lead to more severe and stable impairments in academic functioning (Koponen et al., 2018; see also Willcutt et al., 2013). The results of our study point toward the importance of both shared and nonshared influences of linguistic and basic number skills on reading and arithmetic skill development, supporting the findings by Cirino et al. (2018).

Children with different cognitive profiles were also found to differ from each other with respect to more general cognitive factors, such as short-term memory, working memory, and nonverbal reasoning, as well as parental education (the effect sizes varying from small to medium). In the profiles of consistent linguistic and basic number skills, children differed across all of these measures: children showing high linguistic and high basic number skills performed highest, whereas children showing low linguistic and low basic number skills performed lowest. In the profiles of discrepant linguistic and basic number skills, children differed mainly in terms of memory measures. Children showing high basic number skills in relation to linguistic skills performed highest, and children showing low basic number skills in relation to linguistic skills performed lowest regarding working memory and short-term memory. These results are in line with previous findings suggesting that children with difficulties in math tend to have a weaker working memory capacity than children showing normal math achievement (Swanson & Beebe-Frankenberger, 2004). As working memory systems play an important role in arithmetic (Cragg, Richardson, Hubber, Keeble, & Gilmore, 2017; De Smedt et al., 2009), it is likely that the discrepancy between linguistic and basic number skills, as well as between subsequent reading and arithmetic skills, is at least partly related to working memory capacity. It should be noted, however, that—for all profiles—the children's performances across the measures of working memory, short-term memory, nonverbal reasoning, and inattention/hyperactivity were within the average range, and the differences between the profiles in these variables were not large in magnitude. This result is well in line with the recent findings suggesting that cognitively focused interventions (e.g., training working memory) for children with learning difficulties in reading and arithmetic are less efficient than academic or skills-based interventions focusing on improving academic performance (e.g. letter-sound correspondence) (for a review, see Kearns & Fuchs, 2013).

Overall, whereas the earlier research identified the cognitive antecedents that underlie the rather strong overlap between reading and arithmetic skills in Grades 1 and 7 (Korpipää et al., 2017), the present study identified homogeneous subgroups of children that differ qualitatively in terms of patterns of performance across these cognitive antecedents. This made it possible to investigate interactive effects of linguistic and basic number skills on the overlap between reading and arithmetic (i.e., whether these cognitive antecedents predict differently the overlap between reading and arithmetic depending on the levels of each other). As such, the results of this study provide a deeper understanding of how linguistic and basic number skills operate together in predicting reading and arithmetic skills, as well as their overlap, across grade levels.

From a practical point of view, the results provide valuable information for educators to predict the development of reading and arithmetic skills in relation to each other from primary to lower secondary school. The findings suggest that weaknesses in phonological awareness and letter knowledge in kindergarten do not yet place children at risk for low skill level shared by reading and arithmetic. Rather, the risk becomes evident when weaknesses in letter knowledge and phonological awareness show up together with weaknesses in early counting skills. Weaknesses in counting alone in turn place children at risk for difficulties in arithmetic, especially at the later phase of skill development, independently of the levels of different linguistic skills. Thus, for difficulties in arithmetic skill development, weaknesses in counting skills alone are an equal risk to weaknesses evident in both linguistic and counting skills. Another important finding of the present study is that in kindergarten, weaknesses across linguistic and basic number skills are more common than weaknesses in only one of the domains. In previous literature, weaknesses across different domains have been shown to be related to the most severe and persistent problems in both reading and arithmetic (Koponen et al., 2018). Consequently, assessing the cognitive profiles regarding the shared predictors of reading and arithmetic provide additional information concerning the broadness of difficulties at different phases of skill development in these two basic academic domains.

5. Limitations

The following limitations should be taken into account before generalizing the findings of this study. First, cognitive abilities were assessed at different time points: (1) preskills (phonological awareness, letter knowledge, rapid automatized naming, and counting sequence knowledge) in kindergarten; (2) working memory, short-term memory, and inattention/hyperactivity in Grade 1; and (3) nonverbal reasoning in Grade 3. Second, the measures of working memory, short-term memory, and inattention/hyperactivity were available only from a subsample, and we did not have the data to include executive functioning or processing speed as separate outcome variables. Third, basic number skills included only a measure of counting sequence knowledge, which taps the ability to form and access associative relations (see Fuchs et al., 2016). In future studies, it would be interesting to include other subskills of arithmetic, such as number concept (mapping between the symbolic number words and numbers with quantities) and magnitude comparisons as well. Fourth, the transparent orthography of the Finnish language should be considered when generalizing these results to other languages. Due to the highly consistent grapheme–phoneme correspondence structure, decoding in Finnish requires less advanced phonological processing skills than in more opaque orthographies, such as English.

6. Conclusion

The results of the present study show that, among most of the children, linguistic and basic number skills (in terms of counting skills) were strongly related, which was evident as the children showed either high or low performance levels across all of these skills. This covariation of linguistic and basic number skills predicted overlapping—either high or low overall performance level—in reading and arithmetic skills during primary and lower secondary school. However, among some of the children, linguistic and basic number skills were less related, and the discrepant patterns of linguistic and basic number skills predicted somewhat discrepant levels of subsequent reading and arithmetic skills as well. Furthermore, the weaknesses in both linguistic and counting skills were a more typical pattern than weaknesses in only one of the domains. The results of this study suggest that there is individual variation in the combination of linguistic and basic number skills, and, consequently, these cognitive antecedents predict the overlap between reading and arithmetic differently at early and later phases of development, depending on each individual's cognitive profile. Therefore, individual differences in children's underlying cognitive strengths and weaknesses should be taken into account when supporting the development of these skills.

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III

PREMATURITY AND OVERLAP BETWEEN READING AND ARITHMETIC: THE COGNITIVE MECHANISMS BEHIND THE ASSOCIATION

by

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Prematurity and overlap between reading and arithmetic: The cognitive mechanisms behind the association

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ABSTRACT

It is well-known that very preterm children perform at lower levels than full-term children in reading and arithmetic at school. Whether the lower performance levels of preterm children in these two separate domains have the same or different origins, however, is not clear. The present study examined the extent to which prematurity is associated with the overlap (i.e., common variance) of reading and arithmetic among Finnish school beginners. We also examined the extent to which the association of prematurity with the overlap between reading and arithmetic is due to different prereading skills, basic number skills, and general cognitive abilities. The participants (age 6–7) consisted of 193 very preterm children (< 32 weeks of gestation or birth weight < 1501 g) and 175 full-term control children assessed at the beginning of Grade 1. The results showed that about 40% of the variation in reading and arithmetic skills was common to these two domains and thus, represented the overlap between reading and arithmetic. Prematurity was found to be negatively associated with the overlapping part of reading and arithmetic skills. This association was explained particularly by differences between very preterm and full-term children in prereading (letter knowledge, phonological awareness, and rapid automatized naming) and basic number skills (counting sequence knowledge): Very preterm children showed lower levels of phonological awareness, letter knowledge, counting, and rapid serial naming than full-term children and thus, also demonstrated lower skill level common for reading and arithmetic. Early screening of very preterm children according to the cognitive antecedents that predict the overlap between reading and arithmetic is needed to prevent comorbid difficulties in these domains.

1. Introduction

Prematurity has been shown to be associated with learning outcomes at school (Dempsey et al., 2015; Keller-Margulis, Dempsey, & Llorens, 2011; Taylor et al., 2016). The risk of academic failure is statistically significantly higher among very preterm compared to full-term children, particularly in math (Aarnoudse-Moens, Oosterlaan, Duivenvoorden, van Goudoever, & Weisglas-Kuperus, 2011; Pritchard et al., 2009) but also in reading (for a review, see Kovachy, Adams, Tamaresis, & Feldman, 2014). Thus far, research on such differences between very preterm and full-term children has focused on each skill domain separately, ignoring the evidence that reading and math are highly correlated skills in population-based samples (Hecht, Torgesen, Wagner, & Rashotte, 2001; Koponen, Aunola, Ahonen, & Nurmi, 2007), and difficulties in these domains co-occur more often than would be expected by chance (Kovas et al., 2007; Landerl & Moll, 2010; Willcutt et al., 2013). The strong overlap between reading and math skills is thought to be caused by a common set of cognitive processes underlying both skills (Hecht et al., 2001; Koponen et al., 2016; Koponen, Salmi, Eklund, & Aro, 2013; Korpipää et al., 2017). Because research on the role of prematurity in learning outcomes has thus far focused on only one domain at time (i.e., reading or math separately), the extent to

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which prematurity is related to domain-general variation in basic academic skills (i.e., variation that is common for reading and math) rather than domain-specific variation is far from clear. Consequently, the aim of the present study was to examine the extent to which prematurity is associated with the overlap between reading and arithmetic. Moreover, the cognitive mechanisms mediating this association were investigated. Because learning difficulties occurring both in reading and math domains are more severe and persistent over time than difficulties evident only in one domain (Jordan, Hanich, & Kaplan, 2003, see also Koponen et al., 2018; Willcutt et al., 2013), the question is vitally important from the educational point of view. Understanding the role of prematurity in the overlap between reading and arithmetic may give useful insights not only into the shared background of reading and arithmetic but also into how one should take prematurity into account when supporting children's school learning.

1.1. Differences between very preterm and full-term children in academic skills and related cognitive correlates

According to the meta-analysis by Kovachy et al. (2014), preterm birth is associated with both fundamental components of reading, decoding and comprehension. It has been shown that between the ages of 5 and 20, very preterm children score 0.48 SD lower in reading tests than their full-term peers (for a review, see Aarnoudse-Moens, Weisglas-Kuperus, van Goudoever, & Oosterlaan, 2009). There are also statistically significant differences between the groups regarding many antecedents of reading, such as phonological awareness and letter knowledge (Schneider, Wolke, Schlagmuller, & Meyer, 2004), as well as rapid automatized naming (RAN; Alanko et al., 2017; Saavalainen et al., 2006), which is highly predictive of fluency in reading (Kirby, Georgiou, Martinussen, & Parrila, 2010).

In addition to reading skills, very preterm children between the ages of 5 and 20 years have been found to score 0.60 SD lower than their full-term peers on math tests (for a review, see Aarnoudse-Moens et al., 2009). Evidence indicates that very preterm birth is negatively associated with basic number skills, as well as math skills at school age, such as arithmetic. For example, statistically significant differences between very preterm and full-term children have been found in skills related to number sense (i.e., knowledge of numbers and their relations), and counting sequence knowledge (i.e., the ability to count number words forward, backward, and in steps; Alanko et al., 2017; Guarini et al., 2014). These skills have been shown to be strongly related to arithmetical fluency (Koponen et al., 2013, 2016; Locuniak & Jordan, 2008).

Overall, the findings suggest that despite advances in neonatal intensive care, many very preterm children have subtle cognitive deficiencies that become evident when the children reach school age (for a review, see Aylward, 2005; Roberts, Lim, Doyle, & Anderson, 2011; Taylor et al., 2016). The severity of impairment in cognitive functioning is related to the degree of maturity at birth (Anderson, 2014) but also to parental education and perinatal medical complications (Stålnacke, Lundequist, Böhm, Forssberg, & Smedler, 2015). The cut-offs of 32 gestational weeks referred to as "very low gestational age" or "very preterm" and birthweight below 1500 g referred to as "very low birthweight" are associated with an increased risk of neurodevelopmental problems (Aylward, 2014). Therefore, in the present study we focus on very preterm children who were born before 32 gestational weeks and/or weighed < 1501 g at birth.

1.2. Overlap between reading and arithmetic skills

Studies have shown that reading and math skills are strongly related in population-based (Davis et al., 2014; Koponen et al., 2007; Rutherford-Becker & Vanderwood, 2009) and clinical samples—specifically in children with learning disabilities (Landerl & Moll, 2010; Moll, Bruder, Kunze, Neuhoff, & Schulte-Körne, 2014). The intercorrelation between these skills varies from moderate up to 0.60 (Davis et al., 2014), regardless of gender, family socioeconomic status, or race/ethnicity (Chen & Chalhoub-Deville, 2016). Korpipää et al. (2017) also found among an unselected sample that the overlap between reading and arithmetic skills (i.e., common variation in reading and arithmetic) demonstrates substantial stability across grade levels. This finding indicates that individual differences in performance level common to reading and arithmetic are fairly well established already at the beginning of primary school. The present study adds to this previous research by examining how prematurity is associated with the overlap between reading and arithmetic. In the present study, we use the term *overlap* to refer to that part of variation in reading and arithmetic that is common to these two domains (i.e., domain-general variation; see also Cirino, Child, & MacDonald, 2018; Harlaar, Kovas, Dale, Petrill, & Plomin, 2012). The term *domain-specific variation*, in turn, is used to refer to that part of variation in reading and arithmetic that is unique to a particular skill. In previous research, very preterm children have been shown to have a lower skill level in both reading and arithmetic compared to full-term children (Aarnoudse-Moens et al., 2009; Taylor et al., 2016). This previous research did not, however, shed light on the question to what extent differences between preterm and full-term children in reading and arithmetic are due to the common variation in these skills. Consequently, the first aim of the present study was to examine the extent to which children's prematurity is associated with the overlap (i.e., common variance) between reading and arithmetic at the beginning of Grade 1.

Scholars have suggested that the overlap between reading and arithmetic skills (Hecht et al., 2001; Koponen et al., 2007; Simmons, Singleton, & Horne, 2008) and the comorbidity of related difficulties (Cirino, Fuchs, Elias, Powell, & Schumacher, 2015; Peng & Fuchs, 2016; Willcutt et al., 2013) are partly a result of similar cognitive processes involved in the development of both domains. Based on previous findings, common cognitive predictors of reading and arithmetic include prereading skills (Hecht et al., 2001; Koponen et al., 2007; Simmons et al., 2008), basic number skills (Koponen et al., 2007, 2016), and general cognitive abilities (Alloway & Alloway, 2010; Rohde & Thompson, 2007).

Regarding prereading skills, researchers have found that phonological awareness (i.e., the ability to analyze the sound structure of oral language; Hecht et al., 2001; Korpipää et al., 2017) and rapid naming skill (i.e., the ability to name sequentially presented familiar symbols, such as objects, colors, letters, or digits; Hecht et al., 2001; Koponen et al., 2007; Korpipää et al., 2017) are important indicators of overlap between reading and arithmetic. According to the double-deficit hypothesis (Wolf & Bowers, 1999), deficits in phonological processing and naming speed are separable sources of dysfunction, and this has been confirmed in children with comorbid difficulties in reading and arithmetic (Heikkilä, Torppa, Aro, Närhi, & Ahonen, 2016). In addition, letter knowledge, as the basis for understanding the alphabetic principle, has been shown to be a powerful predictor of overlap between reading and arithmetic (Koponen et al., 2007).

In addition to prereading skills, the overlap between reading and arithmetic skills is strongly predicted by basic number skills, such as counting ability (i.e., the ability to count number words forward, backward, and in steps; Koponen et al., 2007; Korpipää et al., 2017). Research has suggested that counting ability predicts the overlap between reading and arithmetic because fluency in both domains requires effortless processing of serial information in addition to rapid retrieval of visual-verbal associations from long-term memory (Koponen et al., 2016). Furthermore, scholars have found that general cognitive abilities that are essential for learning, as indexed by IQ, are associated with the overlap between reading and arithmetic skills (Korpipää et al., 2017).

The reading and mathematics performance of very preterm children has been shown to be linked with general cognitive abilities indexed by IQ (Schneider et al., 2004; see also Wolke, Samara, Bracewell, & Marlow, 2008). However, linguistic skills, such as rapid automatized

naming, have also been related to very preterm children's underachievement in both domains independently of intelligence (Wocadlo & Rieger, 2007). Because previous studies found statistically significant differences between very preterm and full-term children in early linguistic skills (Guarini et al., 2009; Saavalainen et al., 2006; Schneider et al., 2004), basic number skills (Alanko et al., 2017; Guarini et al., 2014), and general cognitive abilities (Anderson, 2014; Johnson, 2007), and all these variables have been found to be associated with the overlap between reading and arithmetic (Korpipää et al., 2017), the second aim of the present study was to investigate the extent to which the association of prematurity with the overlap between reading and arithmetic is accounted for by prereading and basic number skills and general cognitive abilities in terms of performance and verbal IQ.

1.3. Research questions

The present study examined the following research questions.

Research question 1. To what extent is children's prematurity (very preterm vs. full-term children) associated with the overlap (i.e., common variance) of reading and arithmetic at the beginning of Grade 1? Very preterm children have been shown to have a lower skill level than full-term children in reading and arithmetic (Aarnoudse-Moens et al., 2009; Pritchard et al., 2009; Taylor et al., 2016), and reading and arithmetic have been shown to substantially overlap (Cirino et al., 2018; Korpipää et al., 2017). Therefore, we hypothesized that prematurity is negatively associated with the overlap between reading and arithmetic (hypothesis 1).

Research question 2. To what extent is the association of prematurity with the overlap between reading and arithmetic at the beginning of Grade 1 mediated by linguistic skills (letter knowledge, phonological awareness, and rapid automatized naming), basic number skills (digit knowledge and counting sequence knowledge), and general cognitive abilities (nonverbal and verbal IQ)? Several studies have demonstrated that very preterm children perform at lower levels than full-term children in these indicators (Aarnoudse-Moens et al., 2011; Guarini et al., 2009; Wocadlo & Rieger, 2007). Therefore, we assumed that the association of prematurity with the overlap between reading and arithmetic is accounted for by differences between very preterm and full-term children in linguistic skills, basic number skills, and general cognitive abilities (hypothesis 2).

2. Method

2.1. Participants

The present study is part of the multidisciplinary project Development and Functioning in Very Low Birth Weight Infants from Infancy to School Age (PIPARI) which followed very preterm children and healthy full-term control children from infancy to Grade 1. Inclusion criteria were based on World Health Organization (International Classification of Diseases; ICD-10) definitions of very preterm birth (< 32 weeks of gestation), and very low birth weight (< 1500 g). The targeted sample consisted of all preterm children born in 2001–2004 at the Turku University Hospital, the only facility that provides neonatal intensive care in the hospital's catchment area. All eligible families were asked to participate in the study, and 95% gave their informed consent. The total attrition rate was 26.7%, with early death being the major cause (see Setänen et al., 2013). The very preterm group consisted of 193 (43.0% girls) children. Of them, 153 were born weighing less than 1501 g and at less than 32 weeks of gestation; 15 met only the gestational age criterion, and 25 met only the birth weight criterion. The control group (n = 175; 49.7% girls) was recruited by a research psychologist who asked the parents of the first full-term girl or boy born on each Monday to participate in the study. In the case of refusal, the parents of the next boy or girl were contacted. The inclusion criteria were a birth weight higher than –2 SD according to Finnish growth charts, a gestational age of 37 weeks or longer, and no neonatal care during the first week of life. All the families in the control group lived in the Turku University Hospital catchment area and understood Finnish or Swedish. Table 1 presents additional participant characteristics (for a more detailed description, see Alanko et al., 2017).

Table 1
Background characteristics of very preterm (gestational age < 32 weeks or birth weight < 1501 g) and full-term control children.

	Very preterm group (n = 193)	Full-term group (n = 175)
Birth weight (g)		
Mean (*SD*) [min, max]	1126 (325) [400, 2120]	3673 (442) [2570, 4980]
Gestational age (weeks)		
Mean (*SD*) [min, max]	29 (3) [23, 35]	40 (1) [37, 42]
Male	110 (57.0)	88 (49.7)
Brain pathology in MRI		
Normal (%)	111 (57.5)	
Minor (%)	28 (14.5)	
Major (%)	50 (25.9)	
Maternal education		
≤ 9 years (%)	18 (9.6)	8 (5.3)
9–12 years (%)	45 (23.9)	54 (35.5)
> 12 years (%)	125 (66.5)	90 (59.2)
Paternal education		
≤ 9 years (%)	15 (7.9)	12 (8.2)
9–12 years (%)	107 (56.9)	62 (42.5)
> 12 years (%)	66 (35.1)	72 (49.3)

Note. For a more detailed description, see Alanko et al. (2017).

The participants were either 7 years of age upon entering school or turned 7 during the fall semester of Grade 1. Mothers' level of education at the time of birth did not differ between very preterm and full-term children while fathers with higher education were overrepresented in the full-term children's group. Cranial ultrasounds were carried out on the very preterm children (at 3–5 days of age, 7–10 days of age, 1 month, and each month thereafter until discharge), as well as brain magnetic resonance imaging (MRI; for 190 infants at term on the same day as the ultrasound). For a detailed description of the examinations and classification of the degree of brain pathology, see Maunu et al. (2006, pp. 58–59). The PIPARI Study protocol was approved by the Ethics Review Committee of the Hospital District of Southwest Finland. Parents of all the children participating were informed about the study and gave their written consent.

2.2. Measures

Data were collected at the beginning of first grade during a 6-week period over August and September. As an exception, data concerning the children's general cognitive ability were gathered at age 5 by the research unit at the university hospital. All the tests were administered either individually or in group situations and carried out by trained testers at school.

Criterion validity (defined as predictive validity) and concurrent validity of all the measures used in the present study have been shown to be good in previous studies (Koponen et al., 2007; Korpipää et al., 2017; Leppänen, Niemi, Aunola, & Nurmi, 2004; Torppa et al., 2016). More specifically, correlations between cognitive antecedents measured at kindergarten age and subsequent reading and arithmetic skills at school age have been shown to vary depending on the study, on average, in the moderate range (0.20 to 0.70). Concurrent validity between the measures used is also good, with intercorrelations varying within the moderate range (0.30 to 0.70).

Reading skills. Reading skills were assessed individually at the beginning of Grade 1 with two subtests. (a) *Word reading accuracy* was

assessed with a word list reading test containing two-syllable (seven words), three-syllable (two words), and five-syllable (one word) words (subtest of the ARMI – A tool for assessing reading and writing skills in Grade 1; Lerkkanen, Poikkeus, & Ketonen, 2006). The words were presented one at a time, and the child was asked to read them out loud without a time limit. Meanwhile, (b) *word reading fluency* was assessed using a list of 90 words arranged on a sheet of paper into three columns in order of increasing difficulty (Lukilasse Graded Fluency Test; Häyrinen, Serenius-Sirve, & Korkman, 1999). The child was asked to read as many words out loud as possible within a time limit of 45 s.

For both tests, the score was based on the total number of words read out correctly. The Cronbach alphas for the tests were 0.97 and 0.97, respectively. In the present study, the sum score of standardized *word reading accuracy* and *word reading fluency* was used as the measure of reading skills.

Arithmetic skills. Arithmetic skills were tested in a group situation at the beginning of Grade 1 using the Basic Arithmetic Test (Aunola & Räsänen, 2007). The test consisted of 28 items in total—14 items of addition (e.g., 2 + 1 = _, 7 + _ = 14) and 14 items of subtraction (e.g., 4–1 = _, _–3 = 10)—which gradually increased in difficulty. Participants were given a 3 min time limit to complete as many items as possible. Performance on the test required accuracy and speed (automatization of basic calculation routines). The sum score was based on the total number of correct items (maximum value of 28), and the Cronbach alpha for the test was 0.85.

2.2.1. Prereading skills

Letter knowledge. The children were asked to name all 29 uppercase letters of the Finnish alphabet arranged in three rows in random order and shown one row at a time (Lerkkanen et al., 2006). The sum score was based on the number of correct responses (maximum value of 29), and the Cronbach alpha for the test was 0.95.

Phonological awareness. Three- to seven-letter words were presented phoneme by phoneme in a small group session (Poskiparta, 1995). The participants were told to figure out the resulting word and on an answer sheet with four alternative pictures, mark the one they thought best matched the word. There were nine trials in total, preceded by one practice trial. The sum score was based on the number of correct items (maximum value of 9). The Cronbach alpha for the test was 0.73.

Rapid automatized naming. The standardized Finnish version by Ahonen, Tuovinen, and Leppäsaari (1999) of an object naming task (Denckla & Rudel, 1976) was used to assess rapid automatized naming. Participants were asked to name as rapidly as possible a series of familiar visual stimuli. The task consisted of five familiar objects replicated 10 times on a matrix in pseudorandom order. Documented errors and self-corrections were few, and they were not included in the analysis. The time taken (in seconds) to complete the total matrix (five rows of 10) was then used as the RAN score. According to the manual, the test-retest reliability coefficients ranged from 0.84 to 0.92 for all age groups (Wolf & Denckla, 2005).

2.2.2. Basic number skills

Digit knowledge. The test consisted of 12 one- to six-digit numbers that were presented to the participants in numerical order, starting with 9 and ending with 627,003. The children were asked to name the numbers one at a time without a time limit, but once a child had made two consecutive mistakes, the test was stopped. The Cronbach alpha for the test was 0.82.

Counting sequence knowledge. Counting sequence knowledge was assessed with the following seven subtasks using the Number Sequences Test (Salonen et al., 1994): (a) counting forward from 1 to 51, (b) 6 to 13, and (c) 18 to 25; (d) counting backward from 12 to 7, (e) 23 to 1, and (f) 33 to 17; and finally, (g) counting 5 numbers backward from 23. Two points were given for each task correctly completed, one point for a task completed with two errors or fewer, and zero points if there were more than two errors or participants failed to complete the task. The maximum total score for the test was the sum of the scores for these seven tasks (14), and the Cronbach alpha for the test was 0.82.

2.2.3. General cognitive ability

Cognitive level. A short Finnish version of the Wechsler Primary and Preschool Scales of Intelligence–Revised (WPPSI–R) was used to assess the cognitive level, and two sum scores were created. (a) Verbal IQ was estimated based on the WPPSI–R subtests information, sentences, and arithmetic, and (b) performance IQ was estimated based on block design, geometric design, and picture completion subtests.

Parental education. Parents were asked about their education in years at the time of the child's birth with questionnaire with a 3-point scale (1 = < 9 years, 2 = 9–12 years, 3 = > 12 years). The parental education score was determined by the education score of the more educated parent. The information concerning parental education was gathered from 368 (92.7%) parents.

2.3. Analysis strategy

Analyses were carried out using structural equation modeling (SEM). This modeling approach made it possible to model the dependent variable, that is, the overlap between reading and arithmetic, via a latent variable (latent factor accounting for the intercorrelation of reading and arithmetic) and then explain the individual variation in this latent factor (overlap) with other variables. By using this approach, we were able to divide the variation in reading and arithmetic into two parts: domain-general variation representing overlap between reading and arithmetic and domain-specific variation representing variation that is not related with the other skill domain. The analyses were carried out in the following steps. First, a model was constructed to examine the extent to which prematurity (very preterm vs. full-term children) would account for the overlap between reading and arithmetic skills at first grade in primary school. In this model, the overlap between reading and arithmetic skills (i.e., the intercorrelation of these skills) was modeled using a latent variable that represented the variance common to the measures assessing reading and arithmetic skills, and variation in this latent overlap variable was predicted by prematurity status. In the model, the factor loadings of the indicators of the latent factor—standardized reading and arithmetic skills—were estimated as equal. The paths from prematurity to the residuals of the indicators of the latent variable (i.e., reading and arithmetic) were first constrained to be zero. Inspection of model fit and modification indices were then used to investigate the extent to which prematurity is also associated with the unique (i.e., domain-specific variation not common for reading and arithmetic) variance of reading or arithmetic (see also, Korpipää et al., 2017; Koponen et al., 2007).

Second, to examine the extent to which the association of prematurity with the overlap between reading and arithmetic is the result of shared deficits in prereading skills (letter knowledge, phonological awareness, and rapid automatized naming), basic number skills (counting sequence knowledge and digit knowledge), and general cognitive abilities (verbal IQ and performance IQ), these variables were included in the previous model. Indirect paths from prematurity to the latent variable representing the overlap between reading and arithmetic skills through these variables were estimated. Child's gender (girl vs. boy) and parental level of education were included in the model as covariates. The schematic mediation model is shown in Fig. 1.

The analyses were carried out using the Mplus statistical software program (Version 7.0) and the standard missing at random (MAR) approach–supposing that data would be missing at random (Muthén & Muthén, 1998, 2010). The frequency of children having missing data ranged (depending on the variable) from 0 to 19 among preterm children and between 0 and 14 among full-term children. The parameters of the models were estimated using full information maximum

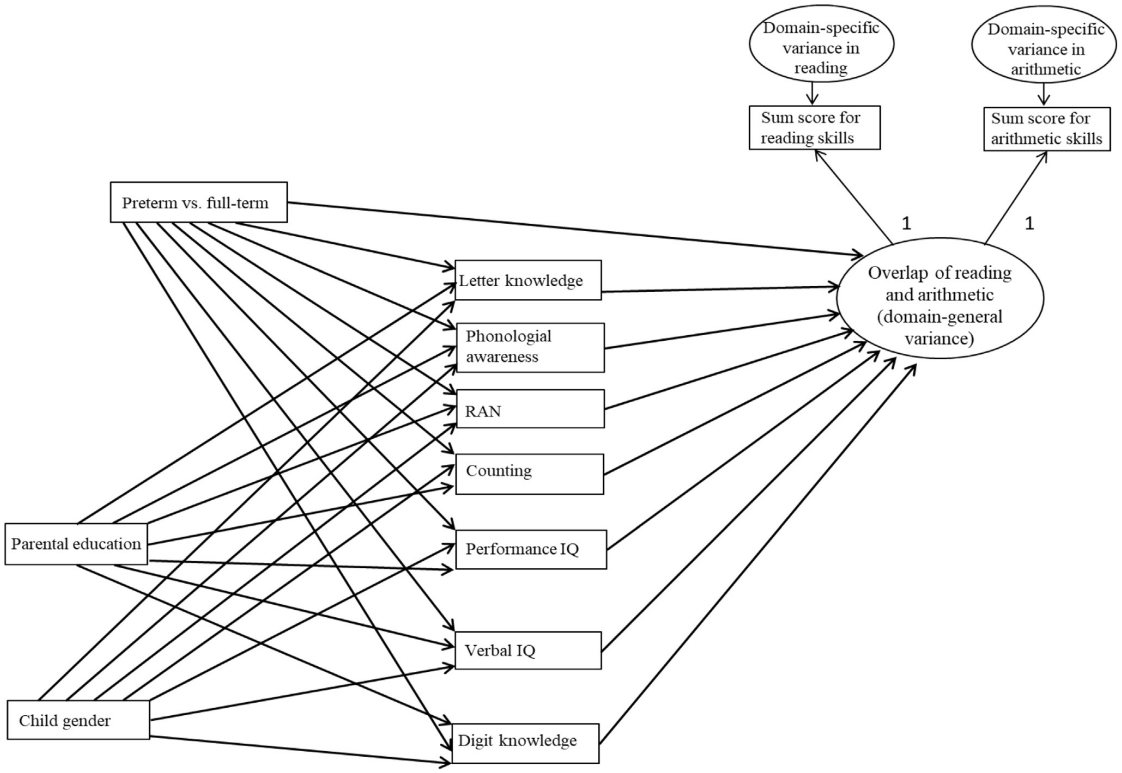

Fig. 1. Schematic structural equation model.

likelihood (FIML) estimation with standard errors robust to non-normality (MLR estimator; Muthén & Muthén, 1998, 2010). This method allowed us to use all of the observations in the data sets to estimate parameters in the models. The following outcomes were taken to indicate that the model fitted the data well: a nonsignificant χ^2 test value, a comparative fit index (CFI) and Tucker-Lewis index (TLI) of greater than 0.95, and a root mean square error of approximation (RMSEA) of lower than 0.06 (Muthén & Muthén, 1998, 2010).

3. Results

3.1. Descriptive statistics

The means and standard deviations of the study variables, as well as the results of independent samples *t*-tests comparing the means between very preterm and full-term children, are shown in Table 2. The correlations between the study variables ranged from –0.43 to 0.73 (Table 2). Reading and arithmetic skills showed a moderate intercorrelation (0.42, $p < .001$). Prematurity correlated negatively with reading (–0.18, $p < .001$) and arithmetic skills (–0.31, $p < .001$). Of the hypothesized mediating variables (linguistic skills, basic number skills, and general cognitive abilities), phonological awareness and letter knowledge showed the highest correlations with reading skills, whereas counting sequence knowledge and digit knowledge showed the highest correlations with arithmetic skills. Of the covariates, parental education correlated statistically significantly and positively with reading and arithmetic. However, these correlations were weaker than those for children's cognitive skills with reading and arithmetic. Child's gender did not correlate with reading or arithmetic.

Comparisons of the means between very preterm and full-term children (see Table 2) revealed that very preterm children performed less well than full-term children in reading and arithmetic. There was also a statistically significant difference between the groups in linguistic skills, basic number skills, and general cognitive abilities in favor of full-term children. No statistically significant difference between very preterm and full-term children was found in parental education or gender.

3.2. The association of prematurity with the overlap between reading and arithmetic skills

The first research question asked to what extent prematurity is associated with the overlap between reading and arithmetic skills at the beginning of school. This question was examined by estimating a model where the overlap between reading and arithmetic was modeled as a latent variable and variation in this latent overlap variable was predicted by prematurity status. The SEM (χ^2 (1) = 5.36, $p = 0.02$; CFI = 0.96; TLI = 0.87; RMSEA = 0.11) results showed poor fit. Inspection of the modification indices suggested that adding a direct path from prematurity to arithmetic (i.e., to domain-specific variation in arithmetic) would improve the fit of the model. After this specification was carried out, the model was saturated. The results showed, first, that 41% of the variance in reading skills and 42% of that in arithmetic, was explained by the latent common factor—overlap between reading and arithmetic—and thus, represented domain-general variation in these skills. In turn, 59% of the variation in reading skills and 58% of that in arithmetic was not explained by the common factor and thus, represented domain-specific variation of these skills. Second, the results showed that prematurity (i.e., the dummy variable *very preterm* vs. *full-term*) was statistically significantly and negatively associated

Table 2
Correlations, means, and standard deviations of the study variables and test of statistically significant differences in the means between preterm and full-term children.

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
1. Reading skills T1	1.00											
2. Arithmetic skills T1	0.42***	1.00										
3. Phonological awareness	0.60***	0.38***	1.00									
4. Letter knowledge	0.55***	0.33***	0.59***	1.00								
5. Rapid automatized naming	–0.42***	–0.38***	–0.43***	–0.32***	1.00							
6. Counting sequence knowledge	0.51***	0.54***	0.50***	0.57***	–0.39***	1.00						
7. Digit knowledge	0.45***	0.54***	0.42***	0.55***	–0.35***	0.73***	1.00					
8. Performance IQ	0.35***	0.40***	0.37***	0.29***	-0.33***	0.38***	0.36***	1.00				
9. Verbal IQ	0.45***	0.37***	0.52***	0.46***	–0.40***	0.47***	0.43***	0.49***	1.00			
10. Parental education	0.18**	0.14*	0.22***	0.28***	–0.12*	0.21***	0.16**	0.11	0.21***	1.00		
11. Gender	0.05	0.10	0.07	0.05	–0.05	0.08	0.03	0.06	–0.06	0.02	1.00	
12. Prematurity	–0.18***	–0.31***	–0.18**	–0.13*	0.24***	–0.29***	–0.27***	–0.39***	–0.17**	–0.00	–0.07	1.00
Preterm children												
M	−0.18	2.10	6.85	23.49	76.33	6.31	4.47	98.28	103.54	2.69	1.43	
SD	0.88	1.72	2.07	6.85	21.22	3.81	2.59	17.36	15.78	0.50	0.50	
Full-term children												
M	0.17	3.48	7.54	25.06	66.89	8.55	5.87	111.54	108.68	2.69	1.50	
SD	0.97	2.47	1.70	5.40	16.98	3.72	2.45	13.28	13.46	0.52	0.50	
t	3.53***	6.11***	3.46**	2.46*	–4.70***	5.68***	5.29***	7.92***	3.20**	0.05	1.29	

Note. The variable *reading skills* is the mean of two standardized reading subtests.
*p < .05. **p < .01. ***p < .001.

with the common variance of reading and arithmetic skills (standardized estimate = –0.29, $p < .001$): Very preterm children showed lower skill level common for reading and arithmetic at the beginning of Grade 1 than their full-term peers. Moreover, prematurity was negatively related to the domain-specific variance of arithmetic (standardized estimate = –0.13, $p = 0.02$): Very preterm children showed slightly lower arithmetic skills than full-term children independent of their reading skill levels.

3.3. The mediating mechanisms

To answer the second research question whether the association of prematurity with the overlap between reading and arithmetic is mediated by various cognitive antecedents, variables representing phonological awareness, letter knowledge, rapid automatized naming, counting sequence knowledge, digit knowledge, verbal IQ, and performance IQ were added to the model. Paths from prematurity to the latent overlap variable through these variables were then estimated. Children's gender and parental level of education were included in the model as covariates. The fit of the model was poor: χ^2 (9) = 54.76, $p < .001$; CFI = 0.97; TLI = 0.78; RMSEA = 0.12. Inspection of the modification indices suggested that estimating direct paths from digit knowledge and letter knowledge to arithmetic skills (i.e., to domain-specific variation in arithmetic) would increase the fit of the model. After these modifications, the model was found to fit the data well: χ^2 (7) = 15.38, $p = .03$; CFI = 0.99; TLI = 0.95; RMSEA = 0.06. The final model including only the statistically significant paths (χ^2 (10) = 14.47, $p = 0.15$; CFI = 1.00; *TLI* = 0.98; RMSEA = 0.04) is shown in Fig. 2.

The results (see Fig. 2) showed, first, that the overlap between reading and arithmetic skills was associated with letter knowledge, phonological awareness, RAN, counting sequence knowledge, and—to smaller extent—performance IQ. The higher the level of these linguistic and basic number skills, as well as performance IQ, the higher the skill level common for reading and arithmetic at the beginning of Grade 1. Second, the association of prematurity with the overlap between reading and arithmetic was fully accounted for by the five antecedents: Very preterm children showed lower letter knowledge (standardized indirect effect = –0.05, $p < .01$), phonological awareness (standardized indirect effect = –0.07, $p < .01$), RAN (standardized indirect effect = –0.04, $p < .01$), counting sequence knowledge (standardized indirect effect = –0.07, $p < .001$), and performance IQ (standardized indirect effect = –0.06, $p < .01$) than full-term children and, consequently, they also demonstrated a lower skill level common for reading and arithmetic (i.e., domain-general part of the skill level) than full-term children. Third, the results showed that prematurity was associated with the domain-specific variation in arithmetic skills through digit knowledge (standardized indirect effect = –0.08, $p < .001$) and letter knowledge (standardized indirect effect = 0.05, $p = 0.01$). These indirect effects, however, partly compensated each other: Very preterm children showed lower digit and letter knowledge than full-term children but whereas digit knowledge was positively associated with domain-specific variation in arithmetic, letter knowledge demonstrated a negative association with it.

4. Discussion

The present study aimed to add our understanding of the role of prematurity in the overlap between reading and arithmetic skills at the beginning of school. The results showed that about 40% of the variation in reading and arithmetic skills was common to these two domains and represented the overlap between reading and arithmetic, whereas 60% of the variation in these skills was domain-specific, that is, not shared by reading and arithmetic. Previous literature has shown that prematurity is associated with lower skill levels in both reading (Kovachy et al., 2014) and arithmetic (Taylor, Espy, & Anderson, 2009). The results of the present study suggest that these associations are mainly due to domain-general variation of these skills. The association of prematurity with the overlap between reading and arithmetic skills was further found to be accounted for particularly by prereading (letter knowledge, phonological awareness, and rapid automatized naming) and basic number skills (counting sequence knowledge) which have been shown to be important indicators of the overlap between reading and arithmetic (Korpipää et al., 2017).

Because beginning reading and arithmetic skills are strongly related (Korpipää et al., 2017), the question arises whether the poor performance of very preterm children in reading and arithmetic is due to processes that are common to these domains. The results of the present study confirmed our hypothesis by demonstrating that prematurity was negatively associated with the overlap between reading and arithmetic: The skill level common to reading and arithmetic was lower among very preterm children than among full-term children. After taking into

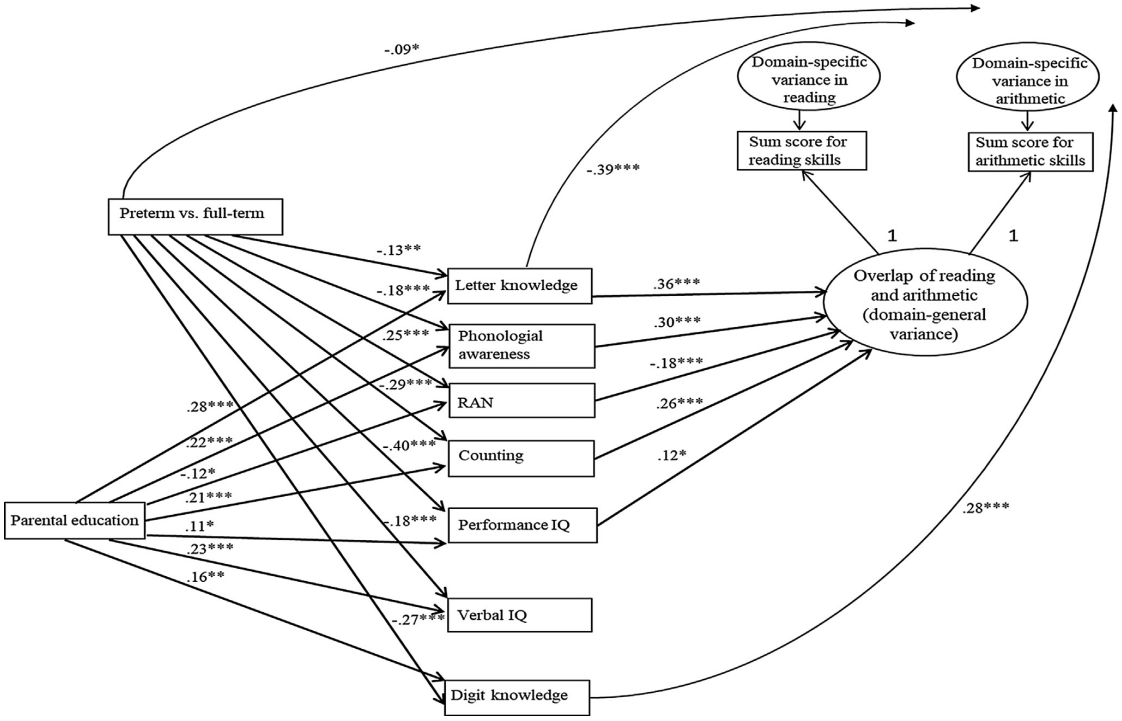

Fig. 2. The structural equation model for the association of prematurity with the overlap between reading and arithmetic and mediators of this association. $^{*}p < .05$. $^{**}p < .01$. $^{***}p < .001$.

account the domain-general variation in reading and arithmetic skills, no differences between the groups were evident in levels of reading skills, contrary to arithmetic skills which still showed a slight difference. Overall, the results suggest that differences between very preterm and full-term children in reading and arithmetic skills are, in large part, related to the factors or processes common to reading and arithmetic. Because learning difficulties that are related to both reading and math domains are more severe and persistent over time than difficulties evident only in one domain (Jordan et al., 2003; see also Koponen et al., 2018; Willcutt et al., 2013), it is important to acknowledge the risk very preterm children have for overlapping learning difficulties.

The second aim was to examine the extent to which different cognitive antecedents, including letter knowledge, phonological awareness, rapid automatized naming, digit knowledge, counting sequence knowledge, and general cognitive level, mediate the association of prematurity with the overlap between reading and arithmetic. In line with the hypothesis, the results showed that differences between the two groups in the skill level common to reading and arithmetic skills were fully accounted for by these cognitive antecedents previously shown to predict the overlap between reading and arithmetic (Korpipää et al., 2017). The most powerful mediators were phonological awareness and counting sequence knowledge, which have been found to be the strongest predictors of the overlap between reading and arithmetic in the early phase of skill development (Korpipää et al., 2017) when both skills are based on serial one-by-one processing (i.e., serial decoding in reading and counting-based strategies in arithmetic; see Koponen et al., 2016).

Group differences were also mediated through rapid automatized naming, which has been found to be related to development of fluency both in reading and arithmetic (i.e., direct retrieval of larger units following practice or retrieving arithmetical facts; Koponen et al., 2013, 2016), as well as to the overlap between these skills across grade levels (Korpipää et al., 2017). In previous studies, counting ability has proved to be a good predictor of the overlap between reading and arithmetic in initial and more automatized phases of skill development in these domains (Korpipää et al., 2017). Therefore, the lower performance of very preterm children in counting and rapid automatized naming at the beginning of school predicts an elevated risk of learning difficulties through lower primary school, including the fluency aspect of both skills. Obviously, this finding calls for early support and close monitoring of skill development through the early grades both in reading and in arithmetic.

Overall, the results of the present study suggest that the association of prematurity with the overlap between reading and arithmetic skills is related to linguistic and basic number skills, such as letter knowledge, phonological awareness, rapid automatized naming, and counting, more than to intelligence, supporting the findings by Wocadlo and Rieger (2007). These results may be explained by the fact that reading and arithmetic skills require the ability to learn and retrieve phonological representations of visual symbols (Koponen et al., 2007), as well as the ability to process serial information (2016; Koponen et al., 2013). In addition, previous studies showing that very preterm children with general cognitive ability within the normal range have impairments in these prereading skills (Guarini et al., 2009; Pritchard et al., 2009; Saavalainen et al., 2006) and basic number skills (Guarini et al., 2014) support this conclusion. Thus, measures of the general cognitive level, such as IQ, are not adequate predictors of low performance levels in reading and arithmetic, and more attention should be paid to prereading and basic number skills that are related to developing fluency in both domains.

In addition to the association with the overlap between reading and arithmetic, we found that prematurity was associated with the domain-specific variation in arithmetic. However, this association was rather weak. Despite the finding that prematurity showed a unique association

with arithmetic independent of the level of reading skills, difficulties in mathematical development among very preterm children seem to have, in part, a linguistic base. This finding is in line with studies underscoring the importance of reading-related skills to mathematical development (Krajewski & Schneider, 2009; Zhang et al., 2014) and supports a similar pattern of findings by Hannula-Sormunen et al. (2017).

5. Limitations

Four main limitations should be considered with respect to generalization of the findings. First, in the absence of relevant data, we did not include executive functions or working memory as predictors of covariation in reading and arithmetic skills. Second, one should note the transparent orthography of the Finnish language. Because Finnish has a simple and symmetrically regular phoneme-grapheme correspondence, decoding requires less advanced phonological processing skills than irregular orthographies, such as English. Third, because phoneme-to-grapheme rules are equally regular for spelling and reading in Finnish, spelling was not investigated in this study. In future studies, and with less transparent orthographies, spelling should be included as a separate outcome variable. Fourth, because the children in the present study were school beginners, their reading and arithmetic skills were skewed to low values.

6. Conclusion

The results of the present study add to our understanding of the association between prematurity and the overlap between reading and arithmetic, as well as the cognitive mechanisms related to lower performance levels across these two domains. Unlike in previous studies, the difference between very preterm and full-term children was investigated in terms of the overlap between reading and arithmetic rather than in each domain separately. Focusing on the overlap between reading and arithmetic made it possible to examine to what extent the group differences in reading and arithmetic skills found previously are domain general rather than domain specific. Overall, the results indicated that the differences between very preterm children and full-term children in reading and arithmetic skills are mainly the result of the domain-general variation of these skills. An important implication is that premature children who are struggling in one domain should be closely monitored for difficulties in the other domain as well (see also Cirino et al., 2018). The results of the present study provide important insights for educators to support very preterm children's development of both reading and arithmetic skills early enough to diminish the achievement gap between them and full-term children. As the overlap between these skills is well established by the first year of school (Korpipää et al., 2017), more attention to training prereading and basic number skills among very preterm children is necessary during the kindergarten year. Such an intensive follow-up might prove valuable in later primary grades. For example, it is not known whether preterm children are overrepresented among students who after some years of typical progress at school develop so-called late-emerging reading difficulties (Catts, Compton, Tomblin, & Bridges, 2012; Torppa, Eklund, van Bergen, & Lyytinen, 2015).

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