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Cognitive predictors of reading-arithmetic associations and dissociations: A longitudinal study

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ABSTRACT

Reading and arithmetic are foundational skills for academic development and are positively associated with one another. The underlying basis of this connection remains unclear, because previous research has primarily focused on either their associations or dissociations, thus considering only one aspect at a time. This longitudinal study aims to fill this gap by investigating predictors of shared and unique variance in reading and arithmetic throughout the first three years of formal instruction. We addressed the contribution of domain-general (nonverbal IQ and working memory) and domain-specific (phonological awareness, RAN, counting, magnitude processing and number knowledge) cognitive factors. The sample comprised 357 English- and German-speaking children. Cognitive predictors were assessed in Grade 1. Reading fluency, arithmetic fluency, and arithmetic accuracy were assessed in Grades 1, 2, and 3. Results of partial correlation and multivariate multiple regression analyses indicated that RAN and number knowledge explained most of shared variance between skill domains, and phonological awareness explained additional covariance with arithmetic accuracy. Domain-general predictors played a less important role. Results of cross-lagged panel models showed that phonological awareness and RAN predicted specific variance in reading, magnitude processing contributed specific variance to arithmetic. Our findings are consistent with the notion of partial overlap, as they suggest that reading and arithmetic share a common basis, related to the integration of verbal, visual and semantic information and symbolic processing. However, these two skill-domains also relate to unique cognitive factors that explain their dissociation.

Introduction

Reading and arithmetic are fundamental academic competences. As distant and different as they may seem, these abilities share common characteristics and, indeed, their performance is correlated (*r*s between 0.41 and 0.77; Landerl & Moll, 2010; Peterson et al., 2017; Willcutt et al., 2019). The cognitive factors explaining this association are still unclear, because previous studies have investigated either associations or dissociations, using different study designs (dimensional and subtyping approaches, respectively) and various statistical methods. As a result, findings are partly inconsistent (for a more detailed consideration of this topic, see Banfi et al. (2024)). In the present study, we aimed to fill this gap by targeting cognitive predictors of shared as well as unique variance in reading and arithmetic outcomes throughout the first three years of formal instruction.

Our goal was to identify cognitive factors that are related to both reading and arithmetic, and to establish whether there are specific connections for one skill domain but not the other. This study aimed to create a unified, cohesive framework that links previous research findings. It will also inform practitioners of cognitive factors that should be included in early screening batteries of academic achievement.

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Cognitive basis of associations and dissociations

There are several similarities between the development of reading and arithmetic. Both require the acquisition of arbitrary symbols (letters and Arabic digits) and rely dominantly on effortful procedural processes (decoding, counting). With growing proficiency, reading and arithmetic rely increasingly on automatized retrieval-based processes (word recognition, arithmetic fact knowledge), which require the integration of visual (letter patterns, Arabic numbers), verbal (word pronunciation, number words), and semantic (word meaning, magnitude representation) information (Dehaene, 1992; Perfetti & Hart, 2002).

According to the Multiple Deficit Model, the co-occurrence of neurodevelopmental disorders in the same individual can be explained by 'partial overlap', i.e., by shared probabilistic risk factors, while unique risk factors in one but not the other domain explain dissociations between disorders (McGrath et al., 2020; Pennington, 2006). This theoretical framework was originally developed to provide a more compelling explanation for complex neurodevelopmental disorders (such as language disorders, ADHD and dyslexia) than provided by single deficit theories. However, because deficient performance is often defined as the lower tail of the ability continuum, which is normally distributed, the logic of the multiple deficit model can be applied to the study of interindividual differences as well. As Vanbinst et al. (2020) put it, we should thus consider a "multiple strength model". Against this background, reading-arithmetic associations can be explained by higher-order cognitive skills that are relevant for many skill-domains, including academic competences. Dissociations are instead driven by predictors that are specific for the domain of reading or arithmetic. In the current study, we identified two domain-general and five domain-specific predictors of reading and arithmetic based on theoretical models (Coltheart et al., 2001; Dehaene, 1992) and research evidence.

Domain-general predictors

Executive functions, language and cognitive factors contribute to learning outcomes in reading and arithmetic (Alloway & Alloway, 2010; Peng et al., 2018; Peng & Fuchs, 2016; Spinath et al., 2010). In the current study, we investigated the role of nonverbal intelligence and working memory.

Nonverbal intelligence. The ability to reason with non-verbal material such as figures and shapes provides an indication of problem-solving and visuo-spatial processing skills that are not directly linked to verbal knowledge. Prior research has shown that nonverbal intelligence predicts reading, arithmetic and their covariance (Bellon et al., 2019; Fuchs et al., 2016; Geary, 2011; Korpipää et al., 2017; Zoccolotti et al., 2020) as well as other cognitive factors such as number transcoding (Clayton et al., 2020). In the current study, we included nonverbal intelligence as a domain-general predictor of reading and arithmetic, and tested whether it contributed variance in addition to domain-specific predictors.

Working memory is particularly important for storing, manipulating, and transforming information, which is necessary for building up factual knowledge and for following spoken and written instructions and therefore learning (Allen et al., 2023; Dunham et al., 2020; Yang, 2011). While verbal working memory is recognized as a predictor of reading performance with a minor contribution compared to other phonological and rapid naming factors (Caravolas et al., 2012; Moll et al., 2014), visuo-spatial working memory has been repeatedly related to arithmetic attainment (Caviola et al., 2020; Szucs et al., 2013). A recent meta-analysis (Zhang, Ma, & Zhou, 2022) including 55 samples of children aged between 6 and 12 years reported reliable correlations between arithmetic and working memory capacity (verbal working memory: $r = 0.33$, visuo-spatial working memory, $r = 0.30$).

Nonverbal intelligence and working memory abilities can facilitate vocabulary learning, language comprehension, and the mastery of numerical symbols and arithmetic concepts and procedures. In line with this general assumption, previous studies reported improvements in early numeracy ability after combined training programs with executive functions (including working memory) and numeracy tasks (Kroesbergen et al., 2014; Passolunghi & Costa, 2016; Prager et al., 2023). Note, however, that a previous meta-analysis reported a small and non-significant effect of working memory training on reading and arithmetic (Melby-Lervåg et al., 2012). With respect to the aims of the present study, it remains an open question whether domain-general predictors play a unique role in reading and arithmetic when domain-specific skills are accounted for. Evidence from neuroimaging studies indicates that fronto-parietal brain regions related to working memory, attention resources and more in general task difficulty are recruited during reading (Cattinelli et al., 2013; Martin et al., 2015) as well as arithmetic tasks (Hawes et al., 2019). This clearly suggests that domain-specific tasks rely on domain-general resources. Evidence from cognitive studies is mixed. Depending on the study design, some studies reported associations between domain-general skills and both reading and arithmetic even after controlling for domain-specific skills (intelligence: Geary, 2011; Korpipää et al., 2017; Korpipää et al., 2019; working memory: Fuchs et al., 2016; Geary, 2011; Korpipää et al., 2017), while others have not (intelligence: Amland et al., 2020; Bernabini et al., 2021; Koponen et al., 2007). In the present study, we tested whether domain-general predictors contribute variance in reading and arithmetic after including also domain-specific predictors in the models.

Domain-specific predictors

Phonological awareness. In early reading, phonological awareness, referring to the ability to identify and manipulate speech sounds, is crucial for decoding letter-sound mappings (Landerl et al., 2022). Phonological awareness is a recognized predictor of reading performance across orthographies (Moll et al., 2014). Its association with reading, however, is not clearly unidirectional: A longitudinal cross-orthography study (Landerl et al., 2021) showed that not only phonological awareness measured at the end of Grade 1 predicted reading at the end of Grade 2, but also reading measured at the end of Grade 1 predicted phonological awareness at the end of Grade 2. Number processing and arithmetic involve verbal resources, when children learn number words and store arithmetic facts verbally (Dehaene, 1992). However, decoding relies on sublexical phonological codes, such as phonemes, while number processing relies on lexical-level information, such as number words. The importance of phonological awareness in learning to read is widely recognized (e.g., Melby-Lervåg et al., 2012). However, its relationship with arithmetic is still debated. Cross-domain research conducted during early developmental periods, with assessments less than a year apart, have consistently observed associations between phonological awareness and arithmetic (accuracy: Amland et al., 2020; Georgiou et al., 2021, Vanbinst et al., 2020). Similarly, phonological awareness has been found to predict the covariance between reading and arithmetic (fluency: Koponen et al., 2020; Korpipää et al., 2019; fluency and accuracy: Cirino et al., 2018). However, when phonological awareness and arithmetic are assessed several years apart, no such predictions have been observed – neither for arithmetic (fluency: Koponen et al., 2016; accuracy: Birgisdottir et al., 2020; fluency and accuracy: Amland et al., 2020) nor for the covariance between reading and arithmetic (fluency: Korpipää et al., 2017; fluency and procedural arithmetic: Koponen et al., 2007). This suggests that while phonological awareness may capture overlapping phonological processes early in development, it is unlikely to be directly linked to long-term arithmetic development. In this study, we thus expected phonological awareness to be a robust predictor of reading performance across time points and to explain variance in early arithmetic attainment at the first time point.

Serial retrieval. Reading and arithmetic fluency requires effortless retrieval of (often sequential) visual-verbal associations, which is common to both rapid automatized naming (RAN), a prominent predictor of reading, and counting, an established predictor of arithmetic. RAN tasks require fluent naming of a sequence of stimuli, and seem to mirror the processes involved in (verbal) reading quite well (e.g., Landerl et al., 2022). Counting tasks usually require reciting the serial order of the verbal count list and are linked to arithmetic fluency (Koponen et al., 2019). Arithmetic also involves direct retrieval of number facts, and this component may be shared with retrieval efficiency measured by RAN tasks (Georgiou et al., 2013). In line with the idea that RAN captures retrieval speed not only in reading, but also in arithmetic, RAN was found to be a predictor of arithmetic fluency (Balhinez & Shaul, 2019; Georgiou et al., 2020; Georgiou et al., 2021; Koponen et al., 2016) and of the covariance between reading and arithmetic (Cirino et al., 2018; Georgiou et al., 2021; Koponen et al., 2020; Korpipää et al., 2017). However, the relationship with untimed arithmetic tasks is less straightforward, with inconsistent results across studies (significant: Geary, 2011; Yang et al., 2020; indirect effect: Fuchs et al., 2016, non-significant: Greiner de Magalhães et al., 2021; Koponen et al., 2007). There is also evidence linking counting to reading fluency (Bernabini et al., 2021; Koponen et al., 2013; Koponen et al., 2016; Koponen et al., 2020) and to the covariance between reading and arithmetic fluency (Koponen et al., 2007; Korpipää et al., 2019). In the current study, RAN was expected to contribute variance to both reading and arithmetic, thus capturing a component related to retrieval speed. The prediction for counting is less clear. We anticipated a minor involvement in reading fluency due to its serial task format and verbal content. However, counting was expected to be a stronger predictor of arithmetic.

Magnitude Processing, involving the ability to compare and process quantities (e.g., symbolic: 2 vs. 3; non-symbolic: ●● vs. ●●●), is a prominent predictor of arithmetic (Schneider et al., 2017). While some studies have linked symbolic magnitude processing to specific aspects of reading (e.g., reading comprehension, but not decoding or fluency, Cirino et al., 2018), the association is small or non-significant (Caviola et al., 2020; Durand et al., 2005). Still, symbolic magnitude processing unlike non-symbolic processing involves the integration of arbitrary visual symbols with semantic information and might explain covariance between reading and arithmetic fluency (Cirino et al., 2018; Koponen et al., 2020). Similarly to counting, we anticipated magnitude processing to be preferentially predictive of arithmetic performance. However, we might expect a small contribution to shared reading-arithmetic variance due to symbolic processing content.

Number knowledge is also a key predictor of arithmetic (Landerl et al., 2021). Transcoding single-digit numbers involves the integration of the visual-Arabic and the verbal representation of a number. Processing multi-digit numbers involves lexical retrieval (for single digits), but also understanding of the complex visual and morpho-syntactic procedures of place value and number word formation (Nuerk et al., 2011). Cross-format integration and learning arbitrary symbol-sound correspondence are also relevant for letter knowledge, an early indicator of later reading (Landerl et al., 2022). Indeed, number knowledge and letter knowledge are correlated ($r = 0.38$–0.62; see Amland et al., 2020; Koponen et al., 2007; Koponen et al., 2020; Korpipää et al., 2019, for details). Number knowledge was also found to be a longitudinal predictor of reading as well as of reading-arithmetic covariance (Amland et al., 2020; Cirino et al., 2018; Koponen et al., 2020). In line with this evidence, we expected number knowledge to specifically predict arithmetic performance as well as variance shared with reading.

The relationship between reading and arithmetic development

Moving beyond merely measuring their correlation, a limited number of studies addressed the reciprocal influence of reading and arithmetic skills throughout time (Bailey et al., 2020; Duncan et al., 2007; Erbeli et al., 2021; Hübner et al., 2022; Psyridou et al., 2025; Shin et al., 2013). The generalisability and consistency of this evidence is constrained by the wide variety of measures and different statistical approaches used. Studies that applied cross-lagged panel models (CLPM) without and with random intercepts (RI-CLPM) to longitudinal data reported bidirectional cross-lagged effects (Bailey et al., 2020; Psyridou et al., 2025). For example, Bailey et al. (2020) analyzed a sample of 9612 US children followed from Kindergarten to Grade 3 over four waves. They computed both CLPM and RI-CLPM, and results consistently indicated high interactivity throughout time points (but note that autoregressive and cross-lagged paths were not identical between different models). The "reading" factor in the study by Bailey et al. included a broad set of language-related and not only reading-related measures (print familiarity, letter recognition, beginning and ending sounds, sight vocabulary, decoding multisyllabic words, vocabulary knowledge, and reading comprehension). Findings may thus not be specific to the reading domain. In another recent study including 2518 Finnish children followed from Grade 1 to 7, Psyridou et al. investigated the relation between reading and arithmetic fluency by computing a RI-CLPM. Results indicated bidirectional influences between skill-domains from Grade 1 to Grade 2. Only the cross-lagged path from reading to math was significant from Grade 2 to Grade 3 and no further cross-lagged relations were significant at further time points. Psyridou et al. reasoned that the interactive pattern found at the start of formal schooling may be explained by shared underlying processes such as automatization of retrieval-related strategies and processing speed. In the later grade, reading may support the development of arithmetic competences. It will be important to test whether results of the current study align with previous research. In this sense, the study by Psyridou et al. is particularly relevant because it focused on constructs and measures similar to those of the present study (reading and arithmetic fluency). This enables a direct comparison of their results with those from our study. We will also examine the relationship between reading fluency and arithmetic accuracy, two tasks that do not share surface characteristics.

Current study

The current study investigated cognitive predictors of shared and specific variance in reading and arithmetic throughout the first three years of formal instruction in English- and German-speaking children. Domain-general and domain-specific predictors were assessed in Grade 1, and children's progress in reading and arithmetic was tracked across Grades 1, 2, and 3. This developmental period is particularly informative, because children typically experience a transition from relying mostly on effortful, serial procedures (i.e. decoding based on sequential grapheme-phoneme conversion or computation by means of counting) to fact retrieval (as in lexico-orthographic reading and arithmetic fact retrieval) thanks to the the build-up of verbal associations (Peters & De Smedt, 2018; Rau et al., 2014). Against this background, we developed the following research questions.

1) What predicts the overlap between reading and arithmetic? We adopted the same approach as in a previous study by Cirino et al. (2018) and used partial correlation analyses complemented by multivariate multiple regressions to test the relation between cognitive factors and academic outcomes. Consistently with the results by Cirino et al. (2018), we expected domain-general predictors, rapid automatized naming (RAN), and number knowledge to account for a significant amount of shared variance.
2) Which cognitive predictors account for variance in reading and/or arithmetic across development?
   a. Domain-general predictors were expected to account for variance in both academic domains, but uncertainties remain regarding their role once domain-specific predictors are considered. We expected nonverbal intelligence to have very little predictive power after including the domain-specific predictors, because this ability is inherent in several cognitive factors. As to working

memory, we anticipated to observe its contribution over and above domain-specific predictors in the arithmetic, but not in the reading domain, due to its more prominent role in the former. However, other cognitive factors, such as phonological awareness and number knowledge require working memory resources and may therefore fully predict the outcomes beyond the contribution of working memory.

b. We expected phonological awareness to preferentially predict reading. Considering that this dimension likely captures language-related processing in early developmental phases, we expected its contribution for initial arithmetic performance in Grade 1. We had a less specific prediction for RAN, as both reading and arithmetic require fast retrieval of visual-verbal associations.

c. Among domain-specific predictors of arithmetic, counting speed and number identification both have verbal components and might also show associations with reading, but we assumed that they (as well as magnitude processing) would account for unique variance in arithmetic beyond the overlap with reading.

3) Which cognitive predictors explain developmental change in the different ability domains? This question aims to test whether cognitive predictors explain variance longitudinally controlling for autoregressive effects. Earlier evidence indicated high stability of development in reading (Georgiou et al., 2020) and arithmetic (Ribner et al., 2023). This high stability suggests that the transition from procedural to increasingly retrieval-based strategies takes place at roughly the same period in all children, with little interindividual variability. If this is the case, cognitive predictors may not account for much variability beyond the variance in reading and arithmetic assessed earlier on.

4) How do reading and arithmetic interact throughout the first three years of formal instruction? Both skills undergo similar developmental steps such as shifting from procedure-based to retrieval-based strategies and they share a cognitive basis. Therefore, it can be assumed that they influence each other through an interactive pattern, as previously shown by Psyridou et al. (2025). However, they may also develop in parallel with no or very limited direct causal relationship between them.

Previous studies mostly used speeded measures of reading and arithmetic. A shared speed factor might at least partly explain the covariance. It is thus important to consider whether reading and arithmetic share variance beyond a common speed factor. Our study goes beyond traditional fluency assessments by including untimed arithmetic tasks with increasing complexity to explore the predictive pattern of arithmetic accuracy compared to standard fluency measures.

The current study was run with sub-cohorts in the UK and Austria. While detailed comparisons of these sub-cohorts were not the aim of the study, a few differences between cohorts should be considered: First, German orthography is phonologically more transparent than English, which may affect the association of phonological awareness with reading (Landerl et al., 2021). Second, German number words implement decade-unit inversion (21 is pronounced as “one and twenty”, see Steiner et al., 2021), which may influence the relevance of number knowledge for arithmetic. Finally, as schooling starts earlier in the UK than in Austria, the grade-matched samples differed in their chronological age.

Method

Participants

The reported analysis is based on a dataset from a cross-linguistic project following English- and German-speaking primary school children from Grade 1 to Grade 3 (dataset: Göbel, Wesierska and Landerl (2020)). Longitudinal data was available from 191 English-speaking (t1: $M_{\text{age}} = 6$ years, 2 months; $SD_{\text{age}} = 3.81$ months; 50 % female; 97 % monolingual) and 166 German-speaking children (t1: $M_{\text{age}} = 7$ years, 2 months; $SD_{\text{age}} = 3.44$ months; 47 % female; 87 % monolingual). Language groups were matched on duration of formal education, but differed in age (∼ 1 year) due to earlier onset of school in the UK than in Austria. Further details about the sample are available in the appendix and in the UK Data Service website (https://reshare.ukdataservice.ac.uk/854398/). The study was conducted in accordance with the principles of the Declaration of Helsinki and consent was obtained from both children and guardians. The ethics committees of the University of York and University of Graz approved the study (Reference number; University of Graz: 39/23/63 ex 2016/17).

Tasks

The assessment of predictors of reading and arithmetic skills took place at t1. These included: 1) Nonverbal IQ, measured with the Raven’s Standard Progressive Matrices Plus (Raven et al., 1998) adapted for group use; 2) Working memory, assessed with Digit Recall Forward, Backward and Block Recall Forward from the Working Memory Test Battery for Children (Pickering & Gathercole, 2001) and a non-standardized Block Recall Backward task; 3) Phonological awareness, measured with phoneme deletion tasks. The English-speaking sample was administered the York Assessment of Reading Comprehension (Snowling et al., 2009), the German-speaking sample was administered a comparable task developed within our lab; 4) RAN tasks with letters and digits from the Comprehensive Test of Phonological Processing (CTOPP; (Wagner et al., 2013)); 5) Counting fluency, administered by means of a timed forward counting task; 6) Magnitude processing, assessed with dots and digits comparison tasks; 7) Multi-digit transcoding, measured with three indicators: number identification, number reading, and number writing. Reading and arithmetic tasks were administered at each time point with similar tasks. Reading fluency was assessed by means of standardized timed tests with words and pseudowords (English: TOWRE−2, (Torgesen et al., 2012); German: SLRT-II; (Moll & Landerl, 2010)). Arithmetic fluency was measured with one-minute timed tasks including additions and subtractions at t1 and t2, multiplication and division subtasks were added at t3. Arithmetic accuracy was measured with the WIAT-II UK (Wechsler, 2005) adapted for group use. Fig. S1 in the Supplementary Information provides a summary of the cognitive predictors and outcomes assessed at different time points. A detailed description of the tasks can be found in the Appendix and in the UK Data Service website (https://reshare.ukdataservice.ac.uk/854398/).

Analysis strategy

In each language group, we computed z-scores of predictors consisting of single variables to account for the one-year-gap between English- and German-speaking children. For constructs investigated with more than one indicator, principal component analysis (PCA) was performed as a data reduction technique to obtain a single composite score. *Z*-scores were computed for nonverbal IQ, phonological awareness, counting fluency and arithmetic accuracy. PCA was performed for working memory (four subtasks), RAN (two subtasks), magnitude comparison (four subtasks), number knowledge (three subtasks), reading (word and nonword) and arithmetic fluency (two subtasks at T2, four at T2, six at T3). Tables S1-S6 in the supplement report factor loadings of these PCAs.

First, we estimated the contribution of cognitive predictors to reading-arithmetic covariance by conducting partial correlations. These analyses examined the extent to which the reading-arithmetic correlation was reduced when cognitive predictors were partialled out. We adopted a similar approach as Cirino et al. (2018). To examine the unique contribution of various sets of predictors, we performed partial correlations using single predictors, as well as sets of domain-general predictors (nonverbal IQ, working memory) and domain-specific predictors (phonological awareness, RAN, counting, magnitude processing, number knowledge). We also considered the combined effects of all cognitive predictors. By assessing these partial correlations, we were able to investigate and compare the distinct contributions of different predictor sets. We complemented this partial correlation analysis with multivariate multiple regression models testing the contribution of cognitive factors to pairs of outcomes (reading and arithmetic fluency / reading fluency and arithmetic accuracy) at each time point.

Second, we computed CLPMs that investigated the relationship between reading and arithmetic throughout three time points and tested the contribution of domain-general and domain-specific cognitive factors on the two skill-domains. The advantage of CLPMs is that we could account for covariance in the two skill-domains across time points while testing the contribution of cognitive factors. Age was included to control for the one-year age gap between language groups. The dichotomic variable referring to the language group was not entered to prevent redundancy due to high collinearity with age. We ran one model predicting reading and arithmetic fluency, and a second one predicting reading fluency and arithmetic accuracy. We fitted a $CLPM_A$ with time-constant covariates, in which cognitive factors contributed variance to outcome variables at the three time points, and a nested $CLPM_B$ with time-specific covariates, in which cognitive factors predicted reading and arithmetic at the first time point only (that is, concurrently). These two nested models were compared by means of a chi-squared difference test and also assessing Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC). The fit of the models was further assessed using the chi-square value and its significance and a specific set of fit indexes: 1) the comparative fit index (CFI); 2) the root-mean-square-error of approximation (RMSEA); and 3) the standardized root-mean-square residual (SRMR). A good model fit is indicated by a small, nonsignificant chi-square, CFI > 0.95, RMSEA <0.06, and SRMR <0.08 (Hu & Bentler, 1999).

Please note that our original intention was to conduct random-intercept CLPMs, given their assumed superiority compared to CLPMs in differentiating between-person stable traits from within-person time-related variation (Hamaker et al., 2015; Mulder & Hamaker, 2021). However, results of our RI-CLPMs revealed negative values in the latent covariance matrix, indicating a substantive identification issue. Specifically, within-person latent variables for reading were very strongly related across time points and this produced multicollinearity. The latent random intercept for reading was very small and its variance did not significantly differ from zero, $s^2 = 0.123$, $p = .775$. Related to this, the correlation between reading and arithmetic random intercepts was greater than 1, thus being mathematically implausible. As suggested by Mulder and Hamaker (2021), the RI-CLPM approach is only appropriate when the variances of the random intercepts are significantly different from zero; otherwise, this modeling approach is redundant. We therefore decided to remove the random intercept components and adopt the CLPM approach instead.

The analysis was run in IBM SPSS Statistics (Version 29) and in R (R Core Team, 2021), *p*-values < .05 were considered significant. We used the R package lavaan to run CLPMs and zeroEQpart with the function pzcor to test whether a decrease in covariance (i.e., the difference between bivariate and partial correlation coefficients) was significant. This function applies bias-corrected and accelerated bootstrapping and in our case 1000 bootstrapping samples. Given the number of comparisons (each time point and covariance = 10 per bivariate correlation), we adjusted the significance level to 0.005 (0.05 / 10). Confidence intervals were calculated using the statistical software SPSS with 1000 bootstrapping samples, because the function to test for significant differences between coefficients (pzcor) does not report confidence intervals for each coefficient.

Results

Table 1 depicts raw scores prior to PCA and z-transformations for illustration. Coefficients displayed in the correlation matrix (Table 2) were generated based on the transformed scores. There was a strong correlation between language and age, reflecting that German-speaking children were older than English-speaking children due to generally later start of schooling, but there were no significant correlations between language, predictors, reading and arithmetic variables. This indicates a similar pattern of associations across the two language cohorts.

Shared predictors of reading and arithmetic

Partial correlations are presented in supplementary Table S7. Because we have 1st, 2nd, and 3rd grade covariance, we report the range of covariance reduction by a certain variable at each grade level. Overall, predictors and sets of predictors reduced the covariance by between 13 and 96 % (t1–t3). To illustrate, a bivariate correlation between 1st grade reading and arithmetic fluency of 0.480 corresponds to 23 % shared variance (based on R^2). The coefficient after controlling for nonverbal IQ was 0.424, which corresponds to 18 % shared variance, the decrease in covariance is thus 22 % ((23–18) / 23 * 100). With few exceptions, decreases in covariance were significant ($p < .005$ as adjusted significance level). In summary, moderate correlations were observed between reading and arithmetic fluency, as well as between reading and arithmetic accuracy across grades. The contribution of domain-specific predictors was more pronounced than that of domain-general predictors: The inclusion of domain-general predictors did not appear to enhance the explained covariance. The covariance between domains was primarily accounted for by RAN and number knowledge. While this pattern was similar for reading covariance with arithmetic fluency as well as accuracy, phonological awareness accounted for 47–55 % of covariance between reading and arithmetic accuracy but only accounted for 28–36 % of the covariance between reading and arithmetic fluency. Results of multivariate multiple regressions are presented in Table S8 and indicate a consistent pattern with that of partial correlations: Both domain-general and domain-specific predictors contributed variance to pairs of outcomes.

Predictors of reading and/or arithmetic in grades 1, 2, and 3

With respect to the models predicting reading and arithmetic fluency, $CLPM_B$ (AIC = 3659, BIC = 3810) showed a better fit than $CLPM_A$ (AIC = 3667, BIC = 3942), $\Delta\chi^2(32) = 56.58$, $p = .005$, thus suggesting that the model with time-specific covariates explaining variance concurrently at T1 fitted the data best. This model had also an overall acceptable fit, $\chi^2(36) = 81.32$, $p < .001$, CFI = 0.98, RMSEA = 0.059, SRMR = 0.03. As shown in Fig. 1, all autoregressive effects were significant, positive and strong, indicating that skill level in each domain was predicted by performance in the previous wave. Among cognitive predictors of the first time point, nonverbal IQ, phonological awareness, RAN and number knowledge made a significant, positive contribution to reading. Working memory, RAN, magnitude processing and number knowledge contributed positive variance to arithmetic fluency. The relationship between reading and arithmetic fluency appeared modestly interactive across time points, with T1 arithmetic fluency significantly predicting T2 reading and T2 reading significantly predicting T3 arithmetic fluency. Covariances were significant at each time point, and their standardized estimates did not change substantially throughout time (*r*s between 0.13 and 0.17).

With respect to the models predicting reading fluency and arithmetic accuracy, $CLPM_A$ (AIC = 4063, BIC = 4338) showed a better fit compared to $CLPM_B$ (AIC = 4188, BIC = 4339), $\Delta\chi^2(32) = 189.20$, p < .001, and this indicates that the model with time-constant covariates predicting all three time points fitted the data best. This model had a moderate fit, $\chi2(4) = 26.93$, p < .001, CFI = 0.99, RMSEA = 0.13, SRMR

Table 1
Descriptive statistics: raw scores of all applied tasks.

	English-speaking (n = 191)					German-speaking (n = 166)					
	M	*SD*	Min	Max	Reliability	*M*	*SD*	Min	Max	Reliability	Reliability (whole sample)
Grade 1 (T1)											
Nonverbal IQ[a]	14.51	4.46	4	26	.75[e]	18.09	4.71	6	29	.77[e]	.79[e]
Digit Recall – Forward[b]	25.63	3.85	13	34		25.74	3.49	18	38		
Digit Recall – Backward[b]	8.58	2.83	0	17	.61[f]	10.08	2.66	4	18	.58[f]	.63[f]
Block Recall – Forward[b]	20.08	4.15	7	31		22.57	3.21	14	30		
Block Recall – Backward[b]	10.51	4.51	2	22		13.46	4.67	0	22		
Phonological Awareness[a]	10.36	3.62	3	17	.80[e]	11.01	4.54	0	18	.87[e]	
RAN-letters[c]	1.46	0.35	0.63	2.32	.90[f]	1.49	0.30	0.76	2.40	.87[f]	.88[f]
RAN-digits[c]	1.44	0.34	0.59	2.40	.91[f]	1.41	0.25	0.71	2.06	.91[f]	.91[f]
Counting[d]	76.93	24.64	12	120		70.90	18.08	13	107		
Symbolic Comparison 1	16.16	6.28	0	36		18.50	5.68	0	37		
Symbolic Comparison 2	14.70	5.83	0	36	.87[f]	18.25	4.85	1	33	.75[f]	.83[f]
Non-symbolic Comparison 1	9.49	4.62	−2	22		10.93	4.31	-2	21		
Non-symbolic Comparison 2	19.69	6.50	0	36		24.42	9.49	2	59		
Number ID[a]	5.46	1.54	1	8	.66[e]	5.13	1.78	1	8	.70[e]	.68[e]
Number Reading[a]	38.65	9.49	5	52	.95[e]	37.49	10.64	6	52	.95[e]	.95[e]
Number Writing[a]	35.34	8.04	13	52	.93[e]	34.16	10.82	10	52	.96[e]	.94[e]
Word Reading[a]	37.15	15.902	7	73	.87[g]	26.34	13.02	5	72	.84[g]	.85[g]
Nonword Reading[a]	19.13	10.78	1	51		23.47	7.38	5	60		
Additions[a]	9.40	4.54	0	24	.78[f]	15.60	4.43	5	30	.81[f]	.87[f]
Subtractions[a]	6.51	3.90	0	22		12.97	4.58	3	30		
Numerical Operations[a]	4.17	1.92	0	9	.69[e]	5.46	1.42	3	9	.60[e]	.69[e]
Grade 2 (T2)											
Word Reading	54.00	12.40	16	77	.85[g]	50.58	18.99	12	111	.87[g]	.86[g]
Nonword Reading	29.13	11.28	2	54		33.69	9.94	13	69		
Additions	14.30	5.73	3	29		20.12	5.55	3	39		
Extra Additions	8.47	4.68	0	28	.93[f]	13.93	5.05	2	28	.93[f]	.95[f]
Subtractions	10.40	4.75	0	27		18.60	6.92	3	44		
Extra Subtractions	7.18	4.57	0	25		14.06	5.92	1	30		
Numerical Operations	8.98	3.05	1	16	.77[e]	11.23	2.65	5	17	.73[e]	.78[e]
Grade 3 (T3)											
Word Reading	62.70	9.88	29	83	.80[g]	68.64	21.42	26	122	.84[g]	.82[g]
Nonword Reading	34.24	10.67	7	59		40.15	10.90	18	75		
Additions	17.46	6.44	2	38		25.41	6.35	14	52		
Extra Additions	11.14	5.26	0	28		19.21	5.52	3	33		
Subtractions	13.46	5.74	0	29	.94[f]	22.84	6.45	9	44	.93[f]	.95[f]
Extra Subtractions	9.82	5.56	0	25		18.18	6.00	3	31		
Multiplications	8.68	6.29	0	34		12.07	5.72	3	32		
Divisions	7.57	6.27	0	39		12.78	6.01	0	40		
Numerical Operations	13.96	5.18	2	24	.87[e]	16.56	3.51	8	26	.75[e]	.84[e]

Note. [a] Number of correct responses. [b] Number of correctly recalled items. [c] Time needed to name all items. [d] Counted numbers within one minute. [e] Cronbach's alpha. [f] Parallel test reliability. [g] Correlations between words and nonword subtasks.

= 0.009. Fig. 2 provides a visualization of significant paths. Autoregressive effects were significant and positive, but substantially lower for arithmetic accuracy as compared to arithmetic fluency. This indicates that the construct of arithmetic accuracy as assessed in the present study is less stable than the one of arithmetic fluency. As to cognitive factors, the pattern of prediction of T1 reading was the same as the model with arithmetic fluency. Additionally, RAN made a significant and positive contribution to T2 and T3 reading fluency. Nonverbal IQ and number knowledge consistently predicted arithmetic accuracy at each time point with positive coefficients. Working memory positively predicted T1 and T3 variance in arithmetic accuracy. The relationship between reading fluency and arithmetic accuracy was not interactive, only T2 reading predicted T3 arithmetic accuracy. Covariances were not significant.

Detailed results of the CLPM including non-significant paths are available in Tables S9 and S10 in the Supplement.

Discussion

The aim of this study was to investigate predictors of associations and dissociations between reading and arithmetic throughout the first three years of primary school. We examined domain-general and domain-specific cognitive predictors in Grade 1 students and followed their academic achievement across Grades 1, 2, and 3. Even though our sample consisted of two cohorts with different language backgrounds and ages, correlation analysis did not suggest any systematic differences: Language did not correlate with the cognitive predictors.

In the following sections, we first discuss results related to the prediction of common variance among reading, arithmetic fluency and accuracy. We then consider concurrent predictive patterns in Grade 1 and longitudinal prediction in Grade 2 and 3. Finally, we discuss the time-related interaction between reading and arithmetic outcomes.

Predicting shared variance in reading and arithmetic

Results of multivariate multiple regressions indicated that both domain-general and domain-specific factors contributed variance to pairs of reading and arithmetic outcomes. Among domain-specific factors, phonological awareness, RAN and number knowledge had a consistent pattern of prediction across models and time points. Partial correlation analyses confirmed and extended this finding: RAN and number knowledge accounted for covariance of reading with arithmetic fluency as well as arithmetic accuracy. Phonological awareness contributed to covariance of reading with arithmetic accuracy, but somewhat less for covariance with arithmetic fluency. We see two

Table 2
Bivariate Pearson correlations.

	T1	1	2	3	4	5	6	7	9	8	10	11	12	13	14	15	16	17
1	Language[a]																	
2	Age	0.834**																
3	Nonverbal IQ	0.000	0.136**															
4	Working Memory	−0.011	0.058	0.417**														
5	Phonological Awareness	0.000	0.042	0.295**	0.434**													
6	RAN	0.000	0.056	0.129*	0.236**	0.360**												
7	Counting	0.000	0.061	0.181**	0.333**	0.321**	0.355**											
9	Magnitude Processing	−0.008	0.114*	0.266**	0.378**	0.251**	0.356**	0.369**										
8	Number Knowledge	−0.013	0.151**	0.387**	0.484**	0.405**	0.429**	0.520**	0.453**									
10	Reading Fluency	−0.009	0.054	0.295**	0.293**	0.546**	0.614**	0.334**	0.303**	0.491**								
11	Arithmetic Fluency	−0.011	0.093	0.325**	0.473**	0.320**	0.477**	0.448**	0.502**	0.653**	0.480**							
12	Arithmetic Accuracy	0.000	0.108*	0.363**	0.448**	0.370**	0.359**	0.381**	0.366**	0.620**	0.423**	0.604**						
	T2																	
13	Reading Fluency	−0.007	0.039	0.260**	0.262**	0.473**	0.615**	0.316**	0.285**	0.444**	0.842**	0.490**	0.355**					
14	Arithmetic Fluency	−0.011	0.099	0.337**	0.419**	0.291**	0.416**	0.382**	0.458**	0.586**	0.408**	0.800**	0.578**	0.464**				
15	Arithmetic Accuracy	0.000	0.114*	0.384**	0.419**	0.369**	0.370**	0.374**	0.350**	0.636**	0.437**	0.580**	0.566**	0.424**	0.626**			
	T3																	
16	Reading Fluency	−0.017	0.020	0.234**	0.224**	0.463**	0.608**	0.307**	0.250**	0.431**	0.765**	0.460**	0.280**	0.898**	0.417**	0.403**		
17	Arithmetic Fluency	−0.008	0.094	0.300**	0.394**	0.316**	0.462**	0.410**	0.431**	0.556**	0.494**	0.776**	0.490**	0.532**	0.842**	0.559**	0.516**	
18	Arithmetic Accuracy	0.000	0.106*	0.489**	0.489**	0.421**	0.371**	0.371**	0.379**	0.652**	0.513**	0.655**	0.591**	0.487**	0.659**	0.672**	0.472**	0.660**

Note. [a]Dummy coded variable: 1 = English-speaking, 2 = German-speaking; $N = 357$; * $p < .05$; ** $p < .01$.

overlapping components among those predictors: First, all three predictors refer to verbal codes, engaging language processing to different extent. Phonological awareness and number knowledge both require active manipulation of verbal units of different grain size (phoneme vs. morpheme level). Number knowledge goes beyond phonological awareness, because it entails integration of phonological elements (number words) and visual symbols (Arabic numerals), it requires not only phonological processing, but also knowledge about how number words are constructed. Second, both number knowledge and alphanumeric RAN entail symbol knowledge and efficient visual-verbal processing. RAN additionally involves a speed factor which certainly contributes to shared variance with speeded measures of reading and arithmetic fluency.

When all domain-specific predictors for both reading and arithmetic were considered, up to 93 % of the covariance in reading-arithmetic fluency and up to 97 % of the covariance in reading-arithmetic accuracy were explained. Further controlling for domain-general predictors did not reduce the covariance. This indicates that overlap between reading and arithmetic is best explained by domain-specific predictors. These predictors also accounted for variance that was previously attributed to the domain-general predictors. Results of our partial correlations analyses thus highlight that domain-general predictors may have an indirect effect on the outcome measures. As previously put forward by Zoccolotti et al. (2020), domain-specific dimensions can be considered as proximal factors that directly and explicitly relate to outcome variables. Domain-general predictors are instead distal factors in the sense that they are indirectly related to the outcome variables via proximal predictors. Findings from previous studies are generally in line with this view (Cirino et al., 2018; Koponen et al., 2020), which should be further tested in larger samples than the current one.

To sum up, results of this analysis indicate that nonverbal IQ and working memory contribute to, but are not the main driving factors of the covariance between reading and arithmetic. Predictors that are traditionally seen as domain-specific, on the other hand, accounted for a substantial portion of covariance.

Concurrent prediction of reading and arithmetic in grade 1

Domain-general predictors

In line with the expectation that domain-general predictors should be relevant for learning in general, nonverbal IQ was found to be a significant predictor of reading and arithmetic accuracy after considering domain-specific predictors. Working memory predicted arithmetic fluency and arithmetic accuracy after accounting for domain-specific predictors. Overall, these findings align with previous evidence indicating working memory as a relevant predictor of arithmetic (Peng et al., 2020).

Domain-specific predictors

We focused our analyses on five domain-specific predictors: Phonological awareness and RAN were expected to be preferentially related to reading. Counting speed, magnitude processing and number knowledge were anticipated to be arithmetic-specific predictors. Phonological awareness consistently predicted reading and accounted for specific variance beyond the other skill-domain, confirming its role as a major and domain-specific predictor of reading (Landerl et al., 2022). Phonological awareness did not predict specific arithmetic variance. Phonological awareness assesses the explicit understanding that language contains sublexical phonological segments like phonemes or syllable onsets and rimes. It is crucial for learning to read, particularly in alphabetic orthographies, as letters represent such sublexical segments. Arithmetic also requires verbal processing, for instance in the context of fact learning. The important difference to reading is that the verbal information necessary for arithmetic is always lexical (i.e., number words). Sublexical phonology is not directly relevant. In line with this reasoning, meta-analytic findings by Peng et al. (2020) showed a

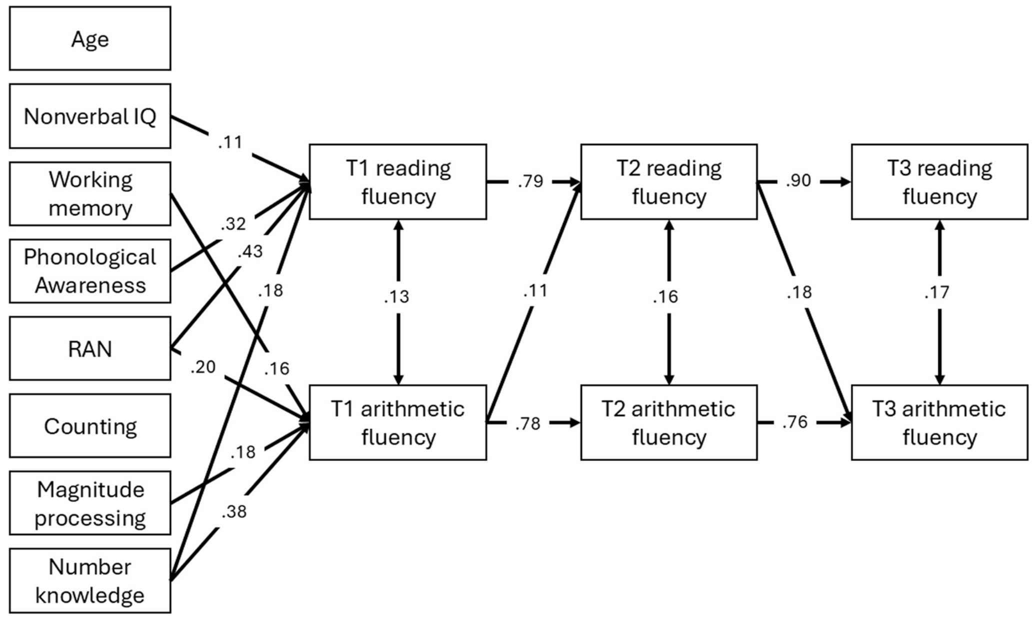

Fig. 1. Significant standardized paths in the CLPM investigating the association of reading and arithmetic fluency through three time points with cognitive factors predicting variance at T1.

moderate association between language and math skills, but note that comprehensive language skills (including listening comprehension, syntax judgement, sentence repetition tasks) yielded stronger correlations with math than phonological awareness.

RAN was a significant and specific predictor of fluency across skill-domains, but did not predict arithmetic accuracy. The contribution of RAN to concurrent reading and arithmetic fluency measures is in line with the hypothesis that this cognitive factor relates to efficiency in retrieving visual-verbal associations (Moll et al., 2009), a cognitive skill necessary for both ability domains. Counting did not contribute significant variance to any CLPM models, and although it showed moderate correlations with reading and arithmetic, its impact was relatively minor. In contrast to earlier evidence in a Finnish sample (Koponen et al., 2020), counting speed correlated only moderately with RAN (0.36).

Magnitude processing did not predict variance in reading and arithmetic accuracy, but was a specific predictor of arithmetic fluency. This pattern of findings corroborates the notion that handling quantities is not required for written language processing (see also Durand et al., 2005; Jöbstl et al., 2023). Magnitude processing was the only predictor not shared between arithmetic fluency and arithmetic accuracy (see also Zhang et al., 2016; Zhang, Tolmie, & Gordon, 2022) and suggests that magnitude processing and arithmetic fluency share a common processing speed component related to efficient and automated manipulation of numerical material. Arithmetic accuracy relies more heavily on procedural knowledge and progress monitoring rather than rapid numerical processing. This might be the reason why magnitude processing did not predict arithmetic accuracy.

The current study confirmed that the ability to transcode between single and particularly multi-digit visual-Arabic numbers and their corresponding number words is a major and unique predictor of arithmetic performance (Banfi et al., 2022; Göbel et al., 2014; Haberstroh & Schulte-Körne, 2022). Importantly, our evidence critically extends these findings, as early understanding of multi-digit numbers also predicted unique variance in concurrent 1st grade reading, above and beyond the variance explained by arithmetic performance. Our findings are consistent with Vanbinst et al. (2020), who showed that single- and multidigit number reading in kindergarten predicted unique variance in early arithmetic (measured as basic addition and subtraction) and in letter naming concurrently, controlling for the other skill-domain. Transcoding numbers requires efficient visual-verbal processing of arbitrary alphanumeric symbols and transcoding of multi-digit numbers involves complex linguistic processing on the phonological (e.g., "thirteen vs. "thirty"), and morpho-syntactic level, which may explain its association with reading.

Longitudinal prediction

In our analyses, we investigated whether cognitive factors explained variance longitudinally accounting for the autoregressive effects of each skill-domain. In the model predicting reading and arithmetic fluency, we observed very high stability. Children's performance at a later point was mostly predicted by earlier performance in the very same skill. There was very little interindividual variability left at further time points and indeed the model with concurrent prediction at T1 fitted the data better than the model with time-constant predictors. These findings are in line with earlier studies (Georgiou et al., 2020; Ribner et al., 2023) and suggest that children who are already efficient users of procedural strategies continue to have advantages when they increasingly change to retrieval-based strategies.

We observed a different pattern in the model predicting reading fluency and arithmetic accuracy. The contribution of autoregressive components was lower here, especially for arithmetic accuracy. Accordingly, the model with time-constant predictors fitted the data better than the model with only concurrent predictors. RAN was the only predictor explaining developmental changes in reading fluency. It did not predict changes in arithmetic accuracy. This finding indicates that there is a closer association of RAN with reading than with arithmetic. This is consistent with previous evidence (Jöbstl et al., 2023) and reflects the inherent relevance of efficient sequential visual-verbal processing for growth in word and nonword reading skills (Landerl et al., 2022). Note that overlap in task format of RAN was also higher with our reading aloud paradigm, as both involved explicit naming.

Developmental changes in arithmetic accuracy were explained by nonverbal IQ and number knowledge. Working memory additionally predicted variance in Grade 3. The contribution of these cognitive factors can be explained by the growing complexity of the arithmetic accuracy task throughout grade levels. This task included a steadily increasing proportion of multi-step procedural calculations involving single and multi-digit numbers arranged in rows and columns

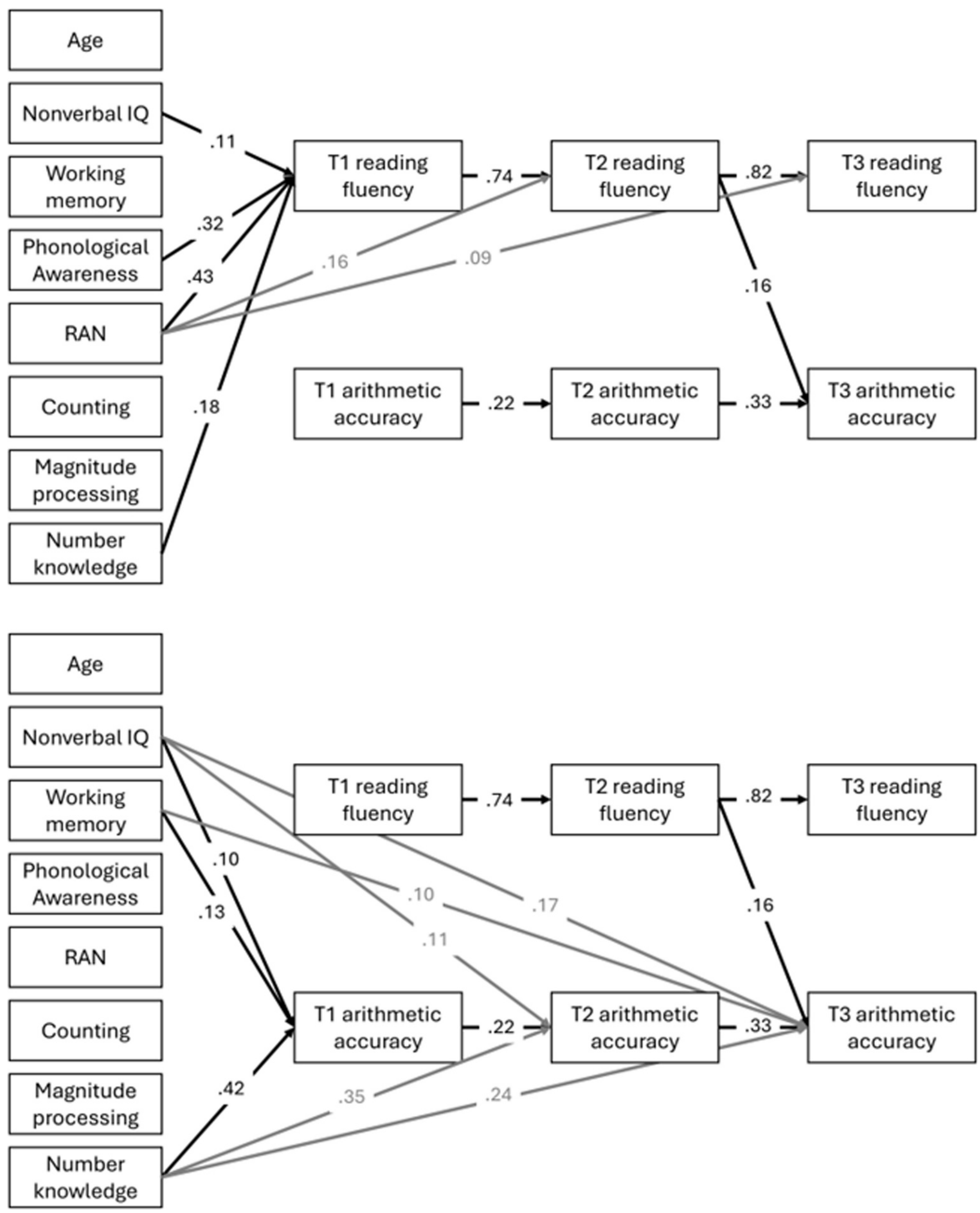

Fig. 2. Significant standardized paths in the CLPM investigating the association of reading fluency and arithmetic accuracy through three time points with cognitive factors predicting variance at each time point. To ease the inspection of the plot, predictors of reading fluency are shown in the panel above, predictors of arithmetic accuracy are shown in the panel below. Black paths indicate autoregressive effects and concurrent predictions, gray paths refer to longitudinal prediction of cognitive factors at T2 and T3.

throughout grades. These calculations require visuo-spatial processing, a higher working memory capacity, fact retrieval and continuous multi-digit transcoding.

Taken together, our findings regarding longitudinal prediction are relevant for two aspects: 1) they confirm the notion that the best predictor of future academic performance is past performance; 2) they underscore the necessity of additional research in this area. Despite the minor impact of cognitive factors in explaining developmental change, our models did not fully explain variance (R^2-like estimates between 0.54 and 0.81 in the CLPM with reading and arithmetic fluency; between 0.44 and 0.82 in the CLPM with reading fluency and arithmetic accuracy). Future studies should investigate why established cognitive factors of written language and arithmetic are unable to provide a satisfactory explanation for their developmental change. It is possible that other non-cognitive dimensions play a relevant role, as for instance environmental, motivational factors and personality traits.

Time-related interaction of reading and arithmetic

We investigated whether reading and arithmetic have an interactive relationship throughout the first three years of formal schooling. Both skills undergo similar developmental steps and share a common cognitive basis. It can be assumed that they influence each other especially in grade levels that witness a shift from procedure- to retrieval-based strategies. Our results are only partly in line with this hypothesis. The CLPM model including reading and arithmetic fluency indicated a moderate interactive pattern with arithmetic fluency at T1 predicting reading at T2 and reading at T2 predicting arithmetic fluency at T3. Fluency measures were also correlated throughout time points. These results are partly in line with the previous study by Psyridou et al. (2025) and highlight the tight connection between fluency measures throughout time.

The model including reading fluency and arithmetic accuracy showed a different scenario with no interactivity. The only significant cross-lagged path was reading fluency at T2 predicting arithmetic accuracy at T3, covariances were not significant. This pattern clearly indicates that there is far less overlap between tasks that do not share surface characteristics. Note that reading fluency and arithmetic accuracy showed significant zero-order correlations (*r*s between 0.42 nd 0.47), but their covariance was fully accounted for by other components of the CLPM models, as for instance the cognitive predictors. The significant path of reading predicting arithmetic accuracy at T3 may suggest that reading starts to contribute variance to arithmetic when computations become more complex. Note, however, that the T3 arithmetic accuracy measure did not involve word problems and therefore there was no reading component in the arithmetic measure.

Taken together, the pattern of interactivity was surprisingly limited for the model with reading and arithmetic fluency and absent for the model with reading fluency and arithmetic accuracy. Our results align with the hypothesis that both skills develop in parallel and their observed association may not be driven by causal, reciprocal influences. The observed cross-lagged paths may be related to intervening variables that we did not assess in the present study, such as the influence of the teaching person and home environmental effects.

Future longitudinal studies including more than three waves of assessment should test the contribution of these factors to better disentangle the direction and the nature of observed causal links.

Limitations

The current study comprised children from two different European countries. Findings were largely consistent across those subsamples, but it should be noted that identifying differences due to language or educational background was not the aim of the current study. The structure of the current data set did not allow us to have at least two indicators per construct, which is why our analysis is based on manifest rather than latent variables as in structural equation models.

Working memory was measured by means of traditional Digit Span and Block Recall tasks. While these tasks have high construct validity, as they are consistent with the working memory theory by Baddeley (Baddeley, 2012; Baddeley & Hitch, 1974), they often result in rather low reliability coefficients in developmental samples (Alloway & Alloway, 2010; Pickering & Gathercole, 2001). Future research endeavors should include measures with higher reliability to improve replicability of results.

The current manuscript provides correlational evidence about the relation between different cognitive dimensions and foundational academic skill domains. Having assessed the cognitive predictors at only one time point, we cannot draw any causal conclusion. Moreover, we were unable to inspect whether their predictive pattern changed depending on grade level.

Educational implications

Our findings confirm the relevance of phonological awareness, RAN, number knowledge and magnitude processing for reading and/or arithmetic. These predictors thus provide a useful battery of tasks for early screening in Grade 1. Our results are also important to understand dissociations among skill domains. Our findings indicate that, for instance, difficulties in grasping the sublexical sound structure of spoken words has a likely impact on reading development, but is not directly relevant for arithmetic development. Note, however, that phonological awareness problems may be associated with broader language problems (Ramus et al., 2013; Snowling, 1998; Snowling & Melby-lervåg, 2016) which would in turn affect arithmetic development too. In contrast, understanding magnitudes is foundational to arithmetic achievement but not to reading.

Conclusion

This study provides evidence for the cognitive basis of associations and dissociations between reading and arithmetic skills throughout the first three years of primary school. Nonverbal IQ and working memory generally contributed variance to both skill-domains, but domain-specific predictors, and especially phonological awareness, RAN and number knowledge, explained a more substantial portion of shared variance. Our results show that the distinction between domain-general and domain-specific predictors is perhaps less informative than previously assumed, as cognitive dimensions in both categories contribute variance across academic skill domains. Terminology should thus be revised.

CRediT authorship contribution statement

Chiara Banfi: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Viktoria Jöbstl:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Silke M. Göbel:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation. **Karin Landerl:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Ethics approval

The study was conducted in accordance with the principles of the Declaration of Helsinki and consent was obtained from both children and guardians. The ethics committees of the University of Graz and the University of York approved the study (Reference number, English: 559; Austrian: 39/23/63 ex 2016/17).

Declaration of competing interest

There are no conflicts of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.appdev.2025.101895.

Data availability

The data analyzed in the current manuscript refer to a longitudinal, cross-linguistic research project and are publicly available (Göbel et al., 2020).

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