Journal of Experimental Child Psychology 231 (2023) 105656

Contents lists available at ScienceDirect

Journal of Experimental Child Psychology

journal homepage: www.elsevier.com/locate/jecp

Early rapid naming longitudinally predicts shared variance in reading and arithmetic fluency

David Hoff [a], Tonje Amland [a,*], Monica Melby-Lervåg [a], Arne Lervåg [b], Athanassios Protopapas [a]

[a] Department of Special Needs Education, University of Oslo, Blindern, 0318 Oslo, Norway
[b] Department of Education, University of Oslo, Blindern, 0317 Oslo, Norway

ARTICLE INFO

Article history:
Received 22 April 2022
Revised 6 February 2023
Available online 12 March 2023

Keywords:
Longitudinal
SEM
RAN
Reading
Arithmetic
Shared fluency

ABSTRACT

A number of cognitive factors have been suggested to underlie development in reading and arithmetic skills. Although the two domains are strongly linked, only a few studies have investigated the processes that are shared between them during the early school years. Rapid automatized naming (RAN) has been identified as a strong predictor of a common fluency factor in reading and arithmetic. In the current study with 232 Norwegian children, we examined how RAN in preschool and Grade 1 relates to the shared and nonshared variance in arithmetic fluency and reading fluency in Grade 3. Furthermore, we examined whether related processing skills (phoneme awareness, working memory, speed of processing, and symbol knowledge) can account for the relationship between RAN and shared fluency—or if they predict variance that is unique to each domain. Our results show that RAN in both preschool and Grade 1 is a strong predictor of shared variance between reading fluency and arithmetic fluency measured several years later, whereas other predictors mainly relate to the nonshared parts of variance in the fluency outcomes. That is, control variables with the theoretical potential to explain some of RAN's relation to the overlap between reading and arithmetic fluency do not in fact account for this relationship. Our findings provide a starting point for future investigations of the mechanisms of rapid naming.

* Corresponding author.
E-mail address: tonje.amland@isp.uio.no (T. Amland).

https://doi.org/10.1016/j.jecp.2023.105656
0022-0965/© 2023 The Author(s). Published by Elsevier Inc.

Introduction

Literacy and numeracy are essential skills. Together they form a foundation for lifelong learning. Interestingly, studies of typically developing children show that reading and mathematics performance are related (Balhinez & Shaul, 2019; Koponen et al., 2020; Purpura et al., 2011). Studies show that there is a moderate correlation between decoding and arithmetic (Swanson et al., 2009) and a moderate group difference in arithmetic skills between schoolchildren with and without dyslexia (Landerl & Moll, 2010). However, the nature of the relationship remains unclear. In the current study, we focused on a possible common substrate of fluency in these two domains, namely the set of skills responsible for performance in rapid automatized naming (RAN) tasks.

It has been repeatedly demonstrated that RAN, together with awareness for sounds in words (i.e., phonemes), reflects a critical factor underlying the development of reading skills (Clayton et al., 2020; Landerl et al., 2019; Powell & Atkinson, 2020; Vander Stappen & Reybroeck, 2022). In RAN tasks, children name aloud an array of objects, colors, or alphanumeric symbols (such as letters or digits) as quickly as they can (Georgiou & Parrila, 2020). Such tasks are associated with the development of reading fluency, that is, the ability to read aloud, accurately and rapidly, with appropriate expression (Kuhn et al., 2010). Children's performance on RAN tasks accounts for variation in reading fluency longitudinally even after controlling for phonological awareness, verbal IQ, and earlier reading skills (de Jong & van der Leij, 1999; Landerl & Wimmer, 2008; Lervåg & Hulme, 2009). In a meta-analysis on the relationship between RAN and reading, Araújo et al. (2014) found a moderate to strong relationship between RAN and reading (r = .43). In particular, the relationship of RAN with reading accuracy is relatively less strong and decreases over time, whereas that with reading fluency is stronger and remains stable.

RAN is also related to early mathematical skills. A meta-analysis of both concurrent and longitudinal studies demonstrated a moderate relationship between math skills and RAN (r = .37) and an even stronger relationship when measures of arithmetic calculation were used rather than general mathematical achievement (Koponen et al., 2017). The correlations were particularly strong for the ability to solve speeded single-digit tasks, that is, what is often labeled as arithmetic fluency. Using different stimuli in RAN tasks (e.g., variations of alphanumeric or nonalphanumeric items) yields somewhat differing predictions of fluency in reading and arithmetic, meaning that different types of RAN make specific contributions (Koponen et al., 2017). However, what is common between RAN tasks seems to be more important than what is unique to each task in explaining why RAN predicts reading and arithmetic fluency (Hornung et al., 2017).

Although RAN is associated with both reading and arithmetical skill development, it is not clear whether the associations are due to the same underlying cognitive mechanisms or may concern partly separable skill domains. RAN tasks may appear superficially simple, but they require a rich and highly coordinated set of processes to be carried out successfully (Norton & Wolf, 2012; Wolf & Bowers, 1999), such that different sources of individual differences can contribute to variation in task performance. This means that the reasons why RAN predicts future reading fluency could be at least partly separable from the reasons why RAN predicts arithmetic fluency. Thus, in the current study we addressed this issue by examining to what extent RAN predicts shared versus nonshared variance between reading and arithmetic fluency.

The importance of fluency in reading and arithmetic

During recent years, reading research has become increasingly preoccupied with reading fluency as an integral part of skilled reading. Beginning readers rely on phonological recoding, using letter–sound associations to produce spoken words from print (Ehri, 2005; Schwanenflugel & Knapp, 2016). With practice, readers become able to process larger chunks of text simultaneously through a process known as unitization. Eventually, readers are able to perform automatic recognition of whole words—known as reading "by sight" (Ehri, 2014). In turn, rapid and effortless sight word reading is thought to permit fluent reading of sentences and passages, in which additional factors of sequential processing come into play and become prominent with increasing skill (Altani et al., 2020).

The ability to effortlessly produce solutions to simple arithmetic problems is commonly referred to as arithmetic fluency (Carr & Alexeev, 2011). However, the arithmetic fluency construct is less well-defined and less understood than reading fluency. Early strategies of arithmetic rely on counting skills to manipulate numbers, but it has been suggested that with repeated practice children become able to retrieve solutions to problems from memory through fact retrieval (Dowker, 2014; Gilmore et al., 2018). In other words, the foundation for developing fluency lies in being able to effortlessly retrieve solutions to calculations involving basic arithmetic units (e.g., 3 + 4).

Thus, fluency is an essential component of skilled performance in both reading and arithmetic. In reading, building fluency is seen as an essential step toward skilled reading; fluent performance frees up cognitive resources, allowing these to be allocated to processes of comprehension (Kim, 2015; Schwanenflugel & Knapp, 2016). Arithmetic fluency is likewise seen as an important step on the way to mastering advanced computation, providing quick access to intermediary answers and lessening the demand for cognitive resources such as working memory (Carr & Alexeev, 2011; Koponen et al., 2016; Rinne et al., 2020). Thus, arithmetic fluency is important for more complex mathematical skills because it frees up resources that can be used for more complex reasoning (Meyer et al., 2010). Difficulties in reading fluency are considered a hallmark of dyslexia (Diamanti et al., 2018; Wolf & Bowers, 1999). Likewise, difficulties in arithmetic fluency have been linked to low mathematical achievement and are seemingly persistent (Geary et al., 2012; Vanbinst et al., 2015).

The role of rapid naming in the relationship between reading and arithmetic fluency

Several studies have reported that RAN predicts the overlap of reading fluency and arithmetic fluency after controlling for a range of domain-general and domain-specific predictors (Cirino et al., 2018; Georgiou et al., 2021; Koponen et al., 2007, 2016, 2020; Korpipää et al., 2017). Previous studies also found that the effects of RAN on reading fluency and arithmetic fluency are unidirectional, specific, and consistent (Georgiou et al., 2020; Lervåg & Hulme, 2009). RAN performance is related to time-invariant, rather than time-specific, shared variance between reading and math (Korpipää et al., 2017). This means that RAN predicts reading and arithmetic due to continually shared processes rather than processes limited to a developmental window. However, the exact nature of this overlap remains unclear.

Three different explanations have been put forward: First, one prominent explanation is that reading fluency and arithmetic fluency overlap due to similar reliance on phonological processing (Koponen et al., 2007). Fluent reading partly relies on automatic retrieval of phonological word forms (i.e., sight word reading). Similarly, arithmetic fluency relies on the retrieval of arithmetic facts, which are also thought to be stored in a language-based format (Dehaene et al., 2003; Koponen et al., 2007; LeFevre et al., 2010). Furthermore, it is also argued that procedural strategies in both domains rely on phonological processing, which is essential for phonological recoding and also for producing and manipulating counting sequences in arithmetic (Fuchs et al., 2016). According to this view, the relationship between RAN and the cross-domain overlap of fluency is observed because RAN tasks measure the rate of access to phonological representations. That is, the relationship hinges on the need to access phonological representations (rather than processing rate). If this is the case, then other measures of phonological processing should also predict the shared variance between reading fluency and arithmetic fluency and thereby explain away at least part of RAN's prediction.

Second, in an alternative account, the relationship between RAN and reading has been proposed to be due to similar reliance on domain-general cognitive abilities such as speed of processing and working memory (Kail & Hall, 1994; Kail et al., 1999). Similar claims have been made about the relationship between RAN and arithmetic (Georgiou et al., 2013; Wang et al., 2020). Whereas controlling for domain-general abilities fails to explain the relation between RAN and reading (Georgiou & Parrila, 2020), controlling for abilities such as speed of processing has been found to account for RAN's prediction of arithmetic fluency (Georgiou et al., 2013; Wang et al., 2020). Similarly, working memory is involved in RAN performance (Georgiou et al., 2013; Norton & Wolf, 2012) and has been found to be related to variance shared between reading and arithmetic (Georgiou et al., 2021; Koponen et al., 2020; Korpipää et al., 2017).

A third proposed explanation is that the domains of fluency overlap due to similar reliance on mechanisms of storage and retrieval of visual–verbal associations—mechanisms that are also thought to underlie rapid naming performance (Koponen et al., 2007; Lervåg & Hulme, 2009). This echoes research on paired-associate learning, although this skill has been found to primarily predict accuracy outcomes in reading and arithmetic rather than fluency (Malone et al., 2019; Poulsen & Elbro, 2018; Warmington & Hulme, 2012).

A related issue concerns the role of symbol knowledge, especially in alphanumeric RAN (tasks including digits or letters), which can be thought of as the outcome of earlier learning of visual–verbal association. It has been proposed that RAN performance is partly a reflection of early individual differences in symbol knowledge (letters and digits), and that number and letter naming accuracy relying on this symbol knowledge underlies performance in both alphanumeric RAN and reading/arithmetic fluency (Bowey, 2005; Koponen et al., 2020). Therefore, it is important to control for symbol knowledge when investigating the prediction of reading and arithmetic fluency by RAN.

The current study

One important unresolved issue relates to the developmental stages at which we measure cognitive predictors and later fluency in reading and arithmetic. Studies examining the RAN–fluency association have not always tested the relationship longitudinally or have assessed children only during the first 2 years of primary school (e.g., Georgiou et al., 2021), before they are old enough to have sufficiently established efficient arithmetic fact retrieval and fluent reading (Juul et al., 2014; Qin et al., 2014). To better understand the connection between fluency and cognitive precursors, it is essential to assess the precursors before children receive formal literacy and numeracy instruction and to measure outcomes at an age when the majority of children are expected to be fluent within each domain. We tackled this by examining how RAN measured both before and shortly after the onset of formal instruction relates to mathematical and reading skills several years into primary education while controlling for a number of related skills.

To summarize the main issues identified above, we were first interested in whether the observed relationships between RAN and reading and arithmetic fluency reflect a prediction of common processes or rather predictions of co-occurring but separate abilities. Thus, our first research question was as follows:

1. To what extent does RAN in preschool and first grade predict shared versus nonshared variance in arithmetic fluency and reading fluency in third grade?

Second, as outlined above, there are three putative theoretical explanations of the shared variance between reading and arithmetic fluency (i.e., the phonological processing theory, the domain general/speed of processing theory, and the theory concerning storage and retrieval of visual–verbal associations); in addition, a role for symbol knowledge has been suggested to partly underlie this relationship. We were interested in whether these domains can account for the prediction of shared variation in reading and arithmetic fluency by RAN. Thus, our second research question was as follows:

2. Can processing skills that have been implicated in the relationship between RAN and reading and arithmetic fluency (i.e., phoneme awareness, working memory, processing speed, and symbol knowledge) account for the relationship between RAN and shared fluency, or does RAN still significantly predict shared fluency after controlling for them?

Answering these questions will help to clarify (a) the relationship of RAN with shared versus nonshared variance in reading and arithmetic fluency from a developmental perspective and (b) the plausibility of theories regarding cognitive domains potentially underlying this relationship.

Method

Participants

Participants in the current study were enrolled in the longitudinal study "NumLit: Development of Numeracy and Literacy in Children." Children were fluent Norwegian speakers recruited from 58 preschools (and subsequently 35 schools) in municipalities around the greater Oslo area that are representative of the national average when it comes to educational level of the parents (Statistics Norway, 2023). Parental consent was obtained prior to testing, and children gave verbal assent at each time point of the data collection. Children already diagnosed with severe learning disabilities or developmental disorders, such as sensory impairments, autism, and intellectual disability, were excluded from the study. Because the children were assessed early in the educational trajectory, the sample may include low-performing children who will receive diagnoses later.

A total of 259 children were assessed during January to March of the final preschool year (126 girls; mean age = 5.5 years) before any formal literacy or numeracy training. Outcome assessment for 236 children took place when they attended third grade (mean age = 8.3 years). Some children could not be assessed due to the COVID-19 pandemic.

Measures

Preschool predictors

Rapid automatized naming. Because most preschool-age children cannot name digits consistently and effortlessly, two nonalphanumeric RAN tasks were used, namely objects and colors. For RAN objects, items included drawings of a door, a boy, a boat, and a mouse. For RAN colors, items included green-, red-, blue-, and yellow-colored circles. After a brief set of 4 practice items in each task, children named all items in a 4×8 array as quickly as possible. Presentation was pseudorandom; each row included two repetitions of each of the 4 items under the constraint that no 2 adjacent items were the same and a row could not end with the same item that started the next row. Raw scores were the total time spent on each task. Reliability (Spearman's ρ between the two tasks) was .65.

Processing speed. This involved two variations of a cross-out task, each with a different target image among four distractor images. Children first practiced with a 7-item sequence and were subsequently presented with 6×7 arrays with randomly placed targets and distractors. Children were given 60 s to cross out all instances of the target item across four different arrays. The total score was the total number of correctly crossed out items over the two tasks.

Working memory. The backward digit recall task from the Working Memory Test Battery for Children (WMTB-C) was used to measure verbal working memory. The examiner read aloud a string of digits, which children then repeated backward. Two practice trials preceded the test. There was a gradual increase in difficulty, with each block consisting of 6 items (sequences) that were one digit longer than those in the previous block. The test was discontinued after 3 mistakes in one block. The score was the total number of items (sequences) produced correctly. Reliability (McDonald's ω) was .88.

Phoneme awareness. A phoneme isolation task was used in which the examiner said a word and children were asked to respond with the first or last sound of the word. Words in the first 4 items were accompanied by pictures to facilitate children's understanding of the task. Two 12-item blocks were administered; the first one contained 5 CVC (consonant–vowel–consonant), 2 CVCC, 1 VCC, 2 CCVC, and 2 CCVCC items, and the second one contained 3 CVC, 7 CVCC, 1 VVC, and 1 CCVCC items. One point was awarded for each item, that is, each correctly produced phoneme. Reliability (McDonald's ω) was .93.

Letter knowledge. Children were asked to produce the names or sounds of Norwegian letters printed on a sheet of paper. There were 9 vowels in the first subtask and 17 consonants in the second subtask.

One point was given for each correct response. The correlation between the two subtasks (Spearman's ρ) was .82.

Number knowledge. A number-naming task was used, in which children needed to name a series of printed numbers of increasing magnitudes, ranging from single-digit to four-digit numbers. There were 29 numbers in total, but the task was discontinued after 4 consecutive incorrect responses. One point was given for each correctly named number. Reliability (McDonald's ω) was .82.

First-grade predictors

In first grade, children were assessed on the same measures of processing speed and working memory as in preschool. In addition, they completed an alphanumeric RAN task, an additional number knowledge task, and a different measure of phoneme awareness.

Rapid automatized naming. In first grade, children completed two digit RAN tasks containing the digits 2, 3, 5, and 6. These were similar in all ways to the preschool RAN tasks (array size; arrangement; and sequence constraints) except that the items were digits. Reliability (Spearman's ρ between the two tasks) was .78.

Number knowledge. Two tasks were used. The first one was the same as in preschool but was extended with more difficult items. The second one was a number identification task (modeled after Göbel et al., 2014) that required drawing a circle around the number corresponding to the one read aloud by the examiner. For example, for the oral prompt "one hundred and sixty-three," children would mark one of the five options 136, 10063, 13, 163, or 16. Target numbers ranged from one to three digits. One point was given for each correct identification. Reliability (McDonald's ω) was .73.

Phoneme awareness. Two 12-item phoneme deletion tasks were administered, one with words and one with nonwords, where children needed to delete sounds in the beginning, middle, or end of words. Testing was discontinued after 6 consecutive errors. A translated example was "Say 'cat' without saying '/k/'." Initial items were monosyllabic CVC, and each test gradually increased in complexity with consonant clusters and additional syllables (up to three-syllable words and two-syllable nonwords). One point was awarded for each item, that is, each correctly produced phoneme. Reliability (McDonald's ω) was .84 for words and .85 for nonwords.

Third-grade outcomes

Word and nonword reading fluency. This outcome was measured using the Norwegian adaptation of the Test of Word Reading Efficiency (TOWRE) (Furnes & Samuelsson, 2011; Torgesen et al., 1999). Children read lists of words and nonwords as quickly and accurately as possible within 45 s. Eight practice words preceded the two word lists, each containing 104 words of increasing difficulty split into four columns, followed by the two nonword lists, each containing 63 nonwords displayed in three columns. Any valid decoding was considered correct (accounting for inconsistencies in Norwegian spelling). One point was given for each correctly read word. The correlation (Spearman's ρ) between word and nonword lists was .88.

Text reading fluency. Two passages were selected from the Norwegian Oral Reading Fluency test (Arnesen et al., 2017), based on the Oral Reading Fluency subtest of Dynamic Indicators of Basic Early Literacy Skills (DIBELS) (Good & Kaminski, 2002; Kaminski et al., 2002). Children were asked to read the passage aloud until prompted to stop. If they struggled with a word for more than 3 s, the tester read the word for them and marked it as an error. Children were given 60 s to read each passage. The total amount of correctly read words was noted. The correlation (Spearman's ρ) between the two passages was .94.

Arithmetic fluency. Four subtasks from the Test of Basic Arithmetic and Numeracy Skills (TOBANS) (Brigstocke et al., 2016) involving addition and subtraction were used. Each of the two operations was divided into two lists, one without carry/borrowing, where all problems had single-digit solutions/operands; and one with carry/borrowing, where problems had a sum/operand from 10 to 18, for a total of four lists (addition without and with carry and subtraction without and with borrowing). Three practice problems preceded each list, and children were then given 60 s to complete as many problems as they could. The number of correct answers was recorded. Reliability (McDonald's ω) was .93 (addition), .90 (addition with carry), .92 (subtraction), and .90 (subtraction with borrowing).

Procedure

Data collection

For the preschool and Grade 1 assessment, tests were administered individually in a fixed order by trained research assistants who visited the children's preschools and (later) schools from early January to late March for three sessions 45 to 60 min long. Grade 3 assessment was carried out in a single (and shorter) session during the fall of the school year.

Data preparation

The distribution of all variables was examined using histograms, Q-Q plots, skew and kurtosis statistics, and inferential tests for normality. RAN times (both preschool and Grade 1) were inversely transformed to better approach the normal distribution. Processing speed (both preschool and Grade 1) and Grade 3 arithmetic outcomes were square-root-transformed. For all these transformations, both the correlation and the distributions of transformed and untransformed variables were examined. Mean composites were created for each of the three Grade 3 reading measures by averaging the scores of the two corresponding lists/passages. A total of 37 cases with missing data for RAN, reading fluency, or arithmetic fluency were removed, leaving a final sample of 232 children for further analysis. Scattered missing data points remained in predictor variables (see data preparation and missing data report at https://shinyibv02.uio.no/connect/#/apps/f618a580-cef1-401f-8817-b2ce63ad489a/access).

Statistical analyses

First, we examined the correlations between the measured indicators of each construct, followed by confirmatory factor analyses (CFAs) to investigate the structure of the outcome variables. Two initial path models, one for each of the first two time points (preschool and Grade 1), were then set up to test RAN's prediction of shared fluency.

Subsequently, structural equation models (SEMs) were specified to test longitudinal predictions with all relevant covariates and control variables. In the initial models, we wanted to examine the extent to which each predictor predicted reading fluency and arithmetic fluency directly, unconstrained by modeling of shared variance. Based on our findings regarding which predictors were significant, we then specified reduced models where RAN predicted shared variance, supplemented by those predictors that were identified as significant in the previous step. Nonsignificant paths were stepwise dropped from the final models. All steps in the analyses were conducted in the free software environment R, and the code can be found in the online supplementary material and at https://osf.io/jxtfs/ along with full output, graphs, and diagnostics.

Results

Descriptive statistics and correlations

Descriptive statistics are shown in Table 1, and correlations between all measures are shown in Table 2.

Correlations between preschool and Grade 1 RAN performance and outcomes ranged from .41 to .52 for reading and from .18 to .50 for arithmetic. Notably, the lower correlations are between RAN and the most complex forms of arithmetic, that is, simple subtraction and subtraction with borrowing.

Table 1
Descriptive statistics for all observed variables.

Task	*N*	*M*	*SD*	Min	Max
Preschool (5 years)					
RAN colors	218	14.41	4.33	4	27
RAN objects	218	14.87	3.44	7	27
Speed of processing	227	4.02	1.43	1	7
Backward digit span	219	5.70	3.44	0	14
Number naming	227	8.32	2.56	1	13
Letter knowledge	227	13.89	8.31	0	26
Phoneme isolation	227	11.21	6.49	2	24
Grade 1 (6 years)					
RAN Digits 1	231	23.47	6.08	11	43
RAN Digits 2	214	22.27	5.78	11	40
Speed of processing	226	5.34	1.35	2	8
Backward digit span	230	9.04	3.12	0	19
Number identification	229	5.43	1.76	1	8
Number naming	229	14.93	4.65	6	22
Phoneme deletion, words	228	6.42	3.28	0	12
Phoneme deletion, nonwords	228	4.73	3.34	0	12
Grade 3 (8 years)					
Word reading	232	63.70	18.48	18	103
Nonword reading	231	37.08	13.04	7	77
Text reading	228	92.98	38.42	7	195
Addition	232	44.74	6.67	26	65
Addition with carry	232	31.15	6.22	17	52
Subtraction	232	37.01	7.46	14	57
Subtraction with borrowing	232	27.02	6.80	14	42

Note. RAN, rapid automatized naming.

This is not surprising given that subtraction is automatized later and to a lesser degree than simple addition and might still require slower procedural strategies.

Factor analyses for fluency outcomes in reading and arithmetic

To assess the relationships between latent factors and their assigned indicators, we first performed a CFA of the latent outcomes. We estimated the latent reading fluency factor with three reading indicators: word reading, nonword reading, and text reading fluency. Arithmetic fluency was estimated with four indicators: addition, addition with carry, subtraction, and subtraction with borrowing. We allowed correlated residuals between word reading and nonword reading, and between subtraction and subtraction with borrowing, to emphasize what is common between reading lists and passages and between addition and subtraction, respectively. The resulting model had acceptable fit, $\chi^2(11) = 19.338$, $p = .055$, root mean square error of approximation (RMSEA) = .057, 90% confidence interval (CI) [.000, .098], comparative fit index (CFI) = .994, standardized root mean square residual (SRMR) = .017. R code and full output for this model and all subsequent models can be found in the supplementary material and at https://osf.io/jxtfs/.

Does RAN predict shared variance in reading and arithmetic fluency?

Following successful outcome modeling, we evaluated whether our data were compatible with RAN predicting shared fluency variance. We added a second-order “covariance” factor to the outcome model, with loadings constrained to be equal across the reading and arithmetic fluency factors measured in Grade 3. We estimated two models separately: one using a RAN factor based on the color and objects tasks measured in preschool and one using a RAN factor reflecting the two digit tasks measured in Grade 1. Initial models were specified so that the RAN latent factor was restricted to predict only fluency covariance. Using Grade 1 predictors, we achieved satisfactory model fit, $\chi^2(23) = 30.853$,

Table 2
Pearson's *r* correlations between all measures.

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Preschool (5–6 years)																						
1. RAN colors	–																					
2. RAN objects	.67***	–																				
3. Speed of processing	.31***	.19**	–																			
4. Backward digit span	.28***	.21**	.05	–																		
5. Number naming	.37***	.33***	.23***	.29***	–																	
6. Letter knowledge	.24***	.25***	.02	.36***	.61***	–																
7. Phoneme isolation	.26***	.24***	.05	.42***	.44***	.61***	–															
Grade 1 (6–7 years)																						
8. Number ID	.25***	.12	.21**	.22***	.49***	.26***	.19***	–														
9. Number naming	.30***	.19**	.16*	.22***	.55***	.33***	.27***	.69***	–													
10. Speed of processing	.22**	.16*	.29***	.08	.12	.07	.05	.20**	.12	–												
11. Backward digit span	.33***	.23***	.15*	.49***	.33***	.32***	.33***	.39***	.36***	.17**	–											
12. Phoneme deletion, words	.36***	.29***	.10	.44***	.35***	.44***	.43***	.28***	.33***	.18**	.44***	–										
13. Phoneme deletion, nonwords	.38***	.30***	.11	.41***	.36***	.38***	.43***	.28***	.37***	.22***	.47***	.76***	–									
14. RAN Digits 1	.48***	.48***	.25***	.26***	.36***	.33***	.32***	.31***	.36***	.22***	.42***	.50***	.44***	–								
15. RAN Digits 2	.43***	.41***	.26***	.20**	.33***	.31***	.34***	.27***	.33***	.22***	.36***	.46***	.49***	.80***	–							
Grade 3 (8 years)																						
16. Word reading	.44***	.43***	.11	.22***	.38***	.36***	.26***	.24***	.28***	.12***	.33***	.40***	.36***	.53***	.51***	–						
17. Nonword reading	.42***	.41***	.07	.21**	.34***	.31***	.25***	.25***	.27***	.12	.33***	.36***	.38***	.48***	.48***	.88***	–					
18. Text reading	.48***	.47***	.09	.26***	.43***	.42***	.34***	.25***	.30***	.13	.40***	.42***	.42***	.53***	.54***	.90***	.84***	–				
19. Addition	.38***	.24**	.25**	.24***	.38***	.21**	.09	.40***	.45***	.30***	.39***	.34***	.32***	.52***	.45***	.51***	.49***	.52***	–			
20. Addition with carry	.32***	.22**	.21**	.27***	.36***	.26***	.18**	.38***	.45***	.22**	.39***	.36***	.33***	.45***	.39***	.48***	.45***	.48***	.77***	–		
21. Subtraction	.31***	.19**	.27***	.29***	.44***	.31***	.20**	.51***	.53***	.23***	.42***	.39***	.36***	.51***	.46***	.47***	.49***	.48***	.77***	.75***	–	
22. Subtraction with borrowing	.29***	.18**	.28***	.20**	.37***	.22***	.09	.48***	.46***	.22***	.32***	.28***	.25***	.38***	.33***	.37***	.33***	.35***	.60***	.65***	.69***	–

Note. RAN, rapid automatized naming.
* $p < .05$.
** $p < .01$.
*** $p < .001$.

p = .126, RMSEA = .038, 90% CI [.000, .070], CFI = .996, SRMR = .023, indicating that RAN was mainly related to what is common between reading and arithmetic fluency (β = .781, p < .001, accounting for 61% of the modeled shared variance) (see Section 3.3 of the supplementary material for model specification and full output).

In contrast, using preschool predictors, it was apparent that RAN was a stronger predictor of reading fluency than of arithmetic fluency because model fit required a direct path from RAN to reading fluency in addition to the prediction of variance shared between reading and arithmetic. Therefore, in the preschool predictor model, RAN was allowed to predict both covariance (β = .549, p < .001, accounting for 30%) and reading fluency (β = .220, p = .014). The model with preschool predictors had the following fit: $\chi^2(22)$ = 31.185, p = .092, RMSEA = .042, 90% CI [.000, .074], CFI = .994, SRMR = .025 (see Section 3.1 of the supplementary material).

Although the content of the RAN tasks differed between preschool and first grade, the contribution of RAN was substantial in both models. To check whether the task differences had an effect on the patterns in our findings, we also fitted a model with a nonalphanumeric RAN predictor from first grade. Given that the patterns remained stable, we can infer that variations in task content do not lead to different results (see Section 3.2 of the supplementary material for script and output).

So far, the analyses have established that RAN measured in either preschool or Grade 1 predicts reading and arithmetic fluency in Grade 3; the prediction from preschool is stronger for reading fluency, requiring an additional direct path, whereas the prediction from Grade 1 concerns shared variance only.

Do other cognitive abilities account for the relationship between RAN and fluency?

In the next step, we aimed to identify which additional variables, beyond RAN, predict reading and arithmetic fluency. To maximize the potential for identifying significant predictors, we temporarily dropped the latent factor modeling shared fluency variance and we tested full models for each set of predictors, with reading fluency and arithmetic fluency as separate latent factors. This was done to assess whether RAN, number knowledge, working memory, letter knowledge, speed of processing, and phoneme awareness could predict reading fluency, arithmetic fluency, or both when entered unrestricted. Variables predicting both types of fluency would be likely candidates to predict their covariance. We then proceeded to exclude nonsignificant paths one by one in a stepwise fashion to arrive at a model including all necessary predictors of each fluency domain.

Preschool predictors of third-grade reading and arithmetic fluency

In the preschool model, all predictors with the exception of RAN were entered as directly observed variables because there was a limited number of measures available from the preschool testing period. This model had acceptable fit, $\chi^2(52)$ = 70.462, p = .045, RMSEA = .039, 90% CI [.006, .061], CFI = .991, SRMR = .039. Stepwise removal of nonsignificant paths confirmed that only RAN significantly predicted variance in both fluency outcomes, making RAN the only likely candidate to explain shared fluency variance. The reduced model had acceptable fit, $\chi^2(58)$ = 79.343, p = .033, RMSEA = .040, 90% CI [.012, .060], CFI = .989, SRMR = .031, and was not significantly worse than the one with all predictor paths included, $\chi^2(6)$ = 8.882, p = .180 (see Section 4.1 of the supplementary material.)

This model showed that the longitudinal relations between nonalphanumeric RAN and reading fluency and arithmetic fluency were not preempted by other variables. Reading fluency was significantly predicted by RAN and letter knowledge, whereas arithmetic fluency was predicted by RAN, working memory, number knowledge, and speed of processing. Notably, phoneme isolation did not account for any variance so long as letter knowledge remained in the model. Therefore, phoneme isolation was removed from the model (see Sections 5.1.1 and 5.1.2 of the supplementary material).

Having ascertained which variables predict each fluency domain, a final preschool model was specified in which variance in reading fluency and arithmetic fluency was split into shared and nonshared components by (a) reintroducing the covariance factor and (b) adding latent factors for nonshared (residual) variance. The resulting model is shown in Fig. 1 (see Section 7.1 of the supplementary material for model specification and full output). The model had good fit, $\chi^2(52)$ = 66.197, p = .089, RMSEA = .034, 90% CI [.000, .057], CFI = .992, SRMR = .030. RAN predicted both shared variance

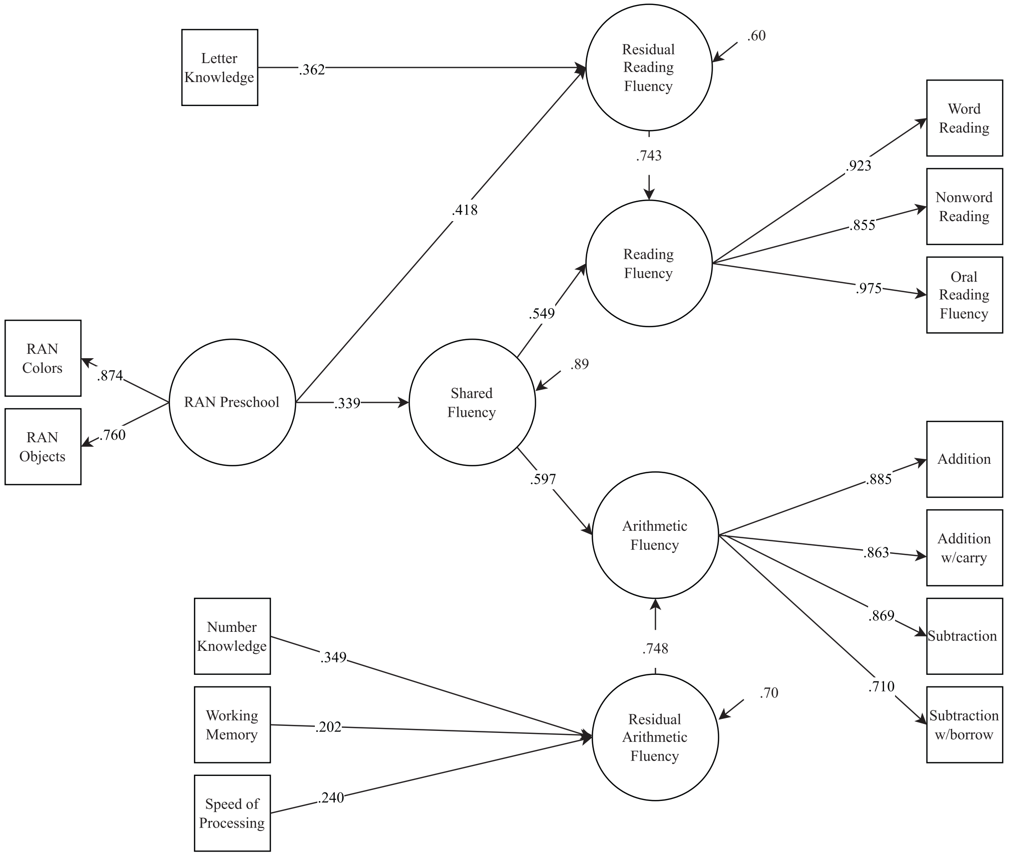

Fig. 1. Structural equation path model with preschool predictors. The structural equation model shows the longitudinal relations between preschool predictors (rapid automatized naming [RAN], letter knowledge, number knowledge, working memory, and speed of processing) and third-grade reading fluency and arithmetic fluency. Single-headed arrows between the variables (circles) are standardized regression coefficients. Arrows pointing from latent variables to observed variables (squares) are standardized factor loadings. Numbers with arrows pointing toward latent variables are standardized residual variances.

(β = .339, p = .019, accounting for 11.5%) and nonshared variance (β = .418, p < .001) in reading fluency. Nonshared variance in reading fluency was further predicted by letter knowledge (β = .362, p < .001), whereas nonshared variance in arithmetic fluency was predicted by working memory (β = .202, p = .015), number knowledge (β = .349, p < .001), and speed of processing (β = .240, p = .003). The predictors accounted for 39.6% of nonshared variance in reading fluency and 29.6% of nonshared variance in arithmetic fluency.

First-grade predictors of third-grade reading and arithmetic fluency

The same procedure was followed with first-grade predictors. However, in contrast to the preschool predictor model, we were able to estimate latent factors for phoneme awareness (with two measures of phoneme deletion as indicators) and number knowledge (with two indicators, namely number identification and number naming). The initial full model allowed predictors to predict variance in the two fluency outcomes without modeled covariation. This model had acceptable fit, $\chi^2(69)$ = 99.234, p = .010, RMSEA = .043, 90% CI [.022, .062], CFI = .987, SRMR = .026 (see Section 4.2

of the supplementary material). Again, RAN was the only significant predictor of both fluency outcomes, making it the only likely candidate to predict shared variance.

The model was reduced by stepwise removal of nonsignificant paths. The reduced model had acceptable fit, $\chi^2(74) = 103.774$, $p = .013$, RMSEA = .042, 90% CI [.020, .059], CFI = .988, SRMR = .030, and was not significantly worse than the one with all predictor paths included, $\chi^2(5) = 4.541$, $p = .475$) (see Section 6.2 of the supplementary material). Variance in reading fluency and arithmetic fluency was then split into shared and nonshared portions by reintroducing the covariance factor and adding factors for residual variance of these two fluency outcomes. The final Grade 1 model is shown in Fig. 2 (and in full detail in Section 7.2 of the supplementary material). This model had acceptable fit, $\chi^2(65) = 88.497$, $p = .028$, RMSEA = .039, 90% CI [.014, .059], CFI = .990, SRMR = .031. RAN provided a sizable prediction of shared variance ($\beta = .707$, $p < .001$, accounting for 50%), suggesting that Grade 1 RAN performance is related to whatever processes overlap between Grade 3 reading and arithmetic fluency. In addition, reading fluency was significantly predicted by phoneme awareness ($\beta = .320$, $p = .003$), whereas arithmetic fluency was predicted by number knowledge ($\beta = .597$, $p < .001$) and speed of processing ($\beta = .181$, $p = .014$). The predictors accounted for 10% of nonshared variance in reading fluency and 42.7% of nonshared variance in arithmetic fluency.

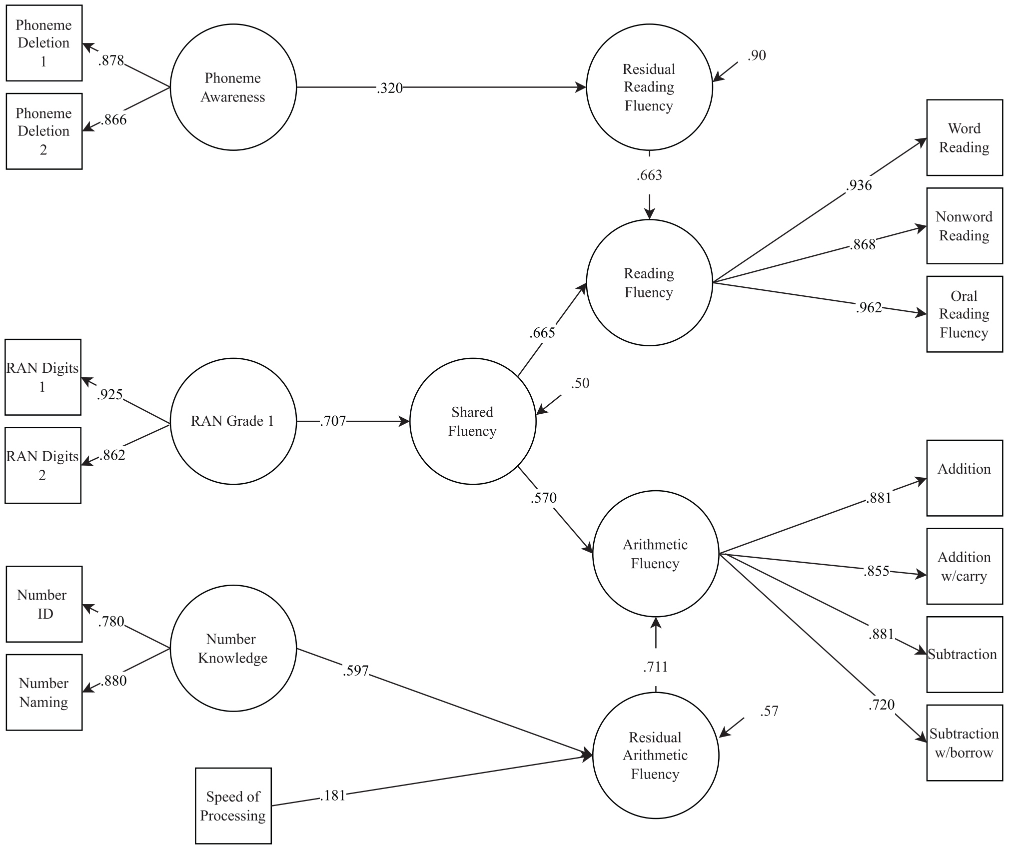

Fig. 2. Structural equation path model with Grade 1 predictors. The structural equation model shows the longitudinal relations between first-grade predictors (rapid automatized naming [RAN], phoneme awareness, number knowledge, and speed of processing) and third-grade reading and arithmetic fluency. Single-headed arrows between the latent variables (circles) are standardized regression coefficients. Arrows pointing from latent variables to observed variables (squares) are standardized factor loadings. Numbers with arrows pointing toward latent variables are standardized residual variances.

Discussion

The purpose of this study was to (1) examine how RAN in preschool and first grade relates to the shared versus nonshared variance in arithmetic fluency and reading fluency in third grade and (2) examine whether related processing skills (phoneme awareness, working memory, processing speed, and symbol knowledge) can account for the relationship between RAN and shared fluency or, instead, predict separable variance in the two fluency outcomes.

In both final models (i.e., with preschool and Grade 1 predictors), the prediction of shared fluency variance by RAN was reduced compared with the corresponding models in which RAN was the only predictor but remained substantial and significant. Both models fit well without the need for paths from other predictors to shared fluency. In the context of the entire modeling procedure described above (and fully documented in the supplementary material), this finding allows us to conclude that the prediction of shared variance in reading and arithmetic fluency by RAN cannot be accounted for by these theoretically motivated predictors taken together. In other words, the prediction by RAN is not fully mediated by these predictors and therefore warrants special attention and explanation.

In particular, the analyses led to several important findings: First, RAN in both preschool and Grade 1 is a moderately strong predictor of shared variance between reading fluency and arithmetic fluency measured in Grade 3. In addition, preschool RAN (but not Grade 1 RAN) predicts Grade 3 reading fluency more strongly than arithmetic fluency. Second, RAN's prediction was not accounted for by phoneme awareness, working memory, processing speed, or symbol knowledge. This is supported by two pieces of evidence. First, none of the variables besides RAN predicted both reading and arithmetic fluency; instead, they seem to be mainly related to nonshared variance in the fluency outcomes. Second, as noted above, RAN remained a strong and significant longitudinal predictor of shared fluency variance with all variables included in the model. This is particularly interesting given that each of these control variables was selected because of its theoretical potential to explain some of RAN's relation to the overlap between reading and arithmetic fluency.

Our findings suggest that there is something unique captured in early RAN task performance that is also required in fluent reading and arithmetic at an age when these skills are thought to largely rely on automatized processes. The results are in line with other studies identifying RAN as a predictor of shared fluency (Georgiou et al., 2021; Koponen et al., 2007, 2016, 2017; Korpipää et al., 2017) as well a recent investigation showing that children with low fluency in both reading and arithmetic also exhibit low performance on rapid automatized naming tasks across the primary school years (Pulkkinen et al., 2022)

Predicting third-grade reading and arithmetic fluency with preschool versus first-grade predictors

The contribution of RAN to Grade 3 fluency is sizable in both models despite the different RAN content; namely nonalphanumeric in preschool versus alphanumeric in Grade 1. We were able to confirm that such content differences have essentially no effect on the pattern of findings by fitting a model using nonalphanumeric RAN predictors from Grade 1 (see script and output in Section 7.2.4 of the supplementary material). In sum, these findings echo previous conclusions on the consistency of RAN as a longitudinal predictor of subsequent reading and mathematics fluency (Georgiou et al., 2020; Pulkkinen et al., 2022).

In the model with Grade 1 predictors, the relationship of RAN with reading and arithmetic fluency is fully accounted for by a single path between RAN and the shared portion of the two fluency outcomes. In contrast, in the model using preschool predictors, RAN was related to reading fluency through an additional direct path beyond the shared variance. This indicates that preschool RAN is more closely associated with future reading fluency development than it is with future arithmetic fluency development, whereas by first grade RAN performance (either alphanumeric or nonalphanumeric) is about equally aligned with fluency development in the two domains. In other words, there seems to be a qualitative change in the performance of RAN tasks between preschool and Grade 1 that makes RAN less reading specific and more fluency general. This structural difference was associated with a quantitative difference; in the model with preschool predictors the proportion of Grade 3 shared fluency variance (R^2) accounted for by RAN was only 11.5%, whereas in the model with Grade 1 predictors it was 50% with nonalphanumeric RAN and 61% with alphanumeric RAN.

Some differences between the models might be explained by formal literacy and numeracy instruction commencing in Grade 1. For instance, Grade 1 number knowledge might explain more of arithmetic fluency in Grade 3 given that it now reflects an ability more closely resembling the outcome it predicts, a pattern that has previously been found for alphanumeric RAN and reading ability (Norton & Wolf, 2012). Similarly, the heightened role of phoneme awareness might reflect gains in this ability due to literacy instruction, altering the distribution to reflect children's capacity to perform the skill more closely while removing variance caused by lack of experience. However, it should be noted that no competing task was administered in Grade 1 because letter knowledge would have been at ceiling. Thus, the apparent importance of phoneme awareness for reading fluency may simply reflect the lack of tasks more closely related to reading.

How do phoneme awareness, working memory, processing speed, and symbol knowledge relate to RAN and shared versus unique fluency?

Whereas RAN predicted the shared fluency variance in both models after controlling for other predictors, none of the other (theoretically important) predictors accounted for shared fluency variance, although most accounted for some nonshared variance in either reading or arithmetic fluency. In this context, the limited contribution of phoneme awareness is noteworthy. In the model with preschool predictors, phoneme awareness and letter knowledge seemed to account for the same variance in reading fluency, leading to phoneme awareness being removed from the final model. Other studies have also found a limited contribution of phoneme awareness once letter knowledge and RAN are considered, at least in transparent orthographies (e.g., Koponen et al., 2013; Zugarramurdi et al., 2022).

Our findings do not mean that preschool phoneme awareness is unrelated to the fluency outcomes but rather that its relationship is subsumed by letter knowledge and therefore its inclusion in this model is unnecessary. Nevertheless, this rules out the possibility that reliance on phoneme awareness can explain the shared variance among fluency outcomes. A similar tendency is visible in the Grade 1 model, where phoneme awareness is specifically related to what is unique in reading fluency rather than to the overlap of fluency between the two domains. Again, phoneme awareness failed to account for the relation between RAN and the shared fluency variance. This finding challenges the notion that fluency mainly relies on the type of retrieval of verbal codes that is involved in tests of phoneme awareness. Such tasks typically require respondents to identify or remove phonemes from auditory stimuli. Instead, the underlying driver may be related to the ability to efficiently activate multiple successive visual–verbal associations, which is required in reading fluency, arithmetic fluency, and RAN, as described by Koponen et al. (2007) and Lervåg and Hulme (2009), among others.

Turning to the other domain-general predictors, working memory showed a relation only to arithmetic fluency, which resembles the pattern observed by Georgiou et al. (2021). However, we found this relation in the model only using preschool measures of working memory skills. This may suggest that increases in number knowledge due to formal numeracy instruction make working memory redundant as a predictor. Still, our measure of working memory did not relate to the covariance of fluency, suggesting that similarities in terms of working memory demands, at least when measured with a backward digit span task, are not responsible for the fluency overlap. This is in contrast to previous findings showing that working memory measured with a backward digit span test predicts the covariation between reading and arithmetic, as in Korpipää et al. (2017). A notable difference between these findings is that Korpipää et al. (2017) found working memory to predict time-invariant covariation between reading and arithmetic fluency rather than time-specific covariation as assessed here. The inconsistent conclusions suggest that the importance of working memory for processes that are unique to and common between arithmetic and reading across development needs further examination.

Speed of processing explained a modest portion of residual variance in arithmetic fluency but no shared fluency variance. This finding diverges from studies (e.g., Georgiou et al., 2021; Koponen et al., 2020) that found speed of processing to explain shared variance between reading and arithmetic. This difference might be attributable to the shorter timespan between predictor and outcome measurement (~6 months in both studies) compared with our 2- to 3-year span. Furthermore, both Georgiou et al. (2021) and Koponen et al. (2020) predicted shared variance in their models that was more aligned with arithmetic than with reading fluency. This means that the shared variance they were predicting might be more closely related to speed of processing given that the shared variance has more in common with arithmetic fluency than with reading fluency. Because speed of processing did not account for any part of the relationship between RAN and the two fluency outcomes in our data, this suggests that generic method variance associated with time-pressured tasks is not a probable explanation for the prediction of shared fluency variance by RAN.

Our findings provide an answer to the question regarding the importance of symbol knowledge for RAN tasks. Number knowledge in both preschool and Grade 1 was found to predict arithmetic fluency, in line with our expectations that having functional number knowledge is an essential part of arithmetic ability. However, number knowledge did not predict shared variance of reading and arithmetic fluency, consistent with the finding of Koponen et al. (2020) using number writing. Interestingly, we found no evidence that number knowledge mediated the prediction of arithmetic fluency made by digit RAN (in the Grade 1 model). This suggests that the relationship between number naming and fluency outcomes is not due to symbol naming accuracy. Likewise, letter knowledge in preschool was only associated with fluency variance unique to reading and did not appear to mediate the prediction of reading fluency by RAN.

Moreover, the role of letter and number knowledge was the same regardless of whether alphanumeric or nonalphanumeric RAN was used in the models with Grade 1 predictors (cf. model outputs in Sections 7.2.1 and 7.2.4 of the supplementary material). Together, these results indicate that symbol knowledge, which is clearly required for alphanumeric RAN tasks as well as for reading and arithmetic outcomes, cannot be the central factor underlying the relationship between RAN in Grade 1 and shared fluency variance across the domains of mathematics and reading measured 2 years later. This is consistent with studies that emphasize the predictive value of RAN tasks in both reading and arithmetic fluency regardless of stimuli used (Hornung et al., 2017), again pointing to the central importance of the efficiency of successive visual–verbal associations.

In sum, by assessing RAN's prediction of shared fluency while controlling for other cognitive skills—which we found to predict nonshared aspects of reading and arithmetic—we extend the findings from previous studies showing the specific nature of RAN's effects on fluency outcomes (Georgiou et al., 2020).

Explaining the relationship of RAN and the fluency overlap

One possible explanation for why RAN predicts reading and arithmetic fluency could be that all of them rely on coordination of underlying abilities. Such similarities in "orchestration" have been suggested to explain why RAN tasks are related to reading and, furthermore, why no mediating ability has been found to explain the RAN–reading relationship (Norton & Wolf, 2012). Therefore, our finding that RAN tasks are mainly related to what is common between reading and arithmetic could mean that if RAN and reading overlap due to demands for coordination, the same relationship might extend to arithmetic. This would mean that the relationship among RAN, reading fluency, and arithmetic fluency is at least partly due to reliance on similar cognitive mechanisms of coordinating underlying processes. Such underlying processes involving (for instance) working memory, speed of processing, and phonological processing might still be important to some extent, but fluency might ultimately rely on the ability of these processes to function in unison. This might involve coordination of a subset of shared component processes; alternatively, these subprocesses themselves might not necessarily be shared, but fluency in both domains may rely on common mechanisms of coordination. The orchestration approach is also compatible with the proposal that it is the efficiency of multiple successive visual–verbal associations that is of central importance for understanding the RAN–fluency connection. In this case, it is not about the coordination of domain-general processes but, rather, is about that of task-specific processes involved in mapping visual inputs to verbal—or phonologically mediated—outputs.

In their investigation of shared fluency in reading and arithmetic in Finnish second graders, Koponen et al (2020) found that a serial retrieval fluency component, composed of RAN and speeded verbal counting, explained a substantial portion of the shared fluency factor. They proposed that this finding could reflect similar cascaded processing mechanisms not only in efficient reading but also in fluent arithmetic. Although the current study did not include speeded verbal measures to test this idea directly, our Grade 3 outcome measures limit the plausibility of this explanation. In particular, it is doubtful that third-grade arithmetic problems are automatized to the extent that full problems are read out as single units, analogous to the automatized reading of words "by sight."

A further complicating factor concerns the role of expressive verbal processes. Studies using variations of RAN tasks with alternative response modes have suggested that neither serial processing nor articulation per se is what drives the relationship with reading; rather, it seems that sequentially mapping each item to its phonological representation may be the critical component (Georgiou et al., 2013). In our study, both the RAN and reading tasks required verbal responses. In contrast, arithmetic fluency was measured with a silent written task, which does not require oral production but presumably requires decoding of the numerical symbols and rapid mapping to their phonological forms as a prerequisite to verbal retrieval of the memorized operation. The need for sequential phonological mapping and its efficient coordination with receptive and expressive processes thus could constitute the common procedural substrate underlying the shared variance between reading and arithmetic fluency and its relationship to RAN.

Limitations and concluding remarks

This study revealed that RAN is a strong predictor of the shared variance of reading fluency and arithmetic fluency. This indicates that the relationship between reading fluency and arithmetic fluency in Grade 3 is at least partly due to processes present in RAN performance in Grade 1 and, to some extent, even in preschool. The explanation of this overlap in fluency outcomes and its prediction by early RAN remains uncertain, but we found that it cannot be accounted for by similar reliance on phoneme awareness, speed of processing, working memory, or letter and number knowledge.

We believe our study to be a particularly strong contribution because of the reliance on latent variables for fluency outcomes and RAN in a structural equation modeling approach. This diminishes the potentially distorting effects of measurement noise, particularly when it comes to controlling for confounding constructs, in comparison with more commonly used multiple regression approaches (Westfall & Yarkoni, 2016). Still, our study remains limited by a moderate sample size and by the limited number of indicators for our constructs, especially in our preschool models, where confounding variables were directly observed rather than multiply indicated latent factors. In regard to the inclusion of relevant variables, previous studies have found that counting predicted shared fluency variance (Georgiou et al., 2021; Koponen et al., 2013, 2016, 2020; Korpipää et al., 2017). In our project, as in Georgiou et al. (2021), the counting variable measured in preschool exhibited severe ceiling effects and therefore could not be used.

In addition, it is not clear whether the findings from this study can be generalized to other languages, orthographies, and educational systems. Norwegian is a Germanic language with an alphabetic, relatively transparent orthography, quite a bit more consistent than English but a lot less consistent than Finnish—two languages in which similar topics have been investigated (Georgiou et al., 2021; Koponen et al., 2020). Moreover, many children in Norway enter first grade without any functional literacy because there is no literacy instruction in preschool. This allows us, on the one hand, to be more confident in our school predictors being "pre-literacy" but, on the other, may render the findings less comparable with those from countries where children at preschool ages have already received substantial literacy instruction.

In this study, we measured predictors before and right after our sample had begun formal literacy and numeracy training. We found that there is little distinction between alphanumeric and nonalphanumeric RAN in how they relate to the fluency outcomes. However, we cannot rule out that this pattern is limited to a specific developmental window. At a later stage, the two types of RAN might be less related, leading to the familiar pattern of alphanumeric RAN predicting reading fluency beyond nonalphanumeric RAN.

The predictors—apart from RAN—were only related to residual nonshared variance in reading and arithmetic fluency. Thus, the results of the current investigation suggest that a number of proposed predictors have less relevance than theoretically expected when it comes to explaining what is shared between fluent reading and arithmetic. Our study highlights the need to investigate the processes underlying performance in rapid naming tasks as a potential avenue for understanding the cognitive substrate of both reading and arithmetic fluency.

Funding

This work was supported by the The Research Council of Norway, Research Grant: 283586; Development of numeracy and literacy: Influence from cognitive skills, social background and gender.

Data availability

We have shared a link to the data, data preparation and code for all analyses at the 'Attach Files' step

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jecp.2023.105656.

References

Altani, A., Protopapas, A., Katopodi, K., & Georgiou, G. K. (2020). From individual word recognition to word list and text reading fluency. *Journal of Educational Psychology, 112*(1), 22–39. https://doi.org/10.1037/edu0000359.

Araújo, S., Reis, A., Petersson, K. M., & Faísca, L. (2014). Rapid automatized naming and reading performance: A meta-analysis. *Journal of Educational Psychology, 107*(3), 868–883. https://doi.org/10.1037/edu0000006.

Arnesen, A., Braeken, J., Baker, S., Meek-Hansen, W., Ogden, T., & Melby-Lervåg, M. (2017). Growth in oral reading fluency in a semitransparent orthography: Concurrent and predictive relations with reading proficiency in Norwegian, Grades 2–5. *Reading Research Quarterly, 52*(2), 177–201. https://doi.org/10.1002/rrq.159.

Balhinez, R., & Shaul, S. (2019). The relationship between reading fluency and arithmetic fact fluency and their shared cognitive skills: A developmental perspective. *Frontiers in Psychology, 10*. https://doi.org/10.3389/fpsyg.2019.01281 1281.

Bowey, J. A. (2005). Predicting individual differences in learning to read. In M. J. Snowling & C. Hulme (Eds.), *The science of reading: A handbook* (pp. 155–172). Blackwell.

Brigstocke, S., Moll, K., & Hulme, C. (2016). *Test of Basic Arithmetic and Numeracy Skills*. Oxford University Press.

Carr, M., & Alexeev, N. (2011). Fluency, accuracy, and gender predict developmental trajectories of arithmetic strategies. *Journal of Educational Psychology, 103*(3), 617–631. https://doi.org/10.1037/a0023864.

Cirino, P. T., Child, A. E., & Macdonald, K. T. (2018). Longitudinal predictors of the overlap between reading and math skills. *Contemporary Educational Psychology, 54*, 99–111. https://doi.org/10.1016/j.cedpsych.2018.06.002.

Clayton, F. J., West, G., Sears, C., Hulme, C., & Lervåg, A. (2020). A longitudinal study of early reading development: Letter-sound knowledge, phoneme awareness and RAN, but not letter-sound integration, predict variations in reading development. *Scientific Studies of Reading, 24*(2), 91–107. https://doi.org/10.1080/10888438.2019.1622546.

de Jong, P. F., & van der Leij, A. (1999). Specific contributions of phonological abilities to early reading acquisition: Results from a Dutch latent variable longitudinal study. *Journal of Educational Psychology, 91*(3), 450–476. https://doi.org/10.1037/0022-0663.91.3.450.

Dehaene, S., Piazza, M., Pinel, P., & Cohen, L. (2003). Three parietal circuits for number processing. *Cognitive Neuropsychology, 20*(3–6), 487–506. https://doi.org/10.1080/02643290244000239.

Diamanti, V., Goulandris, N., Campbell, R., & Protopapas, A. (2018). Dyslexia profiles across orthographies differing in transparency: An evaluation of theoretical predictions contrasting English and Greek. *Scientific Studies of Reading, 22*(1), 55–69. https://doi.org/10.1080/10888438.2017.1338291.

Dowker, A. (2014). Young children's use of derived fact strategies for addition and subtraction. *Frontiers in Human Neuroscience, 7*. https://doi.org/10.3389/fnhum.2013.00924 924.

Ehri, L. C. (2005). Learning to read words: Theory, findings, and issues. *Scientific Studies of Reading, 9*(2), 167–188. https://doi.org/10.1207/s1532799xssr0902_4.

Ehri, L. C. (2014). Orthographic mapping in the acquisition of sight word reading, spelling memory, and vocabulary learning. *Scientific Studies of Reading, 18*(1), 5–21. https://doi.org/10.1080/10888438.2013.819356.

Fuchs, L. S., Geary, D. C., Fuchs, D., Compton, D. L., & Hamlett, C. L. (2016). Pathways to third-grade calculation versus word-reading competence: Are they more alike or different? *Child Development, 87*(2), 558–567. https://doi.org/10.1111/cdev.12474.

Furnes, B., & Samuelsson, S. (2011). Phonological awareness and rapid automatized naming predicting early development in reading and spelling: Results from a cross-linguistic longitudinal study. *Learning and Individual Differences, 21*(1), 85–95. https://doi.org/10.1016/j.lindif.2010.10.005.

Geary, D. C., Hoard, M. K., & Bailey, D. H. (2012). Fact retrieval deficits in low achieving children and children with mathematical learning disability. *Journal of Learning Disabilities, 45*(4), 291–307. https://doi.org/10.1177/0022219410392046.

Georgiou, G. K., Inoue, T., & Parrila, R. (2021). Do reading and arithmetic fluency share the same cognitive base? *Frontiers in Psychology, 12*. https://doi.org/10.3389/fpsyg.2021.709448 709448.

Georgiou, G. K., & Parrila, R. (2020). What mechanism underlies the rapid automatized naming–reading relation? *Journal of Experimental Child Psychology, 194*. https://doi.org/10.1016/j.jecp.2020.104840 104840.

Georgiou, G. K., Tziraki, N., Manolitsis, G., & Fella, A. (2013). Is rapid automatized naming related to reading and mathematics for the same reason(s)? A follow-up study from kindergarten to Grade 1. *Journal of Experimental Child Psychology, 115*(3), 481–496. https://doi.org/10.1016/j.jecp.2013.01.004.

Georgiou, G. K., Wei, W., Inoue, T., & Deng, C. (2020). Are the relations of rapid automatized naming with reading and mathematics accuracy and fluency bidirectional? Evidence from a 5-year longitudinal study with Chinese children. *Journal of Educational Psychology, 112*(8), 1506–1520. https://doi.org/10.1037/edu0000452.

Gilmore, C., Göbel, S. M., & Inglis, M. (2018). *An introduction to mathematical cognition*. Routledge: Taylor & Francis Group.

Göbel, S. M., Watson, S. E., Lervåg, A., & Hulme, C. (2014). Children's arithmetic development: It is number knowledge, not the approximate number sense, that counts. *Psychological Science, 25*(3), 789–798. https://doi.org/10.1177/0956797613516471.

Good, R. H., & Kaminski, R. A. (2002). *DIBELS oral reading fluency passages for first through third grades (Technical Report No. 10)*. University of Oregon.

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

Juul, H., Poulsen, M., & Elbro, C. (2014). Separating speed from accuracy in beginning reading development. *Journal of Educational Psychology, 106*(4), 1096–1106. https://doi.org/10.1037/a0037100.

Kail, R., & Hall, L. K. (1994). Processing speed, naming speed, and reading. *Developmental Psychology, 30*(6), 949–954. https://doi.org/10.1037/0012-1649.30.6.949.

Kail, R., Hall, L. K., & Caskey, B. J. (1999). Processing speed, exposure to print, and naming speed. *Applied Psycholinguistics, 20*(2), 303–314. https://doi.org/10.1017/S0142716499002076.

Kaminski, R. A., Smith, S., & Laimon, S. (2002). *Dynamic Indicators of Basic Early Literacy Skills: DIBELS*. Dynamic Measurement. *Group*.

Kim, Y.-S. (2015). Developmental, component-based model of reading fluency: An investigation of predictors of word-reading fluency, text-reading fluency, and reading comprehension. *Reading Research Quarterly, 50*(4), 459–481. https://doi.org/10.1002/rrq.107.

Koponen, T., Aunola, K., Ahonen, T., & Nurmi, J.-E. (2007). Cognitive predictors of single-digit and procedural calculation skills and their covariation with reading skill. *Journal of Experimental Child Psychology, 97*(3), 220–241. https://doi.org/10.1016/j.jecp.2007.03.001.

Koponen, T., Eklund, K., Heikkilä, R., Salminen, J., Fuchs, L., Fuchs, D., & Aro, M. (2020). Cognitive correlates of the covariance in reading and arithmetic fluency: Importance of serial retrieval fluency. *Child Development, 91*(4), 1063–1080. https://doi.org/10.1111/cdev.13287.

Koponen, T., Georgiou, G., Salmi, P., Leskinen, M., & Aro, M. (2017). A meta-analysis of the relation between RAN and mathematics. *Journal of Educational Psychology, 109*(7), 977–992. https://doi.org/10.1037/edu0000182.

Koponen, T., Salmi, P., Eklund, K., & Aro, T. (2013). Counting and RAN: Predictors of arithmetic calculation and reading fluency. *Journal of Educational Psychology, 105*(1), 162–175. https://doi.org/10.1037/a0029285.

Koponen, T., Salmi, P., Torppa, M., Eklund, K., Aro, T., Aro, M., Poikkeus, A.-M., Lerkkanen, M.-K., & Nurmi, J.-E. (2016). Counting and rapid naming predict the fluency of arithmetic and reading skills. *Contemporary Educational Psychology, 44–45*, 83–94. https://doi.org/10.1016/j.cedpsych.2016.02.004.

Korpipää, H., Koponen, T., Aro, M., Tolvanen, A., Aunola, K., Poikkeus, A.-M., Lerkkanen, M.-K., & Nurmi, J.-E. (2017). Covariation between reading and arithmetic skills from Grade 1 to Grade 7. *Contemporary Educational Psychology, 51*, 131–140. https://doi.org/10.1016/j.cedpsych.2017.06.005.

Kuhn, M. R., Schwanenflugel, P. J., Meisinger, E. B., Levy, B. A., & Rasinski, T. V. (2010). Aligning theory and assessment of reading fluency: Automaticity, prosody, and definitions of fluency. *Reading Research Quarterly, 45*(2), 230–251. https://doi.org/10.1598/RRQ.45.2.4.

Landerl, K., Freudenthaler, H. H., Heene, M., De Jong, P. F., Desrochers, A., Manolitsis, G., Parrila, R., & Georgiou, G. K. (2019). Phonological awareness and rapid automatized naming as longitudinal predictors of reading in five alphabetic orthographies with varying degrees of consistency. *Scientific Studies of Reading, 23*(3), 220–234. https://doi.org/10.1080/10888438.2018.1510936.

Landerl, K., & Moll, K. (2010). Comorbidity of learning disorders: Prevalence and familial transmission. *Journal of Child Psychology and Psychiatry and Allied Disciplines, 51*(3), 287–294. https://doi.org/10.1111/j.1469-7610.2009.02164.x.

Landerl, K., & Wimmer, H. (2008). Development of word reading fluency and spelling in a consistent orthography: An 8-year follow-up. *Journal of Educational Psychology, 100*(1), 150–161. https://doi.org/10.1037/0022-0663.100.1.150.

LeFevre, J.-A., Fast, L., Skwarchuk, S.-L., Smith-Chant, B. L., Bisanz, J., Kamawar, D., & Penner-Wilger, M. (2010). Pathways to mathematics: Longitudinal predictors of performance. *Child Development, 81*(6), 1753–1767. https://doi.org/10.1111/j.1467-8624.2010.01508.x.

Lervåg, A., & Hulme, C. (2009). Rapid automatized naming (RAN) taps a mechanism that places constraints on the development of early reading fluency. *Psychological Science, 20*(8), 1040–1048. https://doi.org/10.1111/j.1467-9280.2009.02405.x.

Malone, S. A., Heron-Delaney, M., Burgoyne, K., & Hulme, C. (2019). Learning correspondences between magnitudes, symbols and words: Evidence for a triple code model of arithmetic development. *Cognition, 187*, 1–9. https://doi.org/10.1016/j.cognition.2018.11.016.

Meyer, M. L., Salimpoor, V. N., Wu, S. S., Geary, D. C., & Menon, V. (2010). Differential contribution of specific working memory components to mathematics achievement in 2nd and 3rd graders. *Learning and Individual Differences, 20*(2), 101–109. https://doi.org/10.1016/j.lindif.2009.08.004.

Norton, E. S., & Wolf, M. (2012). Rapid automatized naming (RAN) and reading fluency: Implications for understanding and treatment of reading disabilities. *Annual Review of Psychology, 63*(1), 427–452. https://doi.org/10.1146/annurev-psych-120710-100431.

Poulsen, M., & Elbro, C. (2018). The short- and long-term predictions of reading accuracy and speed from paired-associate learning. *Journal of Experimental Child Psychology, 174*, 77–89. https://doi.org/10.1016/j.jecp.2018.05.007.

Powell, D., & Atkinson, L. (2020). Unraveling the links between rapid automatized naming (RAN), phonological awareness, and reading. *Journal of Educational Psychology, 113*(4), 706–718. https://doi.org/10.1037/edu0000625.

Pulkkinen, J., Eklund, K., Koponen, T., Heikkilä, R., Georgiou, G., Salminen, J., van Daal, V., & Aro, M. (2022). Cognitive skills, self-beliefs and task interest in children with low reading and/or arithmetic fluency. *Learning and Individual Differences, 97*. https://doi.org/10.1016/j.lindif.2022.102160 102160.

Purpura, D. J., Hume, L. E., Sims, D. M., & Lonigan, C. J. (2011). Early literacy and early numeracy: The value of including early literacy skills in the prediction of numeracy development. *Journal of Experimental Child Psychology, 110*(4), 647–658. https://doi.org/10.1016/j.jecp.2011.07.004.

Qin, S., Cho, S., Chen, T., Rosenberg-Lee, M., Geary, D. C., & Menon, V. (2014). Hippocampal–neocortical functional reorganization underlies children's cognitive development. *Nature Neuroscience, 17*(9), 1263–1269. https://doi.org/10.1038/nn.3788.

Rinne, L. F., Ye, A., & Jordan, N. C. (2020). Development of arithmetic fluency: A direct effect of reading fluency? *Journal of Educational Psychology, 112*(1), 110–130. https://doi.org/10.1037/edu0000362.

Schwanenflugel, P. J., & Knapp, N. F. (2016). *The psychology of reading: Theory and applications*. Guilford.

Statistics Norway (2023). Educational attainment of the population, 7 March 2023. https://www.ssb.no/en/utdanning/utdanningsniva/statistikk/befolkningens-utdanningsniva.

Swanson, H. L., Zheng, X., & Jerman, O. (2009). Working memory, short-term memory, and reading disabilities: A selective meta-analysis of the literature. *Journal of Learning Disabilities, 42*(3), 260–287. https://doi.org/10.1177/0022219409331958.

Torgesen, J. K., Wagner, R. K., Rashotte, C. A., Rose, E., Lindamood, P., Conway, T., & Garvan, C. (1999). Preventing reading failure in young children with phonological processing disabilities: Group and individual responses to instruction. *Journal of Educational Psychology, 91*(4), 579–593. https://doi.org/10.1037/0022-0663.91.4.579.

Vanbinst, K., Ceulemans, E., Ghesquière, P., & De Smedt, B. (2015). Profiles of children's arithmetic fact development: A model-based clustering approach. *Journal of Experimental Child Psychology, 133*, 29–46. https://doi.org/10.1016/j.jecp.2015.01.003.

Vander Stappen, C., & Reybroeck, M. V. (2022). Relating phonological awareness and rapid automatized naming to phonological and orthographic processing of written words: Cross-sequential evidence from French. *Reading Research Quarterly, 57*(3), 1065–1083. https://doi.org/10.1002/rrq.461.

Wang, Y., Ye, X., & Deng, C. (2020). Exploring mechanisms of rapid automatized naming to arithmetic skills in Chinese primary schoolers. *Psychology in the Schools, 57*(4), 556–571. https://doi.org/10.1002/pits.22349.

Warmington, M., & Hulme, C. (2012). Phoneme awareness, visual–verbal paired-associate learning, and rapid automatized naming as predictors of individual differences in reading ability. *Scientific Studies of Reading, 16*(1), 45–62. https://doi.org/10.1080/10888438.2010.534832.

Westfall, J., & Yarkoni, T. (2016). Statistically controlling for confounding constructs is harder than you think. *PLoS One, 11*(3). https://doi.org/10.1371/journal.pone.0152719 e152719.

Wolf, M., & Bowers, P. G. (1999). The double-deficit hypothesis for the developmental dyslexias. *Journal of Educational Psychology, 91*(3), 415–438. https://doi.org/10.1037/0022-0663.91.3.415.

Zugarramurdi, C., Fernández, L., Lallier, M., Valle-Lisboa, J. C., & Carreiras, M. (2022). Mind the orthography: Revisiting the contribution of prereading phonological awareness to reading acquisition. *Developmental Psychology, 58*(6), 1003–1016. https://doi.org/10.1037/dev0001341.