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Early cognitive predictors of spelling and reading in German-speaking children

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Theoretical background: While reading and spelling skills often are interconnected in models of literacy development, recent research suggests that the two skills can dissociate and that reading and spelling are associated with at least partly different cognitive predictors. However, previous research on dissociations between reading and spelling skills focused on children who have already mastered the first phases of literacy development. These findings suggest that dissociations are due to distinct deficits in orthographic processing (i.e., unprecise orthographic representations vs. inefficient serial processing). It is therefore unclear whether dissociations already become apparent during the initial stages, or rather emerge later in development. This study aims to enhance the understanding of the predictors of early spelling and reading skills, investigating potential variations, by considering various cognitive factors beyond well-established ones.

Methods: Data were collected at two time points: cognitive predictors and early reading and spelling skills were assessed at the end of kindergarten (T1) before formal literacy instruction started, and reading and spelling skills were again assessed in Grade 1 (T2). The data analysis included 353 first-grade participants. Linear regression analyses assessed predictive patterns, while logistic regression analyses explained children's likelihood of belonging to different proficiency groups (at-risk or typical skills).

Results: Results revealed phonological processing, letter knowledge, and intelligence, as significant predictors for Spelling in grade 1 (T2), even after adding the autoregressor (Spelling in kindergarten at T1) and the respective other literacy skill (Reading T2). For Reading in grade 1 (T2), phonological processing, and rapid automatized naming (RAN) surfaced as significant predictors after adding the autoregressor (Reading T1). However, only RAN surfaced as a significant predictor for Reading T2 after adding the respective other literacy skill (Spelling T2). In line with these findings, logistic regression analyses revealed that phonological processing predicted group allocation for Spelling T2 and RAN predicted group allocation for Reading T2.

Conclusions: Overall, the study underscores the importance of phonological processing and letter knowledge as early predictors of spelling and reading skills in Grade 1. Moreover, intelligence is identified as a predictor for early spelling, while rapid automatized naming (RAN) emerges as a predictor for early reading.

KEYWORDS

spelling development, reading development, predictors, longitudinal, kindergarten, German orthography

1 Introduction

Mastering literacy skills is a crucial necessity for active participation in today's society. Children must accomplish two essential literacy skills in the initial years of literacy development: reading, which involves accurate and fluent word recognition, and spelling, which requires precisely transcribing words. Proficiency in these basic literacy skills forms the basis for more advanced literacy abilities, such as understanding and creating written content. Difficulties in acquiring spelling and reading skills are remarkable developmental hurdles, significantly impacting children's academic paths, career opportunities, and overall wellbeing (Carroll et al., 2005; Schulte-Körne, 2010; Ritchie et al., 2013). This is concerning, considering the diminished spelling proficiency observed in recent research conducted on German representative school samples. For instance, findings from the IGLU 2007 (Internationale Grundschul-Lese-Untersuchung [International reading assessment in primary schools]) indicate that only 80% of 4th graders were able to reliably apply spelling conventions expected to be mastered by the end of 2nd grade (Bos et al., 2007).

Numerous investigations have evidenced a strong correlation between reading and spelling skills (Ehri, 1986; Landerl and Wimmer, 2008; Caravolas et al., 2012). Spelling and reading in alphabetic orthographies rest upon understanding the alphabetic principle, mastering grapheme-phoneme correspondences for reading, along with phoneme-grapheme correspondences for spelling, and the ability to recognize, manipulate, and understand the individual phonemes (phoneme awareness). As expounded in influential developmental models by Ehri (1986) and Frith (1986), this signifies the alphabetic phase of literacy acquisition, enabling children to decode words for reading and break down spoken words into their constituent phonemes and pair them with the appropriate graphemes for spelling.

Nevertheless, spelling and reading skills do not always progress simultaneously, and deficits in spelling and reading can dissociate, resulting in poor spelling but adequate reading skills and vice versa (Frith, 1980; Wimmer and Mayringer, 2002; Moll and Landerl, 2009; Moll et al., 2020). Furthermore, research suggests that the cognitive predictors associated with spelling differ, to some extent, from those linked to reading (Wimmer et al., 2000; Cirino et al., 2005; Moll et al., 2014). This discrepancy is not only supported by empirical data but is also recognized within the classification systems of the ICD-11 (World Health Organization, 2022). Despite the distinct nature of these two literacy skills, previous research has predominantly focused on reading development and reading interventions, giving relatively limited attention to spelling (Treiman and Kessler, 2005). Furthermore, research directly comparing spelling and reading development in order to identify common as well as unique predictors is still rare. Previous research suggests that both spelling and reading proficiency advance in tandem during early literacy development and are heavily influenced by phonological processing skills and letter knowledge. As literacy development progresses, the acquisition of orthographic knowledge becomes pivotal for both spelling and reading. Based on findings in an orthographic learning experiment, Mehlhase et al. (2019) suggested that dissociations might occur as a consequence of distinct orthographic deficits. Isolated reading disorder is characterized by a deficiency in efficiently processing stored words despite a lack of deficit in storing orthographic representations. Conversely, isolated spelling disorder involves no deficit in efficient processing, but a deficit in storing orthographic representations, resulting in imprecise word representations and in turn many spelling errors. These imprecise representations are still sufficient for word recognition during reading, especially in relatively consistent orthographies like German which are characterized by high consistency between graphemes and phonemes. Compared to other languages like English, characterized by a vast number of syllables and high phonological complexity with simpler inflectional morphology, German exhibits medium phonological complexity, predominantly with closed syllables, and possesses rich derivation and inflectional morphology (Verhoeven and Perfetti, 2022). In contrast to reading, the relationship between phonemes and graphemes in the spelling direction is rather inconsistent in German, as in many other alphabetic orthographies. For instance, the long vowel/o:/in German can be represented in three different ways: "o" as in "Brot" (bread), "oo" as in "Boot" (boat), and "oh" as in "Sohn" (son). Correctly spelling such words demands children to progress beyond the alphabetic phase by forming word-specific representations in their long-term memory. Progression begins through the acquisition of metacognitive skills involving learning orthographic spelling rules and applying morphological principles (Steffler, 2001). As a result of the increasingly diverging mechanisms associated with spelling versus reading (problems), the hypothesis emerges, suggesting that the correlation between spelling and reading is more pronounced in early developmental phases but gradually diminishes as orthographic processing becomes more prominent in later stages of development. However, existing studies on dissociations related to spelling and reading have predominantly employed cross-sectional designs, with the majority conducted at a later stage of development, when children were in Grade 3 or beyond.

This study aims to fill this research gap by delving into the factors influencing early spelling and reading in Grade 1 within the specific context of German orthography. What sets this study apart is its distinctive approach, examining both spelling and reading at an early developmental stage, with a particular emphasis on spelling. This longitudinal study begins in kindergarten and extends through grade 1, allowing for a comprehensive assessment of early spelling and reading development. By assessing spelling and reading before formal literacy instruction starts and in Grade 1, predictive patterns for each skill in isolation can be examined (by controlling for the respective other literacy skill) and together, unraveling the impact of distinct predictors on spelling, reading, and both. Furthermore, the aim is to identify children at risk of spelling and/or reading problems in kindergarten, determining predictors that categorize them into either at-risk or typical proficiency groups in these skills. By integrating these approaches, the goal is to provide a holistic understanding of the intricate interplay between early spelling and reading.

In the following, the included predictors will be discussed in more detail. As mentioned before, the importance of phonological processing skills and grapheme-phoneme/phoneme-grapheme correspondence in spelling and reading proficiency is well-recognized. A third well-known predictor is rapid automatized naming (RAN), which turned out to be especially important for reading proficiency. However, there is a gap in studying additional cognitive factors that might be crucial to early literacy skills within a single study, especially in predicting early spelling proficiency. Thus, visual memory, and visual-spatial/graphomotor skills were included as they are hypothesized to contribute to different subskills of spelling proficiency such as the encoding of orthographic representations, precision and speed of letter formation, and understanding of intricate orthographic rules. Furthermore, intelligence was included as a control variable as it likely affects learning in general.

1.1 Phonological processing skills

The strongest and most consistently reported phonological predictor of literacy skills is phoneme awareness (i.e., the ability to identify and manipulate individual sounds) (phonemes) in spoken words. Numerous empirical studies underscore the robust relationship between phoneme awareness and literacy skills (Cataldo and Ellis, 1988; Landerl and Wimmer, 2008; Diamanti et al., 2017; Schmitterer and Schroeder, 2018), especially in the early phases of development (Babayigit and Stainthorp, 2010; Nielsen and Juul, 2016). The significance of phoneme awareness as a predictor of literacy skills transcends linguistic and writing system boundaries (Furnes and Samuelsson, 2009). Nevertheless, the direct contribution of phoneme awareness to reading may exhibit variability influenced by factors such as task characteristics, developmental stage, and orthographic complexity (Landerl et al., 2019). Therefore, the predictive power might diminish over time, especially in transparent orthographic systems (Landerl and Wimmer, 2000; Leppänen et al., 2006).

Another frequently assessed phonological skill is verbal/phonological memory, which involves the cognitive capacity to perceive and store verbal information, predominantly through the reception and encoding of speech stimuli, thus demonstrating a close connection to phoneme awareness. Indeed, many phoneme awareness tests also draw on verbal memory skills as they require to hold information in memory during manipulation of phonemes (e.g., phoneme deletion tests). Several studies have therefore investigated these two abilities jointly (Vellutino et al., 2004). Its role as an independent predictor appears to be somewhat limited. A large European study on developmental dyslexia suggested that verbal memory played a relatively minor role in predicting dyslexia status (Landerl et al., 2013). Similarly, a cross-linguistic analysis on cognitive mechanisms underlying reading and spelling development revealed verbal memory's relatively limited significance, however, it appears to carry more weight in spelling tasks compared to reading evaluations due to its critical role in storing word-specific knowledge (Moll et al., 2014). Compared to phoneme awareness, verbal memory generally plays a subordinate role (Ziegler et al., 2010; Caravolas et al., 2012).

Vowel length distinction has garnered less research attention, yet studies reveal its intricate relationship with literacy skills. A study by Post et al. (1999) explored the relationship between vowel perception and reading skill, finding a linear association between vowel identification errors and reading. However, in English orthography, the distinction among vowels encompasses not only variations in length but also involves differences in grapheme-phoneme-mapping (e.g., grapheme a: cat vs. car). In contrast, German vowels mainly vary in length, which can be marked in several ways (e.g., by doubling the vowel as in "Saal" hall). Still, there is an anticipation that vowel length distinction does influence reading, given that previous research has shown that German dyslexic children are impaired in phonological, temporal, and spectral vowel length distinction (Groth et al., 2011; Steinbrink et al., 2012, 2014). However, a more pronounced correlation between vowel length distinction and spelling is expected compared to reading, as careful attention to vowel length is essential for many spelling rules and in turn for orthographic spelling (e.g., if there is only one consonant sound after a short vowel the consonant is doubled. Examples are words like Hammer [hammer] and Schiff [ship]). A study involving German-speaking 10-year-old children revealed that the skill to differentiate vowel length was connected to accurately marking vowel length in spelling (Landerl, 2003). However, it still needs to be determined whether the association between vowel length distinction and spelling is already evident at the beginning of literacy instruction or rather emerges when orthographic processing becomes more prominent. Furthermore, studies assessing the role of vowel length distinction for both spelling and reading are still rare.

1.2 Letter knowledge

Extensive research conducted has spotlighted the importance of the alphabetic principle, which is firmly rooted in letter-sound knowledge (Caravolas et al., 2005; Otaiba et al., 2010; Byrne, 2014). These findings align with those of Caravolas et al. (2001) and Furnes and Samuelsson (2010), which highlight the role of letter knowledge as a predictor for both spelling and reading skills, elucidating its significance in explaining group differences between individuals with reading disorders and those with spelling disorders. Furthermore, several studies underscored the significance of letter knowledge as a prerequisite for early reading and/or spelling, emphasizing its role across various stages of literacy development (Ellis and Large, 1988; Lervåg and Hulme, 2010; Schmitterer and Schroeder, 2019). Additionally, studies showed that the influence of letter knowledge is evident in both consistent and inconsistent alphabetic orthographies (Ziegler et al., 2010; Moll et al., 2014).

1.3 Rapid automatized naming (RAN)

The role of rapid automatized naming (RAN) has garnered increasing attention, especially in the development of reading abilities. Numerous studies have demonstrated the predictive power of RAN on reading skills (Moll et al., 2009; Araújo et al., 2014; Papadopoulos et al., 2016; McWeeny et al., 2022). Especially in children at the kindergarten age, non-alphanumeric RAN is especially relevant, as not all children have acquired letter and number knowledge at this stage of development (Lervåg and Hulme, 2009). In both inconsistent and consistent orthographies, RAN has been linked to reading, and especially to reading fluency (Kirby et al., 2003). Mechanisms that are discussed to explain the RAN-reading relationship are verbal access and retrieval of stored information together with efficient serial processing (Protopapas et al., 2018). However, the role of RAN for spelling is less clear. While some studies have found that RAN predicts spelling skills, even after controlling for other variables like phonological awareness and letter-sound knowledge (Furnes and Samuelsson, 2010; Stainthorp et al., 2013), other studies have failed to establish a connection between RAN and early spelling development, especially in longitudinal studies (Landerl and Wimmer, 2008; Vaessen and Blomert, 2013). The inconsistent findings are likely to be due to the fact that the impact of RAN varies depending on factors such as orthographic consistency, the developmental stage, and linguistic characteristics.

In contrast to phonological processing skills, letter knowledge, and RAN, the impact of additional cognitive skills such as visual processing skills and intelligence on predicting literacy (i.e., reading) skills appear to be relatively restrained. While these factors might contribute to explaining variance beyond the primary predictors mentioned, their influence is generally modest, especially in the early stages of reading development. Nonetheless, these factors have the potential to impact spelling, by contributing to various subskills of spelling proficiency, including the encoding of orthographic representations, precision and speed in letter formation, understanding complex orthographic rules, hand-eye coordination, and spatial awareness. However, the extent to which these factors significantly affect spelling (and/or reading), and if so, whether noticeable effects already manifest early in literacy development, still needs to be determined.

1.4 Visual processing skills

Visual processing skills comprise a variety of constructs. With respect to literacy skills, the two constructs that have been predominantly mentioned to affect literacy skills are visual memory and visual-spatial skills.

While the role of *visual memory* for reading seems rather limited, a central question revolves around whether visual memory holds a more substantial role in spelling. This speculation arises from the notion that visual memory might be pivotal in encoding, storing, and retrieving orthographic representations, an important subskill of spelling. Limited research suggests that general working memory (Preßler et al., 2014), and visuo-spatial memory (Bourke et al., 2013) play a significant role in early spelling, over and above the influence of other predictors. Complementing this, Atkins and Tierney (2021) reveal that lower scores on auditory and visual sequential memory are linked to lower spelling and reading scores. However, Giles and Terrell (1997), find that visual memory does not differentiate between poor spellers and controls.

Existing research predominantly focused on visual attentional aspects rather than visual-spatial skills. These studies suggest that there is a predictive pattern between visual attentional skills and performance in spelling and/or reading, though the evidence is limited, and findings are mixed (Bosse and Valdois, 2009; Liu et al., 2016). In a study involving German children, Banfi et al. (2018) found no significant differences in visual attention among typically developing children, those with dyslexia, and those with isolated spelling deficits. Research of *visual-spatial skills* on the prediction of spelling and reading skills is comparatively small. This is unfortunate, given that visual-spatial skills may play a role at the beginning of literacy acquisition, when learners need to distinguish between visually similar yet distinct letters, such as/d/and/b/or/p/and/b/. These skills could impact the precision and speed of letter recognition influencing reading proficiency. With respect to spelling, visual-spatial skills might be especially relevant in combination with *graphomotor skills* when learning to write letters and words as they affect letter formation. Graphomotor skills encompass psychomotor abilities, coordinating cognitive processes with fine-motor skills, and are essential prerequisites for engaging in spelling activities. Therefore, good graphomotor skills release resources important for spelling performance. Investigations on graphomotor skills showed that these skills explain variance in spelling (Pontart et al., 2013; Mohamed and O'Brien, 2022).

1.5 Intelligence

In the current study, intelligence is included as a control variable because it affects learning more generally, rather than being specifically related to literacy acquisition. With respect to literacy, several studies have underscored the noteworthy contribution of intelligence to spelling performance at an early stage of literacy development (Ennemoser et al., 2012; Zarić et al., 2021). Furthermore, a longitudinal German study positions intelligence as a pivotal predictor for academic achievement in early and later stages of development, accentuating its enduring impact (Schneider and Niklas, 2017). On the other hand, the study of Ningrum and Wibowo (2017) illustrates a substantial contribution of intelligence to predicting more complex literacy skills later in development, such as reading comprehension and writing achievement. In addition, several studies introduce the notion that intelligence, lacks detailed correlations or predictive values especially for basic spelling and/or reading outcomes (Caravolas et al., 2001; Yeung et al., 2013). Therefore, the expectation is that the impact of intelligence on literacy skills is relatively small at the beginning of literacy development and increases during development. Furthermore, it is anticipated that intelligence has a more discernible impact on spelling, due to its inherent complexity, than on reading.

The objective of this study is to enhance our understanding of early spelling and reading skills by identifying both common and distinct predictors of reading vs. spelling skills. In this context, spelling's importance is highlighted, bringing attention to the limited literature and less-explored predictors in this domain, which are often overshadowed by research primarily concentrated on reading. This study, to the best of our knowledge, is one of few to investigate the relationship between spelling and reading, considering various cognitive factors beyond well-established ones, during the early stages of literacy development in German orthography. Therefore, the current study goes beyond previous investigations by integrating further potentially relevant cognitive predictors (here defined as secondary cognitive factors) in addition to predictors routinely reported in the literature (primary cognitive factors), and by investigating the differences in their influence on reading vs. spelling. By evaluating spelling and reading performance before formal literacy instruction and in Grade 1, the predictive patterns for each skill can be analyzed independently and collectively. This facilitates the deciphering of the influence of distinct predictors on spelling, reading, and both skills simultaneously, in order to establish if the patterns of predictions for the two literacy skills already dissociate at this early stage in literacy development. Moreover, the aim is to identify children who may face challenges in spelling and/or reading. This involves determining specific predictors that categorize them into either at-risk or typical proficiency groups in these skills.

Regression analyses are employed to identify common and distinct predictors of spelling and reading. Regarding early literacy development, previous findings indicate that phonological processing skills and letter knowledge emerge as the most pivotal predictors. Therefore, the expectation is that both spelling and reading skills will be predicted by these measures. In line with previous research, the anticipation is that the kindergarten measure of RAN will predict later reading skills, but not spelling skills. However, it is unclear, if the association between RAN and reading is already strong at the beginning of reading acquisition when reading is not fluent yet. Concerning secondary cognitive factors, predictive associations are anticipated between visual memory and spelling, as well as between visual-spatial/graphomotor skills and spelling. Furthermore, it is expected that intelligence, due to the inherent complexity of the task in German orthography, will emerge as a substantial predictor of spelling. Furthermore, correlation and logistic regression analyses were used to explain children's likelihood of belonging to different proficiency groups in spelling and reading (at-risk skills or typical skills). It is anticipated that measures of letter knowledge and phoneme awareness will strongly predict allocation to different proficiency groups in spelling and reading. Precise predictions about the role of RAN are avoided at this point, as the precise role in predicting group allocation remains uncertain at this early stage of literacy development. The same applies for the secondary factors.

2 Method

2.1 Participants and procedure

The present study presents findings from the first two time points of an ongoing longitudinal study aiming to assess the early cognitive predictors of spelling skills. At T1 (end of kindergarten) and T2 (mid of Grade 1), each child was tested individually on spelling and reading skills, and on cognitive predictors of literacy skills. A total of 372 students participated at the first two time points. The analyses are based on 353 students with complete data sets for the outcome measures. The final sample consisted of 47% boys; the mean age was 75.83 months (SD = 4.25) at T1 and 83,6 months (SD = 4.36) at T2. Out of the 353 children, 64.3% were brought up monolingually in German, while 35.7% were raised with multiple languages. For T1, all measures were administered individually by trained assistants in a quiet room at the respective kindergartens (n = 301) or at the University Hospital, Munich, Germany (n = 52). The testing period for T1 started at the end of April 2022 and lasted until the end of the summer holidays of 2022 before children were enrolled in schools. Thus, all children have been tested before formal spelling and reading instructions as well as teaching of letter sounds and names started, as it is not systematically taught to children in kindergarten in Germany. However, early reading and spelling skills were assessed not only at T2 but also in kindergarten to account for the fact that some children might already be able to read or spell simple syllables or words. For T2, all measures were administered individually by trained assistants in a quiet room at the University Hospital, Munich, Germany. The assessment period started at the beginning of January 2023 and covered 3 months to the beginning of April. The participants visit a total of 135 different schools and 233 different classes in the Munich district. Due to regional regulations all participants in this study are being taught using "Fibels," which are specifically designed to blend analytical and synthetic approaches. Inclusion criteria were an average scaled score of the two subtests Block Design and Vocabulary from the Wechsler Intelligence Test (WISC-V; Petermann, 2017) of at least 4 at T2 (IQ $\geq$ 70), German language skills for at least 3 years, normal or corrected-to-normal vision, and the absence of neurological deficits. The study was approved by the institutional ethics committee University Hospital, Munich, Germany and was performed in accordance with the latest version of the Declaration of Helsinki and in compliance with national legislation. Parents and children were informed in detail about the study and parents gave their written consent. Children received vouchers in return for their participation. The distinction between children with at-risk spelling and children with typical spelling skills was based on the performance in the standardized spelling test HSP 1 Plus (May et al., 2019) at T2. Children with spelling performance at or below the 25th percentile were assigned to the at-risk spelling group (n = 86, 44.2% girls), and children belonging to the typical spelling group had a spelling score above the 25th percentile (n=267, 55.4% girls). The distinction between children with at-risk reading and children with typical reading skills was based on their performance in the SLRT-III reading test, which is an updated version of the standardized reading test SLRT-II (Moll and Landerl, 2010) at T2. Children with reading performance at or below the 25th percentile were assigned to the at-risk reading group (n = 87, 52.9% girls), and children belonging to the typical reading group had a spelling score above the 25th percentile (n = 266, 52.6% girls). In our study, we opted to use the 25th percentile as the cutoff score for defining risk, considering the balance of sensitivity and specificity of risk identification. This decision was informed by relevant literature (Gersten et al., 2020; Hall et al., 2023), which indicated the applicability of this cutoff in similar contexts.

2.2 Measures

Table 1 provides a descriptive summary table with the characteristics of the measurements.

2.2.1 Phonological processing skills

2.2.1.1 Phoneme awareness

Phoneme awareness was assessed by an experimental test. In the first part of the test (phoneme identification) children had to identify the first or last phoneme of four words and

TABLE 1 Descriptive statistics for the measurements.

Variables	Min.	Max.	*M*	*SD*	Skewness	Kurtosis	*r*
Phoneme awareness[a]	0	100	37.04	29.84	0.42	−1,22	0.93
Verbal memory[b]	3	19	9.19	2.24	0.50	1.16	0.75
Vowel length distinction[b]	1	10	6.23	2.01	0.10	−0.70	0.61
Letter knowledge[a]	6	100	74.24	22.13	−0.75	−0.38	0.93
RAN[c]	0	1	0.82	0.18	0.40	0.21	
Visual-spatial and graphomotor skills[b]	0	30	9.20	6.11	0.62	0.09	0.74
Visual memory[b]	9	30	21.76	4.10	−0.57	0.04	0.83
Intelligence[d]	5	17	11.29	2.16	−0.48	0.29	0.84–0.86
Spelling T1[2]	0	22	9.27	7.84	0.28	−1.38	0.94
Spelling T2[2]	0	39	31.73	6.95	−2.48	6.87	0.94
Reading T1[2]	0	8	2.97	3.05	0.52	−1.31	0.93
Reading T2[2]	0	118	13.98	13.03	3.13	15.68	0.93–0.98

[a]percent correct.
[b]raw scores.
[c]items per second.
[d]scaled scores.

four pseudowords. The maximum score that can be achieved is 8. In the second part (phoneme deletion task) children had to pronounce four words and eight pseudoword without a specified phoneme. The maximum score that can be achieved is 12. The phoneme awareness test has a sample-based Cronbach's alpha of 0.93. Children had two practice trials each and the average accuracy in percent of the two parts was measured.

2.2.1.2 Verbal memory

Verbal memory was assessed using the standardized digit span subtest of the Kaufman-Assessment Battery for children–2nd Ed. (Melchers and Melchers, 2015) with maximum 21 items. After one practice trial, children had to repeat a series of digits of increasing length (from 2 to 9 digits) that were verbally presented by the experimenter. The task is terminated after three consecutive errors (discontinuation rule) so that the number of provided items differs according to the child's performance. The digit span test has a sample-based Cronbach's alpha of 0.75.

2.2.1.3 Vowel-length distinction

Vowel-length distinction was assessed using an adapted version of the vowel length distinction task from a screening tool (Witzel et al., 2023). The screening instrument has a sample-based split-half reliability of 0.61. Children had to decide whether the vowel in a heard word is long or short (e.g., "is the/i/in Schiff (ship) long or short?"). The maximum score that can be achieved is 10.

2.2.2 Letter-knowledge

Letter knowledge was assessed based on two subtests (grapheme-phoneme knowledge and phoneme-grapheme knowledge) from the standardized LRS-Screening (Endlich et al., 2019). the grapheme-phoneme subtest children were shown nine graphemes and were asked to name the corresponding phoneme. Additionally, a list of the 17 remaining graphemes of the German alphabet was presented and children were again asked whether they could name any of them, resulting in a maximum score of 26. The order of letter presentation was random to avoid systematic effects due to alphabetical order. In the phoneme-grapheme subtest children were shown nine separate lists with four graphemes on them each. The experimenter pronounced a phoneme and asked the child to point to the corresponding grapheme. The maximum score for the phoneme-grapheme task that can be achieved is 9. The letter knowledge test has a sample-based Cronbach's alpha of 0.93. The average accuracy in percent of the two letter-knowledge subtests was calculated.

2.2.3 Rapid automatized naming (RAN)

A standard RAN-objects paradigm (Denckla and Rudel, 1976) was presented. Children had to name a matrix of 30 visual stimuli (5 items: fish, clock, glass, leaf, dog) as quickly and accurately as possible. Due to the age of participants, we used a non-alphanumeric paradigm and accounted for accuracy, given the slightly higher error rates (mean = 0.4 errors) observed in this age group compared to older children or adults. The matrix was arranged in six rows with five items each. The item order was randomized. Each item was presented once in each line. The time needed to name the full item set was recorded and any occurring errors were marked. For the analysis, the number of correctly named items per second was computed.

2.2.4 Visual processing skills

2.2.4.1 Visual memory

Visual memory was assessed using the standardized Corsi Block-Tapping-Test from the Working memory test battery for children (Pickering and Gathercole, 2001). A board with nine blocks on it was presented. A series of blocks was tapped by the experimenter and after three practice trials the children had to reproduce the sequence by tapping the same blocks in the correct order. The span of the sequences that the children had to tap gradually increased from 1 to a maximum of 9 items, with 6 sequences each. The score was the number of correctly tapped sequences. The task is terminated after three errors within one sequence (discontinuation rule) so that the number of provided items differs according to the child's performance. The maximum score that can be theoretically achieved is 54. The test has a sample-based Cronbach's alpha of 0.83.

2.2.4.2 Visual-spatial and graphomotor skills

Visual-spatial/graphomotor skills were assessed using a subtest of the standardized German version of the Developmental Test of Visual Perception 2 (Büttner et al., 2008). Four different geometric shapes were presented with two of them having a specific mark. After two practice trials, children received a sheet of paper with the items on it. Within 1 min they had to draw the correct mark in the corresponding shape as quickly and accurately as possible. The maximum score that can be achieved is 63. The test has a retest reliability of $r_{tt} = 0.74$, according to manual.

2.2.5 Intelligence

To get an estimate of general cognitive abilities a non-verbal and verbal subtest from the German version of the Wechsler Intelligence Scale for Children (WISC-V; Petermann, 2017) were administered: Block Design and Vocabulary. During Block Design, the children viewed a model and/or picture and used two-colored blocks to re-create the design within a certain time limit. The subtest belongs to the visual spatial index and reflects the ability to understand visual-spatial relationships. The maximum score that can be achieved is 58. The subtest has a split-half reliability of $r_{tt} = 0.84$, according to manual. Vocabulary required children to name depicted objects and/or define words and is assigned to the verbal comprehension index. The subtest captures children's ability to verbalize meaningful concepts and to access word knowledge. The maximum score that can be achieved is 54. The subtest has a split-half reliability of $r_{tt} = 0.86$, according to manual. The two subtests were combined to have an estimate of intelligence including nonverbal and verbal skills. The average of the scaled scores of the two subtests are reported.

2.2.6 Spelling

2.2.6.1 Spelling T1

In kindergarten, early spelling skills were assessed by an experimental spelling test (Cronbach's alpha sample-based: 0.94). Children spelled a list of 5 two-letter syllables (e.g., la, me) and a list of 3 short high frequency words. The score was the number of correctly spelled graphemes. The maximum score that can be achieved is 22.

2.2.6.2 Spelling T2

Spelling at T2 was assessed using the standardized spelling test HSP 1 Plus (May et al., 2019). Children had to write 4 high frequency words and one sentence consisting of 6 words dictated by the experimenter. The score was the number of correctly spelled graphemes. The maximum score that can be achieved is 40. The test has an internal consistency of 0.94, according to manual.

2.2.7 Reading

2.2.7.1 Reading T1

In kindergarten, early reading skills were assessed by an experimental reading test (Cronbach's alpha sample-based: 0.93). Children read a list of 5 two-letter syllables (e.g., ma, le) and a list of 3 short high-frequency words. Number of items read correctly was scored. The maximum score that can be achieved is 8.

2.2.7.2 Reading T2

At T2, reading was assessed using the word reading subtest of the SLRT-III reading test, which is an updated version of the standardized reading test SLRT-II (Moll and Landerl, 2010). Children were given a list of words and were instructed to read aloud as many words as quickly and correctly as possible within one minute. The number of correctly read items within the time limit was scored. The maximum score that can be theoretically achieved is 156. The test has a parallel-test reliability of $r_{tt} = 0.93–0.98$, according to manual.

3 Results

3.1 Data pre-processing

To identify any differences in performance due to developmental and schooling effects in the three-month assessment period of T2, the performance of children tested at the beginning and at the end of the period for all variables were compared. Differences were found for both outcome variables Spelling T2 and Reading T2 due to the time point of assessment. Therefore, these values were z-standardized separately for each month of testing. Next, the distributional properties of the two spelling and reading measures were examined, in order to meet the assumptions of parametric tests. Due to skewness in both outcome variables, log transformation was performed to normalize their distribution [Spelling (Skewness: −1.05; Kurtosis: 1.45); Reading (Skewness: 1.12; Kurtosis: 2.29)] (Tabachnick et al., 2013). The subsequent analyses are reported based on transformed data but were also confirmed using raw data.

We initially explored reducing the number of predictors by combining theoretically related constructs, like phonological predictors and visual predictors, based on their correlations. An analysis showed a moderate correlation of $r = 0.40$ between phoneme awareness and verbal memory, that was higher than with vowel length discrimination and the two visual measures. Additionally, the phoneme deletion task in our study necessitates verbal short-term and working memory, so that the two constructs are interrelated. Therefore, the two tests (verbal memory and phoneme awareness) were z-standardized separately and merged into a composite variable of phonological processing. Despite the potential theoretical inclusion of vowel length in phonological processing, its correlation of $r = 0.18$ with verbal memory led us to maintain it separately. We further assessed whether visual memory and visual-spatial/graphomotor skills can be combined to

TABLE 2 Means (SD) at T1 and T2 and group comparisons (spelling).

Variables	Typical spelling (267)		At-risk spelling (86)		*t* (351)	*p*	Cohen's *d*	95% confidence interval	
	M	*SD*	*M*	*SD*				Lower	Upper
Intelligence[a]	11.58	2.04	10.39	2.26	4.56	<0.001	0.57	0.32	0.81
Letter knowledge[b]	79.57	19.59	57.68	21.48	8.80	<0.001	1.09	0.83	1.35
Vowel length distinction[c]	6.42	2.09	5.65	1.61	3.12	<0.001	0.39	0.14	0.63
Phonological processing[d]	0.18	0.82	−0.54	0.63	7.43	<0.001	0.92	0.67	1.17
RAN[e]	0.84	0.18	0.76	0.16	3.20	<0.001	0.40	0.15	0.64
Visual-spatial and graphomotor skills[c]	9.85	6.20	7.21	5.37	3.54	<0.001	0.44	0.19	0.68
Visual memory[c]	22.30	3.90	20.08	4.25	4.49	<0.001	0.56	0.31	0.80
Spelling T1[c]	11.06	7.81	3.69	4.68	8.28	<0.001	1.03	0.77	1.28
Spelling T2[d]	−0.23	0.09	−0.52	0.13	23.94	<0.001	2.97	2.64	3.29
Reading T1[c]	3.71	3.05	0.67	1.48	8.89	<0.001	1.10	0.85	1.36
Reading T2[d]	0.35	0.14	0.17	0.08	10.91	<0.001	1.35	1.09	1.62

[a]scaled scores.
[b]percent correct.
[c]raw scores.
[d]z-scores.
[e]items per second.

a single visual processing measure by calculating the correlations between the two measures. The correlation analysis for the two visual processing predictors revealed only a small correlation of $r = 0.23$. Therefore, the two visual predictors were kept separate.

3.2 Design and statistical analysis

Descriptive statistics for age, intelligence, literacy-specific predictors, and literacy outcomes are displayed separately for children with typical skills and those at-risk of spelling and reading disorders separately in Tables 2, 3.

Pearson correlation coefficients between predictor variables at T1 and the two literacy measures at the two time points were calculated and are presented in Table 4. Next, the predictive pattern for Spelling and Reading at T2 was examined separately in a series of stepwise regression analyses. In step 1, individual differences in intelligence were controlled for. The literacy-specific predictors were added simultaneously in step 2, and the unique variance for each predictor variable and the variance shared between predictors were calculated. In step 3 the respective autoregressor was added (Reading T1 for Reading T2; Spelling T1 for Spelling T2). To partial out the mechanisms that overlap between the two outcome measures Spelling and Reading at T2, the respective other literacy variable of the dependent variable (Reading T2 for Spelling T2; Spelling T2 for Reading T2) was included in step 4 of the respective regression analyses. This enabled an examination of the predictive patterns that are unique for spelling or reading, without the influence of the respective other literacy skill. The results are shown in Tables 5, 6. Finally, two logistic regression analyses were run in order to model children's likelihood of belonging to different proficiency groups, both for seplling and reading. The results are shown in Tables 7, 8.

3.3 Descriptive statistics

Tables 2, 3 shows that children with typical spelling and reading skills outperformed the children in the at-risk groups in all predictor and outcome measures. In the domains of both spelling and reading, children deemed at-risk consistently manifest notable deficiencies in primary cognitive risk factors, while differences in secondary risk factors were small to moderate. Biggest effect sizes were found for phonological processing (Cohen's $d_s = 0.92$ and 0.88) and letter knowledge (Cohen's $d_s = 1.09$ and 0.95). This underscores the importance of these two skills for literacy acquisition. Rapid automatized naming (RAN) demonstrates moderate effect sizes (Cohen's $d_s = 0.40$ and 0.61). In line with the important role of RAN for reading, effect sizes were higher in the reading domain (i.e., when comparing children at risk of reading problems with typical readers) than in the spelling domain (i.e., when comparing children at risk of spelling problems with typical spellers).

3.4 Correlations

Results in Table 4 showed that there was a significant, strong, positive correlation between almost all the variables ($p_s < 0.01$). Only the correlations between vowel length distinction and RAN and between vowel length distinction and visual memory were slightly lower ($p_s < 0.05$). Correlations for literacy measures at both time points were particularly high with letter knowledge and phonological processing. In line with our predictions, correlations between the spelling and reading measures were significantly higher for the first time point in kindergarten (0.88) than for the second time point in grade 1 (0.65) ($z = 8.84$; $p < 0.001$; Dunn and Clark, 1969).

TABLE 3 Means (SD) at T1 and T2 and group comparisons (reading).

Variables	Typical reading (266)		At-risk reading (87)		*t* (351)	*p*	Cohen's *d*	95% confidence interval	
	M	*SD*	*M*	*SD*				Lower	Upper
Intelligence[a]	11.57	2.09	10.42	2.14	4.44	<0.001	0.55	0.30	0.79
Letter knowledge[b]	79.02	20.15	59.61	21.61	7.66	<0.001	0.95	0.69	1.20
Vowel length distinction[c]	6.41	2.02	5.68	1.88	3.00	0.001	0.37	0.13	0.61
Phonological processing[d]	0.17	0.84	−0.52	0.59	7.11	<0.001	0.88	0.63	1.13
RAN[e]	0.84	0.18	0.74	0.16	4.92	<0.001	0.61	0.36	0.85
Visual-spatial and graphomotor skills[c]	9.91	6.30	7.06	4.92	3.85	<0.001	0.48	0.23	0.72
Visual memory[c]	22.35	3.89	19.95	4.20	4.90	<0.001	0.60	0.36	0.85
Spelling T1[c]	11.04	7.88	3.84	4.56	8.08	<0.001	1.00	0.74	1.25
Spelling T2[d]	−0.25	0.11	−0.47	0.18	13.88	<0.001	1.71	1.44	1.99
Reading T1[c]	3.65	3.10	0.90	1.60	7.92	<0.001	0.98	0.72	1.23
Reading T2[d]	0.36	0.13	0.14	0.05	15.11	<0.001	1.87	1.59	2.14

[a]scaled scores.
[b]percent correct.
[c]raw scores.
[d]z-scores.
[e]items per second.

TABLE 4 Correlations for study variables.

Variable	1	2	3	4	5	6	7	8	9	10	11
1. Intelligence	–										
2. Letter knowledge	0.26**	–									
3. Vowel length distinction	0.23**	0.30**	–								
4. Phonological processing	0.35**	0.54**	0.31**	–							
5. RAN	0.16**	0.23**	0.12*	0.23**	–						
6. Visual-spatial and graphomotor skills	0.19**	0.30**	0.17**	0.22**	0.15**	–					
7. Visual memory	0.22**	0.31**	0.12*	0.27**	0.21**	0.23**	–				
8. Spelling T1	0.24**	0.79**	0.32**	0.65**	0.26**	0.35**	0.25**	–			
9. Spelling T2	0.35**	0.51**	0.18**	0.51**	0.24**	0.24**	0.29**	0.53**	–		
10. Reading T1	0.26**	0.73**	0.31**	0.63**	0.28**	0.34**	0.24**	0.88**	0.50**	–	
11. Reading T2	0.23**	0.48**	0.20**	0.51**	0.37**	0.21**	0.26**	0.58**	0.65**	0.58**	–

**p < 0.01.
*p < 0.05.

3.5 Regression analyses

The regression results for Spelling T2 as dependent variable are shown in Table 5. Step 1 (intelligence) explained a significant amount (12%) of the variance in spelling ($p < 0.001$). The specific predictors in step 2 explained additional 25.7% of the variance in spelling ($p < 0.001$), with intelligence (2%), letter knowledge (5%), and phonological processing (5%) explaining significant unique variance. However, vowel length distinction, RAN, visual-spatial/graphomotor skills, and visual memory did not significantly predict spelling. The unique variance of the predictors was 13% and the shared variance between the predictors was 25%. In step 3 (autoregressor) the model explained additional 0.9% of the variance in Spelling ($p < 0.001$). Intelligence (2%), letter knowledge (1%), and phonological processing (2%) still explained significant unique variance in spelling, even after adding the autoregressor (Spelling T1) to the model. The unique variance of the predictors was 8% and the shared variance between the predictors was 31%, suggesting a large overlap between predictors at this age. In step 4 (Reading T2), the model explained additional 12.8% of the variance in spelling ($p < 0.001$). The cognitive predictors intelligence (2%), letter knowledge (1%), and phonological processing (1%), continued to explain a significant but small amount of unique variance in spelling after adding Reading T2 to the model. The unique variance of the predictors was 17% and the shared variance between the predictors was 34%.

TABLE 5 Four step regression analysis for spelling as dependent variable (z-standardized values).

	B	*SE B*	*β*	*t*	*p*	*R*	R^2 (%)	ΔR^2 (%)
Step 1 (intelligence)						0.35	12.10	12.10
Constant	−0.30	0.01		−38.35	<0.001			
Intelligence	0.05	0.01	0.35	6.95	<0.001		12.10	
Step 2 (specific predictors)						0.62	37.83	25.74
Constant	−0.30	0.01		−45.21	<0.001			
Intelligence	0.02	0.01	0.16	3.35	0.001		2.02	
Letter knowledge	0.04	0.01	0.28	5.34	<0.001		5.15	
Vowel length distinction	−0.01	0.01	−0.05	−1.20	0.232		0.26	
Phonological processing	0.05	0.01	0.27	5.15	<0.001		4.78	
RAN	0.01	0.01	0.07	1.62	0.106		0.47	
Visual-spatial and graphomotor skills	0.01	0.01	0.05	1.07	0.284		0.21	
Visual memory	0.01	0.01	0.07	1.58	0.115		0.45	
Unique variance step 2							13.33	
Shared variance step 2							24.50	
Step 3 (autoregressor)						0.62	38.73	0.90
Constant	−0.30	0.01		−45.48	<0.001			
Intelligence	0.03	0.01	0.16	3.55	<0.001		2.25	
Letter knowledge	0.03	0.01	0.18	2.59	0.010		1.19	
Vowel length distinction	−0.01	0.01	−0.06	−1.36	0.176		0.33	
Phonological processing	0.04	0.01	0.22	3.74	<0.001		2.49	
RAN	0.01	0.01	0.06	1.43	0.153		0.36	
Visual-spatial and graphomotor skills	0.00	0.01	0.03	0.67	0.500		0.08	
Visual memory	0.01	0.01	0.08	1.74	0.083		0.54	
Spelling T1	0.03	0.01	0.18	2.25	0.025		0.90	
Unique variance step 3							8.14	
Shared variance step 3							30.59	
Step 4 (reading T2)						0.72	51.57	12.83
Constant	−0.45	0.02		−27.15	<0.001			
Intelligence	0.02	0.01	0.15	3.59	<0.001		1.82	
Letter knowledge	0.03	0.01	0.18	2.82	0.005		1.13	
Vowel length distinction	−0.01	0.01	−0.05	−1.24	0.215		0.22	
Phonological processing	0.02	0.01	0.13	2.45	0.015		0.85	
RAN	−0.01	0.01	−0.04	−0.88	0.380		0.11	
Visual-spatial and graphomotor skills	0.01	0.01	0.04	0.95	0.344		0.13	
Visual memory	0.01	0.01	0.05	1.18	0.240		0.20	
Spelling T1	0.00	0.01	0.00	−0.06	0.949		0.00	
Reading T2	0.49	0.05	0.47	9.53	<0.001		12.83	
Unique variance step 4							17.28	
Shared variance step 4							34.29	

The regression results for Reading T2 as dependent variable are shown in Table 6. Step 1 (intelligence) explained a significant amount (5%) of the variance in reading ($p < 0.001$) before adding the specific predictors. In step 2 (specific predictors) the model explained additional 32.2% of the variance in reading ($p < 0.001$). Letter knowledge (4%), phonological processing (6%), and RAN

TABLE 6 Four step regression analysis for reading as dependent variable (z-standardized values).

	B	*SE B*	*β*	*t*	*p*	*R*	R^2 (%)	ΔR^2 (%)
Step 1 (intelligence)						0.23	5.45	5.45
Constant	0.30	0.01		38.36	<0.001			
Intelligence	0.04	0.01	0.23	4.50	<0.001		5.45	
Step 2 (specific predictors)						0.61	37.70	32.25
Constant	0.30	0.01		46.85	<0.001			
Intelligence	0.00	0.01	0.01	0.31	0.754		0.02	
Letter knowledge	0.04	0.01	0.24	4.43	<0.001		3.54	
Vowel length distinction	0.00	0.01	−0.01	−0.19	0.849		0.01	
Phonological processing	0.06	0.01	0.31	5.83	<0.001		6.14	
RAN	0.04	0.01	0.23	5.17	<0.001		4.83	
Visual-spatial and graphomotor skills	0.00	0.01	0.02	0.49	0.624		0.04	
Visual memory	0.01	0.01	0.05	1.12	0.262		0.23	
Unique variance step 2							14.81	
Shared variance step 2							22.89	
Step 3 (autoregressor)						0.65	42.24	4.54
Constant	0.30	0.01		48.59	<0.001			
Intelligence	0.00	0.01	0.02	0.44	0.661		0	
Letter knowledge	0.01	0.01	0.06	0.95	0.344		0	
Vowel length distinction	0.00	0.01	−0.02	−0.50	0.617		0	
Phonological processing	0.04	0.01	0.20	3.56	<0.001		2	
RAN	0.03	0.01	0.20	4.64	<0.001		4	
Visual-spatial and graphomotor skills	0.00	0.01	−0.01	−0.32	0.749		0	
Visual memory	0.01	0.01	0.07	1.47	0.142		0	
Reading T1	0.05	0.01	0.35	5.20	<0.001		5	
Unique variance step 3							10.88	
Shared variance step 3							31.36	
Step 4 (spelling T2)						0.74	54.81	12.57
Constant	0.44	0.01		29.82	<0.001			
Intelligence	−0.01	0.01	−0.05	−1.27	0.206		0	
Letter knowledge	−0.01	0.01	−0.05	−0.82	0.415		0	
Vowel length distinction	0.00	0.01	0.00	0.11	0.910		0	
Phonological processing	0.02	0.01	0.09	1.78	0.076		0	
RAN	0.03	0.01	0.17	4.48	<0.001		3	
Visual-spatial and graphomotor skills	0.00	0.01	−0.03	−0.79	0.429		0	
Visual memory	0.00	0.01	0.03	0.78	0.437		0	
Reading T1	0.05	0.01	0.30	5.04	<0.001		3	
Spelling T2	0.44	0.04	0.45	9.77	<0.001		13	
Unique variance step 4							19.45	
Shared variance step 4							35.37	

(5%) explained significant unique variance in reading. However, intelligence, vowel length distinction, visual-spatial/graphomotor skills, and visual memory did not significantly predict reading. The unique variance of the predictors was 15% and the shared variance between the predictors was 23%. In step 3 (autoregressor) the model explained additional 4.5% of the variance in reading

TABLE 7 Logistic regression results for spelling (z-standardized values).

	B	*SE B*	Wald	*p*	Exp (*B*)	95% C.I. for Exp (*B*)	
						Lower	Upper
Step 1							
Letter knowledge	0.36	0.21	3.05	0.081	1.44	0.96	2.17
Vowel length distinction	0.02	0.15	0.02	0.884	1.02	0.76	1.38
Phonological processing	0.60	0.25	6.01	0.014	1.83	1.13	2.96
RAN	0.16	0.16	1.05	0.306	1.17	0.86	1.59
Visual-spatial and graphomotor skills	0.08	0.17	0.21	0.649	1.08	0.78	1.49
Visual memory	0.21	0.15	1.90	0.168	1.23	0.92	1.66
Spelling T1	0.54	0.28	3.73	0.053	1.71	0.99	2.96
Constant	1.58	0.18	76.61	0.036	4.83		

TABLE 8 Logistic regression results for reading (z-standardized values).

	B	*SE B*	Wald	*p*	Exp (*B*)	95% C.I. for Exp (*B*)	
						Lower	Upper
Step 1							
Letter knowledge	0.16	0.19	0.76	0.385	1.18	0.82	1.69
Vowel length distinction	0.02	0.15	0.03	0.870	1.03	0.76	1.38
Phonological processing	0.52	0.24	4.60	0.032	1.68	1.05	2.69
RAN	0.44	0.16	7.35	0.007	1.56	1.13	2.15
Visual-spatial and graphomotor skills	0.11	0.17	0.42	0.519	1.12	0.80	1.55
Visual memory	0.27	0.15	3.19	0.074	1.31	0.97	1.75
Reading T1	0.76	0.28	7.38	0.007	2.14	1.24	3.69
Constant	1.64	0.19	72.65	0.003	5.17		

($p < 0.001$). Phonological processing (2%) and RAN (4%) still explained significant unique variance in reading, even after adding the autoregressor (Reading T1) to the model. The unique variance of the predictors was 11% and the shared variance between the predictors was 31%, showing again a large overlap between predictors. In step 4 (Spelling T2), the model explained additional 12.6% of the variance in reading ($p < 0.001$). Only the cognitive predictor RAN (3%) continued to explain significant unique variance in reading after adding Spelling T2 to the model. The unique variance of the predictors was 19% and the shared variance between the predictors was 35%.

The results of the logistic regression analysis for spelling are shown in Table 7. The analysis identified one significant predictor for the group allocation of spelling proficiency: phonological processing ($B = 0.60$, $SE\ B = 0.25$, $p = 0.014$), indicating that weaker phonological processing skills are associated with an increased likelihood of being at-risk of spelling problems at T2. All other predictor variables, including letter knowledge, vowel length distinction, RAN, visual-spatial/graphomotor skills, and visual memory did not significantly predict group allocation of spelling proficiency at T2.

The results of the logistic regression analysis, employed to model the likelihood of participants falling into different reading proficiency groups at T2 are shown in Table 8. The results revealed three factors that emerged as significant predictors for the classification of reading groups at T2: phonological processing ($B = 0.52$, $SE\ B = 0.24$, $p = 0.032$), the corresponding literacy skill (here T1 reading; $B = 0.76$, $SE\ B = 0.28$, $p = 0.007$), and RAN ($B = 0.44$, $SE\ B = 0.16$, $p = 0.007$). The other factors, including letter knowledge, vowel length distinction, visual-spatial/graphomotor skills, and visual memory did not predict group allocation of reading proficiency at T2.

4 Discussion

This study aimed to deepen our understanding of early spelling and reading skill, by identifying both common and distinct predictors of spelling and reading skills and deficits in these domains within a large sample of 353 children from kindergarten to second half of Grade 1. Predictive measures (phonological processing, letter knowledge, RAN, visual-spatial/graphomotor skills, and visual memory) were assessed in kindergarten, before formal literacy instruction, the outcome variables (spelling and reading) were measured in kindergarten and in first grade, and the control variable intelligence in Grade 1. Children with typically developing spelling and reading skills in Grade 1 outperformed their counterparts in at-risk groups across all predictor and literacy measures assessed at T1, with largest effect sizes found for literacy skills at T1, letter knowledge, and phonological processing. The regression analysis for spelling abilities at T2 identified phonological processing, letter knowledge, and intelligence, as significant predictors, even after including step 3 (autoregressor Spelling T1) and step 4 (Reading T2) in the model. For reading abilities, phonological processing and RAN surfaced as significant predictors after step 3 (autoregressor Reading T1). However, only RAN (and the autoregressor) turned out to be a significant predictor for reading after step 4 (Spelling T2) was included in the model.

This research, in line with previous studies (Ehri, 1986; Caravolas et al., 2001; Landerl and Wimmer, 2008), underscores at least partly simultaneous enhancement of spelling and reading proficiency in the initial stages of literacy acquisition. However, the study also shows that the correlation between spelling and reading already decreases early in development, with stronger correlations in kindergarten ($r = 0.88$) compared to Grade 1 ($r = 0.65$). It was hypothesized that the association between reading and spelling skills is gradually diminishing during literacy acquisition as orthographic processing becomes more central, and distinct deficits in orthographic processing emerge. This suggests a shift in the dynamics of the relationship between spelling and reading skills over time. Therefore, it is expected, that the correlation will decrease further in grades 2 and 3 as orthographic processing takes on greater significance, and subprocesses of orthographic processing such as the storage of orthographic representations (associated with spelling) and effective processing of orthographic representations (associated with reading fluency) potentially diverge. This expectation aligns with findings from previous studies based on large representative samples of German speaking children in grades 3 and 4, who showed correlations between spelling and reading abilities of r_s between 0.48 and 0.57 (Moll and Landerl, 2009; Landerl and Moll, 2010; Görgen et al., 2021).

To deepen the understanding of distinct cognitive factors associated with early reading vs. spelling, a diverse set of cognitive factors was explored, extending beyond commonly acknowledged predictors of literacy skills. The results confirm the crucial contribution of well-established cognitive factors, such as phonological processing and letter-knowledge, to proficiency in literacy skills. Furthermore, it highlights the pivotal role of RAN in reading (but not spelling). However, the impact of other cognitive factors appears to be limited, with the notable exception of intelligence, which was associated with spelling proficiency.

In line with previous research (Cataldo and Ellis, 1988; Landerl and Wimmer, 2008; Diamanti et al., 2017; Schmitterer and Schroeder, 2018), the results revealed that kindergarten proficiency in phonological processing skills significantly predicted performance in spelling and reading during Grade 1, even after adding the respective autoregressor. A novel finding of the current study was that when identifying predictors that are specifically related to either reading or spelling by controlling for the respective other literacy skill (step 4), phonological processing turned out to be specifically related to spelling and to the variance shared between reading and spelling, but not to the variance related to reading only. The association between phonological processing and the shared variance between reading and spelling suggests that phonological processing taps into mechanisms underlying reading as well as spelling acquisition, most probably the understanding of the sound structure of words. The specific association between phonological processing and spelling might reflect the role of phonological processing in building-up precise word specific representations, which are crucial for spelling words correctly. Alternatively, the strong association of phonological processing with spelling might be the consequence of the higher demands on phonological processing associated with spelling compared to reading. The strong association between phonological processing and spelling is not restricted to the German orthography, but is also reported in other alphabetic orthographies, such as Norwegian (Lervåg and Hulme, 2010), Danish (Nielsen and Juul, 2016), and English (Caravolas et al., 2001; Moll and Landerl, 2009; Lervåg and Hulme, 2010). With respect to reading, the study identified no relationship between phonological processing and early reading skills, after controlling for Spelling T2. This is in alignment with Landerl et al. (2019), who found no predictive link between phonological awareness and reading in Grade 1 German children. The important role of phonological processing for early spelling was also evident when determining group allocation (at-risk or typical). Phonological processing was the only significant kindergarten measure for predicting spelling group allocation in Grade 1. Phonological processing also predicted reading group allocation, but played a less important role compared to reading at T1 and RAN, who turned out as the most important predictors for reading group allocation.

In addition to phonological processing, vowel length distinction was included as an independent factor. Despite its intricate relationship with literacy skills in previous studies (Groth et al., 2011; Steinbrink et al., 2012, 2014), the study found no significant predictive link between vowel length distinction assessed in kindergarten and Grade 1 spelling or reading abilities. It also did not emerge as a significant predictor for spelling and reading group allocation. These findings do not seem to be the result of a large overlap between vowel length distinction and phonological processing given that the correlation between both measures was relatively low ($r = 0.31$). There are at least two potential explanations for this finding. First, the association between vowel length distinction and literacy skills might depend on the stage of literacy development of the participants. Vowel length distinction is crucial for following spelling rules and, by extension, achieving precision in orthographic spelling (e.g., doubling of a single consonant following a short vowel in the German orthography). This interpretation aligns with the observation that prior research on this subject predominantly focused on participants in more advanced stages of literacy development. For example, the studies by Groth et al. (2011) and Steinbrink et al. (2012) centered on young adults or 3rd and 4th-grade children (Steinbrink et al., 2014). Secondly, vowel length distinction might predominantly develop alongside literacy acquisition and might be fostered by explicit teaching. Thus, vowel distinction might be rather difficult for children in kindergarten, which is supported by our data. Even though the mean score in our sample for the vowel length distinction task was above chance rate ($M = 6.42$), some children did not score above the rate level of 5, reducing sensitivity regarding predictive patterns. Taken together, vowel length distinction assessed in kindergarten does not seem to predict literacy skills in the first year of literacy acquisition but might play a role in later developmental stages when orthographic processing and the acquisition of spelling rules becomes more relevant.

The significance of letter knowledge skills has been firmly established in the context of early literacy development (Ellis and Large, 1988; Lervåg and Hulme, 2010; Schmitterer and Schroeder, 2019). The current findings align, to some extent, with previous studies, as letter knowledge was found to significantly predict spelling but not reading in all four steps of the regression analyses. The predictive power for spelling persists even after introducing the autoregressor (Spelling T1) in step 3 and Reading T2 in step 4, emphasizing the substantial contribution of letter knowledge for spelling abilities. In the prediction of Grade 1 reading abilities, letter knowledge (4%) played a substantial role in explaining significant unique variance in reading abilities, before the introduction of the autoregressor (Reading T1). However, once the autoregressor (Reading T1) was included in the model in step 3, letter knowledge did not continue to explain significant unique variance in reading. A potential explanation for this finding is that the assessment of letter knowledge in kindergarten incorporates a higher number of items aligned with the reading direction (grapheme-phoneme correspondence) in comparison to the spelling direction (phoneme-grapheme correspondence). Thus, by controlling for the autoregressor (Reading T1), the variance assessed by the grapheme-phoneme correspondence measure seems to be accounted for by the initial reading skills in kindergarten. Moreover, letter knowledge in kindergarten did not emerge as a significant predictor in determining group allocation for spelling and reading abilities in Grade 1 in the logistic regression analyses. The findings that letter-knowledge did not predict group allocation is likely to be due to the overlap between letter-knowledge and T1 spelling and reading skills, as evident from the high correlations of 0.73 and 0.79. Still letter-knowledge turned out to be an important predictor, especially in children who cannot read and spell yet. In the current sample, 34.6% of the kindergarten children were unable to decipher a single syllable or word from a possible maximum score of 8, and 21% of the children struggled to spell a single grapheme from a potential maximum score of 22. Among children unable to read or spell, the mean percentage score for letter knowledge was 53.4% and 49.6%, respectively, suggesting they knew about half of the letters. Consequently, it is essential to consider letter knowledge as well as early reading and spelling skills in the early stages of literacy development.

Several studies have emphasized the robust predictive capacity of RAN on reading skills (Moll et al., 2009; Papadopoulos et al., 2016; McWeeny et al., 2022). While the mechanisms connecting RAN and reading involve verbal access, retrieval, and efficient serial processing, its impact on spelling remains inconclusive. Some studies assert a predictive role of RAN in spelling (Furnes and Samuelsson, 2010; Stainthorp et al., 2013), while others do not establish a clear connection (Landerl and Wimmer, 2008; Vaessen and Blomert, 2013). Consistent with previous research, the current study found a significant predictive relationship between RAN and reading performance, with RAN also significantly predicting reading group allocation in Grade 1. This extends existing research by illustrating that RAN predicts reading abilities already in early development, but not spelling skills. The finding that RAN is associated with reading in very early phases when reading still strongly relies on decoding rather than on fluent recognition of whole-words or larger units (e.g., syllables or morphemes) supports the idea that RAN reflects efficient serial processing, encompassing whole words as well as single letters, or smaller units during decoding, rather than focusing on orthographic processing (Moll et al., 2009; Protopapas et al., 2013).

This research not only considered established cognitive predictors of early literacy but also explored secondary factors influencing spelling subskills. Visual memory, potentially crucial for encoding orthographic representations, was examined for its role in spelling proficiency. Despite limited research indicating the significance of visuo-spatial working memory in early spelling (Bourke et al., 2013), this study, aligning with Giles and Terrell (1997), found that visual memory did not significantly predict later spelling or reading skills. It also did not emerge as a significant predictor for spelling and reading group allocation in Grade 1. Thus, the predictive value of visual memory for early spelling and reading skills appears constrained. Furthermore, a task measuring visual-spatial and graphomotor skills was included. Several studies established the notion, that visual-spatial skills (Bosse and Valdois, 2009; Liu et al., 2016) and graphomotor skills (Pontart et al., 2013; Suggate et al., 2018; Mohamed and O'Brien, 2022) explain variance in spelling and reading. However, our results are not in line with these findings. Visual-spatial and graphomotor skills did not significantly predict later spelling or reading skills and did not emerge as a significant predictor of spelling and reading group allocation in Grade 1. A possible reason for the differences in results might lie in the divergence of the specific constructs measured. The studies by Bosse and Valdois (2009) and Liu et al. (2016) primarily concentrated on visual-spatial attention, while the works of Pontart et al. (2013), Suggate et al. (2018), and Mohamed and O'Brien (2022) focused specifically on graphomotor skills. In contrast, the measurement used in the current study assesses the visual and motor speed at which a child can draw predetermined symbols into specific shapes, concurrently involving visual discrimination, fine motor skills, and execution speed. Thus, future studies will have to examine the associations between different visual-spatial and graphomotor constructs and their relation to literacy skills and whether this changes during development.

Moreover, intelligence was integrated as a general cognitive factor. Previous research reported mixed findings, with some studies providing evidence for the pivotal role of intelligence in spelling skills (Ennemoser et al., 2012; Zarić et al., 2021), while others showed limited correlations or predictive values (Caravolas et al., 2001; Yeung et al., 2013). Anticipating a relatively modest impact on early reading skills but a more pronounced effect on spelling due to its complexity in the German orthography, the current results indeed revealed that intelligence significantly predicts Grade 1 spelling skills but not reading. This phenomenon can be attributed to the strong asymmetry of the German orthography (and the majority of other alphabetic orthographies), where spelling is considerably more inconsistent and complex than reading. The findings are in line with previous research based on

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German (Ennemoser et al., 2012; Zarić et al., 2021), and English samples (Caravolas et al., 2001), and extend previous research by showing that intelligence predicts spelling abilities already in early development alongside established predictors. Future research is needed to identify the exact mechanisms underlying the relationship between intelligence and spelling in early and later spelling development.

Finally, it is necessary to discuss some limitations and, by doing so, provide suggestions for future research. One limitation is the relatively short period of 1 year. Therefore, future studies should aim to investigate the evolving predictive patterns of spelling and reading skills over an extended period in one and the same sample. Furthermore, in the early phases of development, where formal literacy instruction is yet to be introduced, a notable range of diversity in literacy and precursor skills is due to environmental factors, such as the home learning environment, the extent of parental support, and the training of precursor skills in kindergarten. Therefore, future research should examine the interplay between cognitive and environmental factors in order to enhance our understanding of literacy development in the initial stages. Finally, as a result of examining preliterate children in kindergarten, the use of a standardized spelling or reading test was not feasible at T1. Consequently, it was not possible to utilize the same tests for spelling and reading in both kindergarten and Grade 1, limiting the comparability of spelling and reading performances between the two assessment periods. However, the data demonstrated that the reading and spelling tasks in kindergarten differentiated between at-risk children and successfully predicted performance in Grade 1. Finally, it should be mentioned that any cutoff to define specific risk groups is somehow arbitrary and needs to balance sensitivity and specificity of risk identification. Identifying too many children as at-risk can be economically burdensome and may lead to the stigmatization of these children. Conversely, identifying too few can result in overlooking children who are on the borderline, thus missing the opportunity for early intervention, which is crucial particularly in the early stages.

The outcomes of the present study carry significant practical implications. In line with previous research, phonological processing and letter-knowledge were the most important predictors for reading and spelling when early reading and spelling skills cannot yet be assessed. Once children can read and spell first syllables, these early reading and spelling skills are good predictors of later literacy skills and should therefore be included in kindergarten screening tools. Importantly, the current study also highlighted predictors that were specific to either reading or spelling, already at this early stage in development. The findings particularly underscore the pivotal role of phonological processing in shaping early spelling abilities, suggesting the necessity of targeted interventions for those who struggle with phonological processing and especially with phoneme awareness. In terms of reading abilities, RAN emerged as a critical predictor over and above the autoregressor (Reading T1) and Spelling T2, and differentiated between children with and without risk for reading problems. Thus, RAN plays an important role in the diagnostic process and in the early identification of children at risk of reading problems and should therefore be part of screening and diagnostic reading tools (see for example LRS-Screening; Endlich et al., 2019). The findings support the idea that RAN signifies efficient serial processing, encompassing decoding of whole words, as well as single letters, or smaller units. Enhancing efficient serial processing by training to read frequent syllables, morphemes, and letter clusters has been shown to be effective (Thaler et al., 2004; Hintikka et al., 2008). Whether RAN itself can be effectively trained and whether training effects transfer to reading, is still a matter of debate. The few existing studies on RAN training show very inconsistent findings (Fugate, 1997; de Jong and Vrielink, 2004; Vander Stappen and Reybroeck, 2018).

The distinct predictive pattern of reading and spelling was also reflected in the predictors of Grade 1 group allocation. Phonological processing in kindergarten emerged as the most important predictor for spelling, while RAN in kindergarten was the key predictor for reading. Further investigation is needed to understand the developmental trajectories of various precursor abilities and to identify effective methods for integrating them into early education programs.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: https://osf.io/pvakt/?view_only=5629362e40344025828fc58a28f860a7.

Ethics statement

The studies involving humans were approved by Ethics Committee of the Medical Faculty of the University of Munich. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin.

Author contributions

JS: Writing—original draft, Writing—review & editing. HM: Writing—original draft, Writing—review & editing. GS-K: Writing—original draft, Writing—review & editing. KM: Writing—original draft, Writing—review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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