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Sound–symbol learning and the relationship to spelling in first-grade children



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ABSTRACT

Early spelling depends on the ability to understand the alphabetic principle and to translate speech sounds into visual symbols (letters). Thus, the ability to associate sound–symbol pairs might be an important predictor of spelling development. Here, we examined the relation between sound–symbol learning (SSL) and early spelling skills. A large sample of first-grade children ($N = 365$) was tested on well-known cognitive predictors of spelling ability (intelligence, phoneme awareness, and verbal short-term memory) and completed a novel sound–symbol learning paradigm, which required the serial application of newly learned sound–symbol correspondences to mirror spelling acquisition. The results revealed that performance on the SSL task explained unique variance in spelling performance in young children at risk of spelling problems beyond well-known cognitive predictors of spelling. The SSL task can be a useful tool for the early identification of spelling problems given that the SSL differentiated between children with poor and typical spelling skills.

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Introduction

Early spelling across alphabetic orthographies depends on the ability to identify the speech sounds (phonemes) of a spoken word, to assign the corresponding letters or letter groups (graphemes), and to

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write them down in the correct order (serial processing). Therefore, children first need to understand the alphabetic principle: Spoken words can be divided into speech sounds (phonemes) that correspond to written symbols (graphemes). At the beginning of literacy instruction, children systematically acquire these associations between speech sounds and symbols (phoneme–grapheme correspondences). This allows them to produce phonologically correct spellings, which means spelling a word the way it sounds by splitting the word into its constituting phonemes (e.g., splitting the word /hat/ into the phonemes /h/ + /æ/ + /t/) and assigning the corresponding graphemes (h + a + t) one after the other sequentially in the correct order.

Spelling of words with consistent phoneme-to-grapheme mappings can proceed along these lines. However, many words cannot be spelled correctly by simply applying phoneme–grapheme conversion rules. For example, spelling irregular words (e.g., yacht) correctly or words consisting of phonemes that correspond to several phonologically plausible graphemes (e.g., the phoneme /k/ in cat vs. kind) requires orthographic knowledge. Theories of spelling development differ in how children acquire orthographic knowledge and how different word types, such as regular words, irregular words, and nonwords, are processed (Deacon & Sparks, 2015; Treiman, 2017b; Treiman & Kessler, 2014; Westwood, 2018). According to stage and phase theories (Ehri, 2000; Frith, 2017; Gentry, 1982), children move from phonologically based spellings in the alphabetic phase to the orthographic stage by relying increasingly on morphological and orthographic patterns, including sublexical units (e.g., morphemes) and whole words stored in long-term memory as a consequence of repeated decoding of words. Similarly, dual route theories (Barry, 1994; McCloskey & Rapp, 2017; Tainturier & Rapp, 2000) distinguish between known words stored in the orthographic lexicon, which can be directly accessed via the lexical route, and words that have not (yet) been stored in the orthographic lexicon, which therefore are spelled by applying phoneme–grapheme conversion rules (sublexical route). Beginning spellers primarily rely on the sublexical route, whereas more experienced spellers increasingly use the lexical route. In contrast, connectionist models claim that all word types are processed by a single network, which develops based on experience and on the different probabilities of spelling patterns (Bullinaria, 1994; Harm & Seidenberg, 1999; Seidenberg & Zevin, 2006). Finally, the *integration of multiple patterns* (IMP) theory (Treiman, 2017a; Treiman & Kessler, 2014) combines different approaches by suggesting that spelling and spelling development rely on a variety of spelling patterns, including phoneme–grapheme correspondences, morphological knowledge, and probabilistic patterns. Despite these differences between spelling theories, they all highlight the importance of the alphabetic principle and of learning phoneme–grapheme correspondences at the beginning of learning to spell. The current study focused on this early developmental stage by trying to better understand the mechanisms that are involved in phonologically based spelling in beginning spellers (Grade 1).

Therefore, we developed a sound–symbol learning (SSL) paradigm, which allowed us to assess the different processes of learning the alphabetic principle. This involves being aware of a word’s constituting sounds (phoneme awareness) and knowing how speech sounds are linked to their corresponding letters (phoneme–grapheme correspondences) (Caravolas et al., 2005; Otaiba et al., 2010; Ritchey, 2008). In addition, writing a word further involves recalling and writing down all the graphemes in the word in the correct order. For example, when a child wants to spell the dictated German word “Maus” (mouse) for the first time, the word needs to be divided into its three constituting phonemes /m/, /av/, and /s/. These phonemes need to be mapped to the corresponding graphemes “M”, “au”, and “s”, which can then be written down one after the other in the correct order (= serial processing). Therefore, it can be assumed that phoneme awareness together with sound–symbol learning plays an important role during the beginning of spelling development. Although the importance of phoneme awareness for early spelling development has been repeatedly shown across different alphabetic orthographies (Caravolas et al., 2001; Cataldo & Ellis, 1988; de Bree & van den Boer, 2019; Diamanti et al., 2017; Furnes et al., 2019; Furnes & Samuelsson, 2010; Lervåg & Hulme, 2010; Nielsen & Juul, 2016), including German (Landerl & Wimmer, 2008; Sigmund et al., 2024), the role of SSL, and how SSL relates to spelling over and above phoneme awareness, has not yet been examined.

Previous studies assessing SSL have focused on the reading process (see “Sound–symbol learning” section for more details). Importantly, results from reading research cannot be directly transferred to spelling for several reasons. First, spelling is considered more difficult than reading (Bosman & Van Orden, 1997). One reason is that symbol–sound processing (reading direction) only requires the

recognition of graphemes presented in a given order, whereas sound–symbol processing (spelling direction) requires the recall of all graphemes in the correct order. Another reason is that in most alphabetic writing systems, including German, the relationship between phonemes and graphemes (spelling direction) is less consistent than the relationship between graphemes and phonemes (reading direction) (Galuschka et al., 2020). Second, several studies have shown that the development of reading and spelling as well as problems in the two literacy domains can dissociate (Bruck, 1990; Bruck & Waters, 1990; Fayol et al., 2009; Frith, 1980; Holmes & Castles, 2001; Moll et al., 2020; Wimmer & Mayringer, 2002) and that reading and spelling disorders are at least partly associated with different underlying cognitive deficits (e.g., (Mehlhase et al., 2020; Moll & Landerl, 2009).

Understanding the processes underlying typical as well as atypical spelling acquisition therefore is of high relevance, especially in the early stage of spelling development. The high prevalence of spelling disorders, without or with concurrent reading disorders, makes it urgent to investigate early spelling in more detail and to identify possible influencing factors and predictors, particularly because previous studies have shown that spelling ability also affects more advanced literacy skills such as text production. Children with spelling problems write fewer words than good spellers (Abbott et al., 2010; Moats et al., 2006), and they receive lower grades on their text productions due to more spelling errors, even when producing the same content as children with good spelling skills (Graham et al., 2011). Consequently, spelling problems have serious negative effects on academic careers and also affect individual well-being (Carroll et al., 2005).

Because our SSL task is the first to model the spelling process, our results can contribute to a better understanding of spelling development. In addition, our SSL task might be a useful tool for early identification of children at risk of spelling disorders, which in turn can contribute to early intervention in order to prevent pronounced spelling problems.

Sound–symbol learning

Previous studies focused on the relationship between symbol–sound learning (reading direction) and reading performance (Aravena et al., 2013; Blomert & Vaessen, 2009; Ehm et al., 2019; Elbro et al., 2012; Gellert & Elbro, 2018; Horbach et al., 2015, 2018), whereas studies examining sound–symbol learning (spelling direction) are very rare (for an exception, see Aravena et al., 2013). To the best of our knowledge, no previous study assessed the spelling process of newly learned phoneme–grapheme correspondences.

In addition to the learning direction (symbol–sound vs. sound–symbol learning), learning tasks differ in several aspects. First, stimuli for the learning task can be familiar letters or an artificial orthography. Using artificial orthographies, where symbols or unfamiliar letters (e.g., in Hebrew) are used, has the advantage of eliminating possible influences from previous print exposure. Thus, the symbols to be learned are novel for all learners, allowing assessing the learning process independent of previous print exposure and letter knowledge. Second, it is important to distinguish between simple sound–symbol associations (paired associate learning (PAL)) and the application of the learned associations when writing a letter string using the learned symbols. To go beyond pure sound–symbol mapping and to mirror the spelling process, studies that investigate the serial application of the learned correspondences are needed.

Because we are not aware of any study that has investigated the serial application of learned associations in the spelling direction, we report on studies that have investigated the reading direction. In an artificial orthography setting, Aravena et al. (2013) examined letter–speech sound learning comparing typically developing children and children with dyslexia. Both letter knowledge (= letter naming) and word reading ability (= serial application) within the artificial script (unfamiliar letters in Hebrew) were assessed. The authors found that typically developing children outperformed children with dyslexia on the word reading task (= serial application) containing words written in the artificial orthography. However, these differences were independent of their knowledge of single artificial letters given that no group differences were found in naming the artificial letters after training. In contrast to the study of Aravena et al. (2013), where the participants already had reading experience (age range from 7.5 to 12.4 years), Horbach et al. (2015, 2018), and Gellert and Elbro (2018) studied pre-school children and depicted the reading process systematically. In the symbol–sound learning task of

Horbach et al. (2015), the children needed to learn the association between two graphical symbols (● and –) and their corresponding sounds (/ta/ and /ma/). First, the symbols were presented separately on the screen and the children needed to name the corresponding sound, similar to a classical PAL task. Next, several symbols were presented together in a string of two symbols, and later of three or four symbols, and the children needed to recall the string (= serial application) of the newly learned associations (● – – corresponds to /ta ma ma/). One year later in first grade it was found that after controlling for phonological awareness, verbal short-term memory, and rapid automatized naming, the symbol–sound paradigm (SSP; = serial application) explained additional variance (8%) in first-grade word reading in the preliterate non-readers group. In another study by Horbach and colleagues (2018), the predictive value of SSP using the same paradigm was even higher, explaining more than 62% of the variance in reading performance 3 years later (after controlling for IQ, letter knowledge, and age). Similar to the SSP of Horbach et al. (2015), Gellert and Elbro (2018) administered a decoding task in kindergarten, where children were taught three artificial letters and their corresponding sounds (▮ = /s/, ◊ = /m/, and ◼ = /α/ as in *calm*) and how to read nonwords built of these three artificial letters (e.g., ◊ ◼ ▮ ◼ [masa]). The decoding task (reading of syllables and words within the artificial script) explained an additional 11% of the variance in later (end of Grade 1) reading after controlling for kindergarten measures (i.e., letter knowledge and phoneme identification; accounting for 41% variance). However, none of these studies analyzed the opposite direction (sound–symbol learning) and the relationship with spelling abilities.

To the best of our knowledge, the study of Aravena and colleagues (2018) is the only one that examined sound–letter learning in relation to standardized reading *and* spelling. However, Aravena and colleagues did not ask children to spell within the artificial orthography (i.e., draw the symbol sequence that corresponds to the dictated word), and therefore they did not investigate the spelling process directly. They developed a sound–letter training in which children needed to learn eight speech sound–letter pairs within an artificial orthography. In the training, the children needed to match familiar speech sounds (Dutch phonemes) to their corresponding orthographic representations (unfamiliar Hebrew letters). After the training, sound–letter identification (matching task) and word reading ability (= serial application) in the artificial script were assessed. Spelling within the artificial orthography was not measured. The authors found that the training was able to differentiate between typical and poor readers. Typical readers outperformed poor readers on both the sound–letter identification task and the word reading task. Within the group of poor readers, reading speed (in a standardized reading test) correlated significantly with sound–letter identification speed, whereas spelling (in a standardized spelling test) correlated significantly with sound–letter identification accuracy. Both reading and spelling showed a strong correlation with the serial application of the learned sound–letter correspondences in the artificial word reading task (words per second).

To the best of our knowledge, no previous study examined sound–symbol learning in the context of spelling. Previous studies concentrated on depicting the reading process or on PAL (matching tasks). Studies that model the spelling process, and in which children need to produce dictated written words (= serial application) in the artificial orthography, are missing. The current study aimed to close this gap. Therefore, we developed a sound–symbol learning task to mirror the spelling process and analyzed whether this task predicts differences in early spelling ability in children with and without spelling difficulties.

The current study

The aim of the current study was to model spelling acquisition by examining the role of serial application of newly learned sound–symbol correspondences and its association with early spelling skills. For this reason, we designed an SSL task using an artificial orthography (i.e., symbols) to assess sound–symbol learning independent of the children's letter knowledge and previous print exposure. The sound–symbol learning task was developed based on the symbol–sound learning paradigm (reading direction) by Horbach and colleagues (2015, 2018), who assessed children in the same age range. To model the spelling process, we modified their task by changing the direction. Instead of naming written symbols, the children in our task heard a sound string (nonword) and were asked to draw the corresponding symbols.

More specifically, we wanted to examine possible differences in SSL performance between typically developing spellers and children at risk of spelling disorders. The second aim was to investigate performance in SSL and its association with spelling skills using correlation analyses. To investigate the unique contribution of performance on our SSL task in predicting spelling abilities, a series of regression analyses were run (i.e., for the whole sample and also separately for typical and poor spellers) controlling for well-known predictors of spelling, namely phoneme awareness (PA), verbal short-term memory (verbal STM), and intelligence (IQ).

Method

Participants and procedure

The current study is part of a longitudinal study assessing the development of spelling skills from kindergarten to Grade 3. At Time 2 (middle of Grade 1), each child was tested individually on spelling skills, on well-known cognitive predictors of literacy skills (PA, verbal STM, and IQ), and on the SSL task.

A total of 372 students participated in the SSL task. Due to examiner errors, 7 children needed to be excluded from the analyses because of missing data on the SSL task. Thus, in this article we report results from 365 students with complete data sets. The mean age was 83.5 months ($SD = 4.4$), and 46% were boys. Inclusion criteria were an average scaled score on the two subtests Block Design and Vocabulary from the Wechsler Intelligence Scale for Children–Fifth Edition (WISC-V; Wechsler, 2017) of at least 4 ($IQ \geq 70$), German language skills for at least 3 years, normal or corrected-to-normal vision, and the absence of neurological deficits. The children went to 238 classes in 136 schools in rural and urban areas in and around the city of Munich, Germany. The majority of children were in schools located in urban areas; only 7% of the children were in schools in rural areas (12 children with at-risk spelling and 15 children with typical spelling skills). The study was approved by the institutional ethics committee 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.

All measures were administered individually by trained assistants in a quiet room at the LMU University Hospital. The testing period to test all 365 children started in January in Grade 1 (about 4 months after the start of formal literacy instruction) and covered 3 months to the beginning of April. In Germany, letters (graphemes) and letter sounds (phonemes) are not systematically taught in kindergarten, and formal literacy instruction does not start until Grade 1. Thus, our children in Grade 1 can be seen as beginning spellers. The distinction between children with at-risk spelling and children with typical spelling skills was based on their performance on the standardized spelling test HSP 1 Plus (May et al., 2019). Children with spelling performance at or below the 25th percentile were assigned to the at-risk spelling group ($n = 85$; 43.5% girls), and children belonging to the typical spelling group had a spelling performance above the 25th percentile ($n = 280$; 55.5% girls).

Measures

To identify any potential differences in performance due to developmental changes in the 3-month assessment period, we first compared the means of all variables for the 3 months. Significant increases in performance between the monthly means were observed for PA and spelling. Therefore, these two variables were z-standardized separately for each month based on the current sample.

Intelligence measure

Two primary subtests from the German version of the WISC-V (Wechsler, 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. This subtest (split-half reliability: $r_{tt} = .84$; convergent validity: Wechsler Adult Intelligence Scale–Fourth Edition [WAIS-IV]

$r = .76$) belongs to the visual–spatial index and reflects the ability to understand visual–spatial relationships and requires efficient hand–eye coordination. Vocabulary required children to name depicted objects and/or define words that were read aloud by the experimenter and is assigned to the verbal comprehension index. The subtest (split-half reliability: $r_{tt} = .86$; convergent validity: WAIS-IV $r = .67$) captures children’s ability to verbalize meaningful concepts and to access word knowledge. The two subtests were combined to receive an estimate of intelligence including nonverbal and verbal scores. The average of the scaled scores of the two subtests is reported (population mean is 10 and the standard deviation is 3).

Verbal short-term memory

The digit span test from the standardized Kaufmann Assessment Battery for Children-II (K-ABC; Melchers & Melchers, 2015) was assessed. Children needed to repeat a series of digits of increasing length (from two to nine digits) that were verbally presented by the experimenter. The digit span test has a retest reliability of $r_{tt} = .88$ and a convergent validity of $r = .53$ WISC-IV (working memory). The score was the number of correctly repeated series.

Phoneme awareness

Two tasks (phoneme identification and phoneme deletion) developed in our lab were used. In the first subtest, children needed to identify the first or last phoneme of a word/pseudoword (four words and four pseudowords). In the second subtest, children needed to pronounce a word/pseudoword (four words and eight pseudowords) without a specified phoneme (phoneme deletion task). Both subtests included 2 practice trials. Cronbach’s alpha (sample-based) was .83 for the first subtest and .84 for the second subtest. The average accuracy in percentage of the two subtests was measured. To account for the significant increase in performance over the 3-month assessment period, scores were z-standardized separately for each month of testing based on the current sample.

Spelling

Spelling was assessed using the standardized spelling test HSP 1 Plus (May et al., 2019). Children needed to write four high-frequency words and one sentence consisting of six words dictated by the experimenter. The score was the number of correctly spelled graphemes (max = 40). The test has an internal consistency of .94, according to the manual. To account for the significant increase in performance over the 3-month assessment period, scores were z-standardized separately for each month of testing based on the current sample.

Sound–symbol learning task

Based on the symbol–sound learning paradigm of Horbach et al. (2015) simulating the reading process, we designed a sound–symbol learning paradigm to simulate the spelling process and to examine the relationship between SSL and early spelling skills. Our SSL task consisted of four consecutive parts: introduction phase, Training Phase 1, Training Phase 2, and testing phase (Fig. 1). The introduction and first training phase were similar to a verbal–visual PAL task, and children needed to associate sounds to graphical symbols. In the second training phase and the test phase, the serial application of the second training phase and the test phase of the newly learned sound–symbol correspondences was required. Thus, serial assignment was already required in Training Phase 2, but to a lesser extent than in the test phase. To reduce working memory load, we implemented only three different symbols (○, –, and +), which were visible to the children during the entire experiment.

Introduction phase. The SSL task started with the introduction phase, where three syllable sounds (/ta/, /ma/, and /sa/) and the corresponding symbols (○, –, and +) were presented by the experimenter. Based on Horbach’s symbol–sound learning paradigm (Horbach et al., 2015) we used syllables instead of single phonemes to facilitate sound identification in the training phases. The vowel of each syllable was kept constant (/a/) to reduce memory load. The children were told that they were going to learn the foreign language of some aliens (which they had seen in an earlier task) and that the unique aspect about the aliens’ language is that the aliens do not use normal letters but rather different symbols. Next, the experimenter presented the three symbols on a white A4-size piece of paper and named

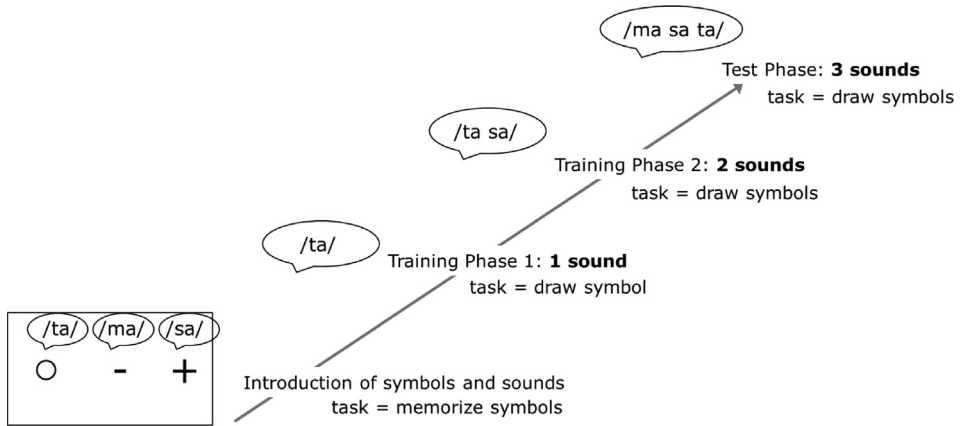


Fig. 1. Procedure of the sound-symbol learning task.

the sound of each symbol twice (e.g., “This symbol is called /ta/”) while pointing at the symbol. The children were asked to listen carefully and to memorize the syllable sound of the corresponding symbol: /ta/ = ○, /ma/ = −, and /sa/ = +.

Training phase 1. The first training phase followed directly after the introduction. In Training Phase 1, six syllable sounds were named by the experimenter (each sound two times) in a fixed order, and the children needed to draw the corresponding symbol. Feedback was given after each sound. If the children drew the correct symbol, they received positive feedback (e.g., “Yes, correct, this symbol is called /ta/” while pointing at the symbol), and then the experimenter moved on to the next sound. If the drawn symbol was incorrect, the experimenter provided negative and corrective feedback (e.g., “No, this symbol is called /ma/” while pointing at the symbol), and the trial was repeated by the experimenter. The children had a maximum of three attempts per sound. If they drew the symbol correctly on the first attempt, they received 3 points, then 2 points on the second attempt, and 1 point on the third attempt. If they did not manage to draw the correct symbol on the third attempt, they got 0 points. The total score of Training Phase 1 was the percentage of achieved points of a maximum of 18 points (6 sounds × 3 points).

Training phase 2. The second training phase followed directly after Training Phase 1. In the second training phase, each trial consisted of two sounds. Children needed to draw two of the recently learned symbols named by the experimenter in a string of two sounds (e.g., named sounds: “/ta ma/”; correct drawing: “○ −”). Because the children now needed to process two sounds in the correct order, serial application of two of the learned associations was required. Feedback was given in the same way as in the first training phase. Again, the children had a maximum of three attempts per trial and received 3 points if the first attempt was correct, 2 points if the second was correct, 1 point if the third attempt was correct, and 0 points for an incorrect answer on the third attempt. An attempt/trial was correct, when both symbols were drawn correctly. In total, there were 6 trials, and the score was the percentage of the achieved points of a maximum of 18 points (6 sounds × 3 points).

Test phase. The second training phase was followed directly by the test phase, which was the main outcome measure of the SSL task. In the test phase, the serial application of three learned sound-symbol correspondences was required. The test phase consisted of 8 trials with three sound strings. The sound strings were named by the experimenter in the same way as in the training phase (e.g., named sounds: “/ta sa ma/”; correct drawing: “○ + −”) except that feedback was no longer given. The children had only one attempt to draw the three symbols, and an attempt was correct if all three symbols were drawn correctly and in the correct order. Thus, the maximum was 8 correctly solved trials. The score was the percentage of correct trials.

Results

Participant descriptives

Table 1 shows descriptives (means and standard deviations) and the results from the group comparisons (one-way multivariate analysis of variance) between children at risk of spelling problems and typically developing spellers. Children with typical spelling skills exceeded the at-risk group in all measures. Regarding age, the effect size was only small and children with typical skills were only 1.5 months older than the at-risk group of children. Differences due to the duration of school attendance and developmental aspects at the assessment were taken into account using the described z-standardization for PA and spelling. In line with the literature, children with typical spelling skills showed higher PA skills and better verbal STM than the group of children at risk of spelling problems. The two groups also differed in the IQ measure, with higher performance in the typically developing children. However, it should be noted that the mean IQ value of children at risk of spelling problems was average and corresponded to the population mean of the norm sample. To account for differences in PA, verbal STM, and IQ, we accounted for these variables in the hierarchical linear regression analysis. Regarding sex distribution, the groups did not differ significantly, $\chi^2(1) = 3.76, p = .052$. Reflecting the group classification, the two groups of children differed significantly in their spelling skills with large effect sizes.

Performance on the SSL task

A repeated-measures analysis of variance (Greenhouse–Geisser corrected) was run with the task phase (Training Phase 1, Training Phase 2, or test phase) as the within-participant factor and group (at-risk or typical spellers) as the between-participants factor. A significant main effect of task phase, $F(1.15, 417.67) = 243.43, p < .001$, was found. In both groups, performance decreased significantly from phase to phase (Fig. 2), reflecting the increasing task difficulty.

A significant main effect of group, $F(1, 364) = 25.09, p < .001$, reflected the generally poorer performance on the SSL task of children at risk of spelling problems compared with children with typical spelling skills. Importantly, the main effects were modified by a significant interaction between task phase and group, $F(1.15, 417.67) = 10.88, p = .001$. The interaction reflects that both groups started at the same high-performance level in Training Phase 1 (at-risk group = 95.10% correct; typical spelling group = 97.19% correct; mean difference = 2.09%) and did not differ after correction for multiple testing, $t(100,41) = -2.10, p = .04$. In contrast, in Training Phase 2, the performance of children in the typical spelling group was significantly higher compared with the children in the at-risk spelling group, $t(102,96) = -4.33, p < .001$. The group difference was further increased in the test phase, $t(130,21) = -3.88, p < .001$ (see Table 2). This suggests that the at-risk spelling group was specifically impaired in the serial application of the newly learned associations (Training Phase 2 and test phase) compared with the typical spelling group. Given that the two groups of children differed regarding age and IQ, which might affect performances in the learning task, we also conducted an analysis with a sub-sample of $n = 200$ typical spellers that corresponds to the at-risk group with regard to age and IQ, which led to similar results.¹

Association between SSL and spelling performance

First, Pearson correlation coefficients were calculated between the predictors and spelling performance separately for the two groups. For children with typical spelling skills, PA ($r = .355$), verbal STM ($r = .227$), and IQ ($r = .234$) were moderately correlated with spelling performance (all $ps < .001$). The SSL test phase ($r = .147, p = .007$) showed only weak associations with spelling. In children at risk of spelling problems, PA ($r = .602$) was strongly correlated with spelling ($p < .001$), whereas verbal STM

¹ The additional analyses with a subsample of the group of typical spellers revealed no differences between the two groups in Training Phase 1 after correction for multiple testing, $t(283) = -2.32, p = .02$, but found significant differences in Training Phase 2, $t(115,95) = -3.68, p < .001$, and in the test phase, $t(283) = -3.39, p < .001$.

Table 1
Descriptives (means and standard deviations and group comparisons).

	At-risk spelling (<i>n</i> = 85; 43.5% girls)		Typical spelling (<i>n</i> = 280; 55.5% girls)		<i>F</i>	<i>p</i>	Cohen's <i>d</i>
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>			
Age	82.36	4.27	83.90	4.33	8.28	.004	0.30
IQ	10.24	2.28	11.60	2.05	27.15	<.001	0.55
PA	-0.89	1.16	0.32	0.67	146.10	<.001	1.28
Verbal STM	8.60	2.02	10.30	2.16	41.85	<.001	0.68
Spelling	-1.26	1.13	0.43	0.31	563.56	<.001	2.35

Note. Age in months; IQ, intelligence scaled scores (*M* = 10, *SD* = 3); PA, phoneme awareness (z-scores); Verbal STM, verbal short-term memory (row scores); Spelling, correct graphemes (z-scores).

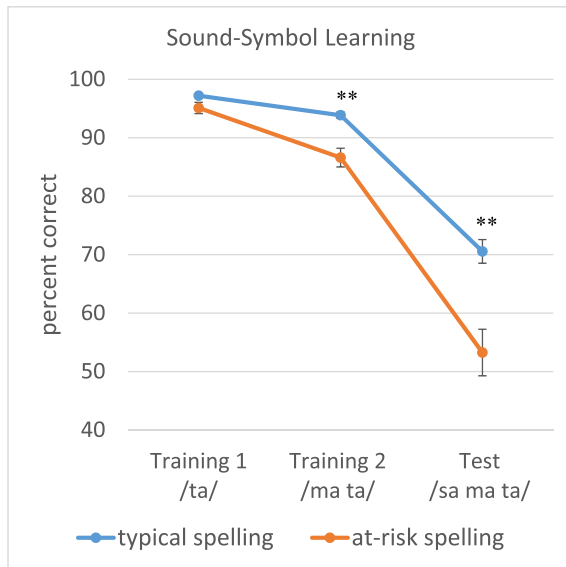


Fig. 2. Performance on the phases of the sound-symbol learning task in the two groups. ***p* < .001.

Table 2
Performance (percentages correct) in the phases of the sound-symbol learning task in the two groups.

	At-risk spelling	Typical spelling	<i>t</i>	<i>p</i>
Training Phase 1 (max = 18 points)	95.10% (17.12)	97.19% (17.49)	-2.10	.04
Trainings Phase 2 (max = 18 points)	86.60% (15.59)	93.85% (16.89)	-4.33	<.001
Test phase (max = 8 points)	53.24% (4.26)	70.55% (5.64)	-3.88	<.001

Note. Points are in parentheses.

(*r* = .328, *p* = .001), IQ (*r* = .270, *p* = .006), and SSL (*r* = .236, *p* = .015) were moderately correlated with spelling performance.

Before running the regression analysis to investigate whether the serial application of newly learned sound-symbol correspondences (SSL test phase) explains variance in early spelling skills beyond the well-known cognitive predictors of spelling, we tested whether the requirements for

Table 3
Hierarchical linear regression model predicting spelling performance.

	Children with at-risk spelling (<i>n</i> = 85)					Children with typical spelling (<i>n</i> = 280)				
	<i>t</i>	<i>p</i>	<i>R</i>	<i>R</i> ²	ΔR^2	<i>t</i>	<i>p</i>	<i>R</i>	<i>R</i> ²	ΔR^2
Step 1	–2.66	.009	.62	.38	.38**	–0.04	.969	.40	.16	.16**
IQ	1.41	.164				2.11	.036			
PA	5.65	<.001				4.98	<.001			
STM	0.52	.608				2.05	.041			
Step 2	–2.38	.020	.65	.43	.05*	–0.31	.759	.41	.17	.01
IQ	0.69	.490				2.06	.040			
PA	6.20	<.001				4.78	<.001			
STM	0.04	.971				1.95	.053			
SSL	2.56	.012				1.33	.186			

Note. PA, phoneme awareness; STM, verbal short-term memory; SSL, sound-symbol learning testing phase.

* $p < .05$.

** $p < .001$.

linear regression analyses were met. Given that spelling performance was not normally distributed (skewness = –2.51 and kurtosis = 8.04), we also ran the analysis with logarithmically transformed spelling values (skewness = –1.16 and kurtosis = 1.59), which led to similar results.² Therefore, we report the analysis based on the raw data. In Step 1, the well-known cognitive predictors of spelling (IQ, PA, and verbal STM) together explained 48% of the variance in spelling, with PA accounting for the largest unique proportion (27%). After controlling for these predictors, SSL explained an additional 1% of the variance, which was significant ($p = .003$).

Next, we conducted separate regression analyses for children at risk of spelling problems and children with typical spelling skills to investigate whether the influence of SSL test phase differs among children with different spelling abilities (Table 3). For children with typical spelling skills, Step 1 (IQ, PA, and verbal STM) explained 16% of the variance in spelling performance. After controlling for common spelling predictors, the SSL test phase did not contribute significantly to the explained variance in spelling ($p = .19$). Two of the well-known predictors explained a significant amount of unique variance (IQ = 1% and PA = 7%) in Step 2, and 7% of the variance was predicted by the shared variance of the four predictors (IQ, PA, STM, and SSL). Among the children at risk of spelling problems, Step 1 explained 38% of the variance in spelling performance. After controlling for the cognitive predictors, the SSL test phase significantly explained variance in spelling ability (5%). Thus, the serial application of newly learned sound-symbol correspondences significantly resolves variance in spelling performance in young children at risk of spelling problems beyond well-known cognitive spelling predictors. Besides SSL, only PA contributed significantly to the explained variance (27%) in Step 2, and 11% of the variance was predicted by the shared variance of the four predictors (IQ, PA, STM, and SSL).

Discussion

The aim of the current study was to explore the role of serial application of newly learned sound-symbol correspondences in predicting spelling skills. A large sample of first-grade children completed a novel sound-symbol learning paradigm, which was developed to mirror spelling acquisition. The results revealed that performance on the SSL task explained additional and a significant amount of variance in spelling, especially in children at risk of spelling problems.

² In the regression analysis including logarithmically transformed spelling values, the well-known cognitive predictors of spelling (IQ, PA, and verbal STM) together explained 48% of the variance in spelling in Step 1. After controlling for these predictors, the SSL explained additional variance (1%, $p = .002$).

To depict the process of learning to spell, we developed a task in which children first needed to learn the association between sounds and symbols, similar to a classical paired-associate learning (PAL) task. Then, in the next step, a string of two- and three-syllable sounds was presented and the children needed to recall them sequentially one after the other in the correct order. Results showed that both groups had no difficulties in learning the sound–symbol associations in Training Phase 1, which means that there were no differences in PAL between children with typical spelling skills and children at risk of spelling problems. In Training Phase 1, the three sounds were presented one by one and nearly all children easily drew the corresponding symbol for the sound. Our results are in line with existing studies examining PAL in children with dyslexia (e.g., [Litt & Nation, 2014](#); [Mehlhase et al., 2019](#)) that have shown that performance difficulties largely depend on the output modality and are only evident in PAL tasks with verbal output (e.g., visual–verbal and verbal–verbal tasks). Our task is based on the symbol–sound learning paradigm simulating reading acquisition of [Horbach et al. \(2015\)](#). In contrast to our results, Horbach et al. reported that early readers in kindergarten outperformed their non-reading peers even in the first phase of their experiment. Given that their experiment required a verbal output, their findings together with ours are in line with the literature and suggest that children with dyslexia are only impaired when verbal output is required. However, an alternative interpretation is that the first training phase was too easy (ceiling effect) to differentiate between the two groups. We decided to use only three symbols (after piloting) to ensure that the children can master the more complex test phase of the SSL paradigm, which was our main interest. Thus, we cannot rule out that children at risk of spelling problems are affected when they need to learn more than three sound–symbol associations. Thus, future research needs to investigate whether sound–symbol learning in Training Phase 1 (PAL) is indeed unaffected when a larger number of pairs need to be learned.

When analyzing performance in the other two phases of our sound–symbol learning paradigm, a difference between the two groups emerged. In contrast to Training Phase 1, the other phases (i.e., Training Phase 2 and even more so the test phase) required the serial application of the newly learned sound–symbol pairs, thereby increasing the demands in comparison with a standard PAL task. Especially in the test phase with the highest demand on serial application of three sound–symbol associations, the typical spelling group clearly outperformed the group at risk of spelling problems. Comparing our results on spelling with previous research on reading, a number of similarities emerge. In line with our findings, [Aravena and colleagues \(2013\)](#), who examined SSL in the reading direction, also reported differences between non-dyslexic and dyslexic readers in applying knowledge of new symbol–sound correspondences in a serial reading task. Just as in our findings, group differences were restricted to the serial application but did not occur when comparing the groups on their knowledge of single sound–symbol pairs. In addition, [Aravena et al. \(2018\)](#) showed that the serial processing of the learned letter–speech sound associations (number of words read correctly per second within the artificial orthography) accounted for a significant amount of variance in predicting reading speed (34%) and spelling to dictation (37%). Furthermore, the reading task within the artificial orthography (= serial application) explained more variance in reading and spelling ability compared with a sound–symbol matching task where the sounds were presented one by one. Thus, together with previous research, our results suggest that the serial processing component is affected in children at risk of spelling problems. Our findings extend previous research by showing that already very early in spelling acquisition, the serial component seems to be a relevant factor associated with spelling performance. It is important to note that the test phase and Training Phase 2 differ from Training Phase 1 in their complexity and therefore place greater demands on the phonological system (due to the processing of two and three sound–symbol pairs). We assume that the group differences in the test phase and Training Phase 2 result from the greater demands in these tasks that have a stronger impact on children at risk of spelling problems due to their impaired phonological system. Our paradigm does not allow us to differentiate whether poorer performance in the test phase results from difficulties in keeping to the sequence of correctly assigned sound–symbol pairs or from difficulties in storing the correct sound–symbol pairs in long-term memory in order to maintain them over time. However, the paradigm was able to show that the test phase, with its complex demands on the phonological system, was able to differentiate between the groups beyond pure mapping (Training Phase 1).

Furthermore, we investigated the predictive role of the performance in the test phase of the SSL task and found that the SSL test phase explained unique variance in spelling performance over and above well-known cognitive predictors of spelling (PA, IQ, and verbal STM). More important, when conducting separate regression analyses for children at risk of spelling problems and children with typical spelling skills, it turned out that the effect was driven by the lower end of the distribution. After controlling for PA, IQ, and verbal STM, performance in the SSL test phase explained unique variance in spelling performance in the at-risk group but not in the typical spelling group. The findings suggest that given that the typical spellers have already mastered the phoneme-grapheme association and its serial application in the spelling process (alphabetic principle), performance on the SSL task, which mirrors this process, can no longer make an additional contribution in explaining individual differences in spelling skills. Our findings are in line with those reported for reading by [Horbach et al. \(2015\)](#), who found that their SSL task (test phase) explained a significant amount of variance in the non-readers group but not in the readers group. To conclude, the SSL paradigm used in our study was able to differentiate between children with poor and typical spelling skills and therefore might be suitable for identifying children at risk of spelling difficulties in the early phase of spelling acquisition.

We also controlled for well-known cognitive predictors and analyzed the associations between phoneme awareness, verbal short-term memory, and intelligence and early spelling skills. PA turned out to be the strongest predictor of early spelling skills in the whole sample and in both subgroups, which is in line with many previous studies supporting the importance of PA for spelling (e.g., [Caravolas et al., 2001, 2005](#); [Cataldo & Ellis, 1988](#); [Gentry, 1982](#); [Henderson & Beers, 1980](#)). For example, [Cataldo and Ellis \(1988\)](#) found in their longitudinal study that PA predicted spelling ability in the first years of school. [Caravolas and colleagues \(2001\)](#) followed the spelling progress of British schoolchildren and found that spelling development was predicted consistently by phoneme isolation skills over the first 1½ years of schooling. The association between PA and spelling was found not only in English but also in other orthographies such as Norwegian ([Lervåg & Hulme, 2010](#)), Danish ([Nielsen & Juul, 2016](#)), Greek ([Diamanti et al., 2017](#)), and German ([Landerl & Wimmer, 2008](#); [Moll & Landerl, 2009](#)). Thus, our results confirm previous findings and support the importance of PA for early spelling.

In addition to PA as a proximal cognitive predictor of spelling, we also included potentially relevant factors that might affect learning more generally like verbal STM and IQ. We found that verbal STM and IQ correlated moderately and significantly with spelling performance in first-grade children. Previous studies showed that general cognitive abilities and working memory skills independently predict spelling (e.g., [Alloway & Alloway, 2010](#); [Schneider & Niklas, 2017](#); [Zarić et al., 2021](#)). For example, [Schneider and Niklas \(2017\)](#) found that working memory and IQ explained a significant amount of additional variance in spelling performance (working memory = 4% and IQ = 10%) at Grade 2 after controlling for participants' age, sex, and socioeconomic status. [Zarić and colleagues \(2021\)](#) also found that general intelligence contributed significantly to spelling performance, explaining 10% of the variance, and [Lervåg and Hulme \(2010\)](#) showed that verbal STM predicted word and non-word spelling in Norwegian children. Although the significant correlations of verbal STM and IQ with spelling could confirm previous findings, we only found significant or marginally significant contributions of verbal STM and IQ to the explained variance in spelling in the typical spelling group, but not in children at risk of spelling problems. The different contributions of verbal STM and IQ are likely due to the different influence of PA in the two groups. PA explained a much higher amount of variance in the at-risk group (27%) than in the group of typical spellers (7%). Therefore, it is likely that the strong influence of PA overshadows the influence of STM and IQ in the at-risk group. Previous studies have shown that PA has a decisive influence specifically on early spelling performance and that this influence decreases over time in more consistent orthographies ([de Jong & van der Leij, 1999](#); [Landerl & Wimmer, 2000](#)). Therefore, PA mainly plays a role in early spelling development, where the focus is on building letter-sound correspondences and on applying the alphabetic principle (i.e., to spell a word the way it sounds). After this goal is achieved, the impact of PA decreases and other factors, such as orthographic or morphological processing skills, become more important. The at-risk spellers were still in the alphabetic phase and were in the process of learning to spell phonetically correctly, and therefore both PA and SSL played an important role here. In contrast, the children in the typical spelling group had already understood the decoding mechanism and could already spell many words

phonetically correctly (as evident from the standardized spelling test), so that the influence of PA probably decreased and other factors, in this case verbal STM and IQ, were able to gain influence. Verbal STM and IQ are likely to play an increasing role in more complex tasks such as orthographic processing, where learning spelling rules is more important.

Limitations and future research

The current cross-sectional study showed that the SSL task is a useful paradigm to simulate the spelling process. However, we cannot draw conclusions about the longitudinal predictive power of the SSL task. Future research should investigate whether the association between SSL and spelling will last into second grade and whether performance on the SSL task in first grade still predicts spelling skills in second grade.

Nearly all children were able to master the sound–symbol assignment in Training Phase 1 very well, resulting in a ceiling effect in the first training phase. To be able to assess individual differences in Training Phase 1, an extended set of sound–symbol pairs need to be used in this phase.

Furthermore, the current findings do not allow for differentiating whether poorer performance in the test phase in children at risk of spelling problems is a consequence of keeping to the sequence of correctly assigned sound–symbol pairs or of difficulties in maintaining the learned sound–symbol associations until the test phase. The latter explanation seems unlikely given that there was only the short Training Phase 2 between the test phase and the Training Phase 1, and at-risk children already showed difficulties in Training Phase 2, which followed directly after Training Phase 1. Nevertheless, we cannot completely rule out this alternative explanation. Future research should add one-syllable trials to the test phase to differentiate between these alternative explanations.

Finally, because our SSL task is independent of formal spelling instruction and children's letter knowledge, it would be conceivable to use the task with preschool children. Future studies could examine the application of our SSL paradigm in kindergarten. Due to the use of symbols and the reduced verbal memory load of the syllable sounds, the SSL task might also be suitable for children with impaired language skills. Therefore, future studies could investigate performance differences in the SSL task in children with and without language problems. Furthermore, the task could be used for cross-linguistic comparisons given that it is not limited to a specific language.

Conclusion

The current study showed that the serial application of newly learned sound–symbol correspondences explains variance in spelling performance in young children at risk of spelling problems beyond well-known cognitive predictors of spelling. The SSL task (Testing Phase 2 and the test phase) differentiates between children at risk of spelling problems and typically developing spellers and therefore might be a useful tool for the early identification of children at-risk of spelling problems. The task is independent of formal spelling instruction and children's letter knowledge. Therefore, the task could be used even before school enrollment in order to recognize potential problems at an early stage.

CRediT authorship contribution statement

Heike Mehlhase: Writing – review & editing, Writing – original draft, Project administration, Investigation, Data curation. **Jan Luis Sigmund:** Writing – review & editing, Writing – original draft, Data curation. **Gerd Schulte-Körne:** Writing – review & editing, Writing – original draft, Funding acquisition, Conceptualization. **Kristina Moll:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Funding acquisition, Conceptualization.

Data availability

Data will be made available on request.

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