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Auditory attention influences trajectories of symbol–speech sound learning in children with and without dyslexia

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ABSTRACT

The acquisition of letter–speech sound correspondences is a fundamental process underlying reading development, one that could be influenced by several linguistic and domain-general cognitive factors. In the current study, we mimicked the first steps of this process by examining behavioral trajectories of audiovisual associative learning in 110 7- to 12-year-old children with and without dyslexia. Children were asked to learn the associations between eight novel symbols and native speech sounds in a brief training and subsequently read words and pseudowords written in the artificial orthography. We then investigated the influence of auditory attention as one of the putative domain-general factors influencing associative learning. To this aim, we assessed children with experimental measures of auditory sustained selective attention and interference control. Our results showed shallower learning trajectories in children with dyslexia, especially during the later phases of the training blocks. Despite this, children with dyslexia performed similarly to typical readers on the post-training reading tests using the artificial orthography. Better auditory sustained selective attention and interference control skills predicted greater response accuracy during training. Sustained selective

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attention was also associated with the ability to apply these novel correspondences in the reading tests. Although this result has the limitations of a correlational design, it denotes that poor attentional skills may constitute a risk during the early stages of reading acquisition, when children start to learn letter–speech sound associations. Importantly, our findings underscore the importance of examining dynamics of learning in reading acquisition as well as individual differences in more domain-general attentional factors.

Introduction

Learning to read is a complex and dynamic process, one that is influenced by multiple environmental, cognitive, and genetic factors (e.g., Landerl et al., 2019; Olson et al., 2014; van Bergen et al., 2014). Correspondingly, young readers differ substantially in learning trajectory and ultimate reading fluency, including 5–12% of children showing persistent reading difficulties due to developmental dyslexia (Peterson & Pennington, 2015).

Learning associations between distinctive visual symbols (graphemes) and speech sound units (phonemes) is a necessary prerequisite for reading acquisition (Blomert, 2011; Rueckl et al., 2015; Ziegler & Goswami, 2005). Across alphabetic languages, early reading progress has been shown to correlate with children's knowledge of letter–speech sound associations, their ability to segment and manipulate spoken speech at the phonemic level (phonological awareness), and their rapid automatized naming (RAN) of familiar items (Caravolas et al., 2012; Schatschneider et al., 2004). Despite significant progress in identifying these and other behavioral predictors of reading outcomes (Catts & Petscher, 2018; Verwimp et al., 2020), our ability to capture the drivers of individual variation in reading outcomes remains limited (Petersen et al., 2016; Gellert & Elbro, 2017b).

Neuroimaging evidence has shown that efficient acquisition of letter–speech sound correspondences is critical for the emergence of preferential activation to print in the ventral occipitotemporal cortex (Brem et al., 2010; Pleisch et al., 2019). Such preferential activation has been related to fast and automatic word recognition and greater expertise in fluent reading (e.g., Benjamin & Gaab, 2012; Brem et al., 2006; Pugh et al., 2001). Compared with typical readers, adults, adolescents, and children with dyslexia may also show smaller differences in brain responses to congruent and incongruent letter–speech sound pairs and CVC (consonant–vowel–consonant) sequences (Blau et al., 2009, 2010; Kronschnabel et al., 2014; van Atteveldt et al., 2004; for a recent review, see Richlan, 2019). Furthermore, electroencephalography (EEG) evidence showed that reduced audiovisual mismatch negativity responses to spoken–written vowels in 8- to 10-year-old dyslexic readers correlated with individual differences in reading (dis)fluency (Žarić et al., 2014).

Behavioral evidence of a letter–speech sound integration deficit in children with dyslexia is scarcer, and findings are less consistent. For example, difficulties in associating familiar letters and speech sounds were found in Dutch-speaking kindergarten children at familial risk of dyslexia (Blomert & Willems, 2010). In contrast, in letter–speech sound priming tasks, 7- to 13-year-old and 9- to 11-year-old English-speaking children with dyslexia showed similar behavioral congruency effects (faster responses to congruent pairs) compared with typical readers (Clayton & Hulme, 2018; Nash et al., 2017). Furthermore, in a phonetic recalibration paradigm, comparable text-induced shifts in the perception of ambiguous speech sounds were found in 8- to 10-year-old children with and without dyslexia (Romanovska et al., 2019, 2021; but see Keetels et al., 2018, for different findings in adults).

Artificial script learning paradigms have shown more consistent evidence of poorer abilities in dyslexic readers compared with age-matched controls. For example, Aravena and colleagues (2013) asked children to learn eight grapheme–speech sound correspondences using unfamiliar symbols (Hebrew letters) and familiar native (Dutch) phonemes in two 30-min training blocks. After the training, children with dyslexia and typical readers did not differ in their knowledge of the novel symbols. However, children with dyslexia did make more mistakes during the training when sounds and symbols needed to be matched under time pressure and also performed more poorly on a word reading task with the novel orthography (Aravena et al., 2013). Two subsequent studies with shorter (20-min) training using the same materials found that dyslexic readers were less able to read words written with the novel orthography (Aravena et al., 2017; Law et al., 2018). However, other results from these studies were inconsistent; Aravena et al. (2017) found poorer performance by dyslexic readers on the post-training symbol–sound identification task, whereas Law et al. (2018) found no significant group differences on the same assay. Furthermore, Aravena et al., (2017) found that children's learning ability was related to concurrent individual differences in reading and spelling, but Law et al. (2018) did not replicate this effect when controlling for phonological and orthographic skills. Finally, in a study investigating the prognostic value of these learning measures, symbol–sound learning ability was found to predict children's reading improvements after a 10-month specialized dyslexia intervention over and above traditional standardized reading-related measures (Aravena et al., 2016). Behavioral studies with kindergartners also showed that children's future reading level can be predicted from accuracy scores on learning tasks of grapheme–speech sound pairs (Gellert & Elbro, 2017b) and symbol–tone pairs (Horbach et al., 2015, 2018). Altogether, these findings underscore the potential of learning paradigms in capturing individual differences in (a)typical reading development.

Thus far, training studies involving symbol–speech sound association learning in children focused primarily on behavioral scores on post-training tasks (Aravena et al., 2013, 2017; Horbach et al., 2015, 2018; Law et al., 2018), outcome measures of the training task itself (Gellert & Elbro, 2017a, 2017b, 2018; Karipidis et al., 2017), training duration (Karipidis et al., 2017; Pleisch et al., 2019), or the number of required instructional prompts (Cho et al., 2017, 2020). However, neuroimaging evidence suggests that neural effects of learning rapidly unfold *during* learning and can be detected very early—at least in adults—after only 5 to 10 min of training (Hämäläinen et al., 2019). Thus, characterizing children's behavioral learning trajectories *during* symbol/speech sound training, in addition to outcome scores of learning, may be key to improving our understanding of individual differences in children's reading skills as well as different factors that affect their learning abilities.

The relationship between letter–speech sound learning and attentional processes

Whereas most studies on letter–speech sound integration have focused on reading-specific cognitive processes (e.g., phonological and orthographic processes), considerably less is known about the influence of domain-general factors such as attention. During letter–speech sound learning, directing attention to the auditory and visual information may facilitate subsequent multisensory integration (Fraga González et al., 2017). More generally, neuroscientific models of multisensory integration have emphasized the role of top-down attentional influences (Koelewijn et al., 2010; Talsma et al., 2010), particularly when multiple stimuli within each unisensory modality are present and compete for further processing (Talsma et al., 2010). In real-life situations, the attended auditory and visual inputs very rarely correspond to one single small unit but rather correspond to, for example, multi-letter strings or multi-speaker environments (Lallier & Valdois, 2012). Thus, it is plausible that beginner readers must suppress irrelevant auditory and visual representations to facilitate the integration of relevant representations in audiovisual units (Lallier et al., 2013) and to efficiently retrieve phonological representations from print (Altemeier et al., 2008). In turn, successful decoding skills may facilitate attention to the regularities of grapheme–phoneme relations by increasing their salience (McCandliss & Noble, 2003).

An EEG study with typically reading adults observed visual cortical responses to words written with newly learned symbols when attention was directed on grapheme–phoneme units during training. When the training involved holistic focus at the word level, this learning transfer effect did not occur (Yoncheva et al., 2010), demonstrating the importance of selective attention to grapheme–phoneme associations for learning to read.

In poor readers, electrophysiological studies reported diminished attention-mediated responses to phonological and audiovisual stimuli (Savill & Thierry, 2011a, 2011b, 2012; Žarić et al., 2014) and to rapidly presented nonspeech visual and auditory stimuli compared with typical readers (Lallier et al., 2010). In behavioral studies, reported nonspeech attentional difficulties ascribed to difficulties in selecting or prioritizing relevant information (Menghini et al., 2010; Roach & Hogben, 2008) and inhibiting task-irrelevant information (Brosnan et al., 2002; Facoetti et al., 2006; Gabay et al., 2020; see also Lonergan et al., 2019, for a review). However, poor attentional engagement (Facoetti et al., 2008, Ruffino et al., 2010) and shifting (Lallier et al., 2010, 2013) have also been demonstrated. More specifically for the auditory modality, complementary evidence of putative attentional deficits in dyslexic readers stems from their challenges in perceiving speech in complex acoustic environments such as in noisy backgrounds or with competing speech (e.g., Dole et al., 2012; Nittrouer et al., 2018; see Calcus et al., 2018, for a review). These difficulties were hypothesized (e.g., Calcus et al., 2018; Ziegler et al., 2009) and shown (Guerra et al., 2023) to be related to their auditory selective attention skills.

Altogether, previous evidence has pointed toward a putative role of attention to early phonological and audiovisual integration processes as well as to attentional difficulties in dyslexia. To date, it remains unclear whether individual differences in auditory attentional skills are associated with children's letter–speech sound learning abilities.

The current study

In the current study, we investigated the contribution of the ability to *learn* symbol–speech sound correspondences to children's reading fluency skills. To this goal, we examined the unfolding of learning trajectories of 7- to 12-year-old children with and without dyslexia *during* a short ~14-min symbol–speech sound association training. Children were asked to learn to associate eight artificial symbols with eight Dutch speech sounds and to read out loud words and pseudowords written with the artificial symbols. We compared learning trajectories of children with and without dyslexia and examined the relationship between individual differences in reading fluency and symbol–speech sound association learning independently from the contribution of phonological, vocabulary, and rapid naming abilities to reading skills. Because learning trajectories may differ between younger and older readers, in these analyses we also included a categorical measure of age.

Furthermore, because little is known about the contribution of domain-general auditory attention to specific reading subskills, we tested the hypothesis that auditory attention skills support the learning of symbol–speech sound correspondences. We employed two experimental measures of auditory attention: sustained selective attention and interference control. Specifically, we evaluated the relationship between auditory attention and symbol–speech sound learning when controlling for phonological awareness, rapid naming, and vocabulary abilities given previous evidence showing the importance of these abilities for the acquisition and retrieval of audiovisual associations (e.g., Ehm et al., 2019).

Method

Participants

A total of 113 7- to 12-year-old children participated in this study. All the children were native Dutch speakers. Of this sample, 63 children had a diagnosis of dyslexia and 50 were typical readers. Children with dyslexia were recruited from the Regional Institute of Dyslexia (RID) and on a waiting list for treatment. Dyslexia diagnosis was provided by the RID, based on the results of extensive psychodiagnostic testing. Parents gave written informed consent for participation in the study, and verbal assent was obtained from children at the beginning of the testing session. Children received a small gift and a certificate as a reward for participating. The study was approved by the ethics committee of the Faculty of Psychology and Neuroscience at Maastricht University.

Data from 2 children with dyslexia were excluded due to hearing impairments, and additional data from 1 participant were excluded due to already having completed treatment for dyslexia at another institution. After these exclusions, data from 110 children remained. None of the children with dyslexia was diagnosed with attention-deficit/hyperactivity disorder (ADHD). One child with a diagnosis of Asperger's syndrome was also included in the final sample. The typically reading children were siblings or acquaintances of the participants with dyslexia or were recruited via word of mouth. Parents were asked to report the presence of a diagnosed neurodevelopmental disorder and whether the child had any relatives with a diagnosis of dyslexia. None of the typical readers was diagnosed with dyslexia and/or ADHD or any other neurodevelopmental disorder. Group comparisons of reading(-related) skills of typically reading children with versus without dyslexia family risk (as indexed by having a relative diagnosed with dyslexia) showed no significant differences ($p > .05$).

For children with dyslexia, data of the Wechsler Intelligence Scale for Children (WISC), One-Minute Test (EMT; Brus & Voeten, 1973), and 3DM test battery (Differential Dyslexia Diagnosis; Blomert & Vaessen, 2009) were extracted from the diagnostic assessment battery administered by the RID. In typical readers, these measures were assessed during the testing session. The 3DM test battery included RAN, phonological awareness (phoneme deletion), word reading, and letter–speech sound identification and discrimination tasks. The letter–speech sound identification and discrimination tasks were not administered to typical readers due to time constraints. Participants' age, IQ, and reading(-related) skills are reported in Table 1. Data from the 3DM battery test of 4 children in the typical readers group were not saved due to software issues, and 2 children were not administered the EMT due to time constraints. Multiple imputation in SPSS (Version 26.0; IBM Corp., Armonk, NY, USA), with EMT scores functioning as a predictor, was used to replace missing 3DM reading scores of 4 typical readers. Reading scores from the 3DM reading task were then used in the analyses as a measure of reading fluency.

Table 1
Participants' characteristics, reading, and reading-related skills

	Dyslexic readers (n = 60)			Typical readers (n = 50)			Dyslexic vs. typical readers	
	Ratio						$\chi(df)$[a]	p
Sex (M/F)	32/28			31/19			0.837(1)	.360
	M	SD	Range	M	SD	Range	$t(df)$[b]	p
Age (months)	114.58	13.19	92–149	114.62	15.72	88–148	−0.013(95.98)	0
Verbal IQ (vocabulary)	10.92	2.59	6–17	11.77	3.16	4–19	−1.542(106)	.126
Nonverbal IQ (block design)	9.78	2.93	3–19	10.27	3.25	4–17	−0.814(107)	.417
EMT (standardized)	2.97	2.40	1–10	9.12	3.21	2–19	−11.487(108)	<.0001
EMT (raw)	30.59	13.12	5–65	56.24	17.77	20–102	−8.459(88.466)	<.0001
3DM word fluency (T-score)	29.45	6.15	20–41	49.84	10.14	34–75	−12.439(77.580)	<.0001
3DM word fluency (raw)	61.02	27.12	2–112	112.38	29.97	23–175	−9.427(108)	<.0001
3DM word accuracy (T-score)	31.63	11.35	20–55	50.75	9.35	23–61	−9.518(108)	<.0001
3DM word accuracy (raw)	84.92	11.79	43–99	96.78	4.47	86–109	−7.193(78.321)	<.0001
	Dyslexic readers (n = 60)			Typical readers (n = 45[c])				
Phonological awareness (T-score)	37.88	7.97	21–54	48.66	9.74	27–67	−6.236(103)	<.0001
RAN letters (T-score)	35.26	8.08	20–53	46.27	9.82	24–71	−6.293(103)	<.0001
RAN digits (T-score)	37.80	8.41	20–57	45.80	9.73	28–68	−4.509 (103)	<.0001

Note. EMT, One-Minute Test; 3DM, Differential Dyslexia Diagnosis test battery; RAN, rapid automatized naming.

[a] Chi-square test.

[b] Independent-sample t test.

[c] Data from 5 participants were lost due to software issues.

Procedure and measures

Children underwent electrophysiological (EEG) and behavioral testing. Nonspeech sustained auditory selective attention was assessed during the EEG session. EEG results and discussion are reported elsewhere (Guerra et al., 2023). During behavioral testing, symbol–speech sound learning abilities, interference control, and typical readers' reading(-related) abilities were assessed. The computerized

Table 2
Symbol–speech sound pairs presented in the task

	Block 1			
Grapheme		 [a]		
Phoneme[b]	[n]	[ʌu]	[ɛ]	[t]
Phoneme duration (ms)	734	505	387	194
	Block 2			
Grapheme	 [c]			
Phoneme[b]	[ɛɪ̯]	[z]	[ɔ]	[f]
Phoneme duration (ms)	527	516	383	303

[a] In the BACS-1 artificial alphabet (Vidal et al., 2017), this symbol corresponds to the Latin case “A”.
[b] International Phonetic Alphabet.
[c] In the BACS-1 artificial alphabet (Vidal et al., 2017), this symbol corresponds to the Latin case “H”.

tasks were programmed and presented with Psychtoolbox-3 in MATLAB 9.1.0 (MathWorks, Natick, MA, USA). An HP ProBook 640 G2 laptop with a 1920 × 1080 screen, Core i5-6200 microprocessor, and Intel HD Graphics was used. The auditory stimuli were presented over headphones (Sony Professional MDR-7510) at 70 to 72 dB SPL, as measured using a RION NA-27 Sound Level Meter with an NH-20 microphone.

Symbol–speech sound learning task

In the symbol–speech sound (hereafter, S-SS) learning task, children were asked to learn eight novel S-SS pairs. The stimuli consisted of artificial characters taken from the Brussels Artificial Character Sets (BACS) uppercase artificial alphabet (Vidal et al., 2017) along with Dutch phonemes spoken by a native female speaker. The phonemes were matched to the corresponding artificial symbol as designed by Vidal and colleagues (2017) except for the Dutch phonemes /ʌu/ and /ɛɪ̯/ with no corresponding BACS symbol. Those phonemes were then matched to different symbols. An overview of the symbol–phoneme pairs is displayed in Table 2.

The task consisted of four blocks: two blocks of 48 trials each and two blocks of 56 trials each. In Blocks 1 and 2, four of the eight symbol–phoneme pairs were presented in one block and the remaining four pairs were presented in the other block. Blocks 3 and 4 included all eight symbol–phoneme pairs.

As illustrated in Fig. 1, the first three blocks required participants to perform a symbol identification task. On each trial, participants heard one of the phonemes while two symbols were simultaneously presented for 1000 ms in black on a white background. Participants' task was to identify the symbol matching the presented phoneme by pressing the corresponding button on the left or right side of the keyboard. The button-press was followed by a blank screen, which remained on the screen for 1000 ms. This was followed by a feedback screen; for correct/incorrect responses, a happy/sad cartoon face appeared, and when response time exceeded 4000 ms, a cartoon character appeared with the text “Faster!” After the feedback screen, a fixation cross was presented during the intertrial interval (ITI) with equiprobable durations of 500, 750, and 900 ms. ITI was jittered to discourage anticipatory responses (see, e.g., Verbruggen et al., 2019). In each block, the presentation of the two symbols was counterbalanced with respect to the possible combinations of symbols. In this way, each symbol was presented equally often within one block. The position on the screen of the correct symbol was randomized.

The last block (Block 4) consisted of a match/mismatch task. Each trial included the presentation of one visual symbol followed by one of the phonemes; participants' task was to decide whether the phoneme matched the symbol. The visual symbol was presented for 1000 ms at the center of the screen; the phoneme was presented 1500 ms after visual symbol onset. After the button press, the trial structure was the same as in the first three blocks.

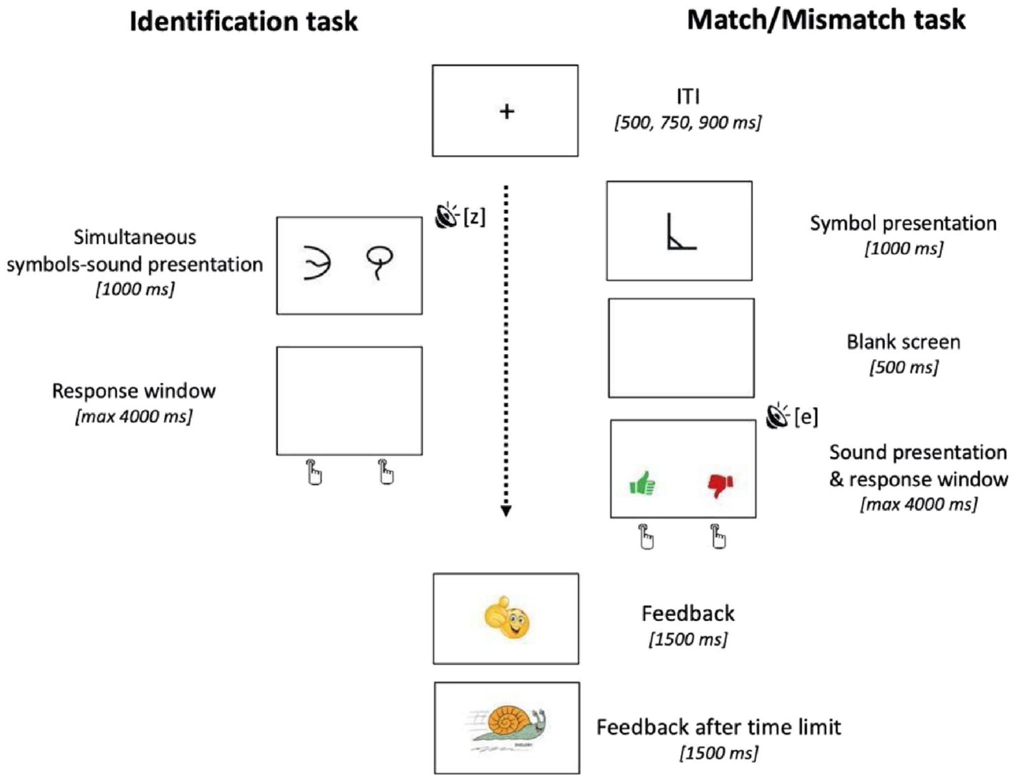

Fig. 1. Schematic of the trial design of the first three blocks (identification task) and the fourth block (match/mismatch task) of the symbol–speech sound learning paradigm. The trials were response-terminated, but they timed out after 4000 ms. ITI, intertrial interval.

Before the task, children were instructed to try to learn a secret code inferring the symbol–sound associations from the feedback received. A short explanation of the trial structure and feedback pictures was also provided. The task lasted approximately 14 min.

Word and pseudoword reading tests within the artificial orthography

After the learning task, children were presented with a list of 14 high-frequency Dutch words, followed by a list of 14 pseudowords, all written with the newly learned artificial symbols. The pseudowords were matched to the words for phonological complexity. The words of the two lists were arranged in a column and presented to the children on a paper sheet (see Word and Pseudoword lists in online supplementary material). Children were instructed to correctly read as many words/pseudowords as possible. Children were encouraged to read quickly; however, the task had no time limit. Before being presented with the list of pseudowords, children were told that the words were not real words. The number of words read correctly in 1 min and the number of pseudowords read correctly in 1 min were summed into a total (pseudo)word reading score. Participants were not aware of this part of the test before the start of the computerized task.

Nonspeech sustained selective attention task

Stimuli. The basic stimulus unit consisted of sequences of three cosine-ramped sine tones. Each tone was 166.67 ms long and was followed by 166.67 ms of silence. Tones were grouped in lower (370, 415.3, and 466.2 Hz) and higher (740, 830.7, and 932.5 Hz) frequency bands, with tones corresponding to musical notes F#4, G#4, and A#4 for the low band and F#5, G#5, and A#5 for the high band. The high and low band sequences were temporally interleaved. Thus, in 1 s, participants heard a sequence of six successive tones in each trial, each 166.67 ms in duration, with the first, third, and fifth tones taken from the low-frequency band and the second, fourth, and sixth tones taken from the high-frequency band. The six tones were then followed by a 333.33 ms silence. Based on in-lab piloting, tones in the high-frequency band were presented at 40% of the amplitude of lower-frequency tones to ensure that the perceived loudness of the two bands was approximately balanced.

Task. The task consisted of two active conditions of 10 blocks each; each block was made of 30 sequences and was 41 s long. In the first condition, participants were asked to attend to the high band; in the second condition, they were asked to attend to the low band. The presentation order was fixed across all participants to minimize cross-participant variability due to condition order given that a primary goal was to investigate individual differences. Children also participated in a third condition involving passive listening to the stimuli. This passive condition is not included in the current work and served as a control measure for the EEG analyses that are reported elsewhere (Guerra et al., 2023).

During the active conditions, children were asked to detect within-attended-band sequence repeats via a Cedrus RB-844 response box. In each block, there were five repeated sequences in each band; the timing of repeats was quasi-random (repeated sequences were always separated by at least one nonrepeated sequence). Participants were asked to ignore the distracting band and the sequence repeats within it (Fig. 2); across blocks, there were equivalent numbers of repeats in both bands. A repeat was recorded as being correctly detected if the participant provided a response between 333 ms before and 1670 ms after the end of the last tone in a repeated sequence. Correct target detection began before the end of a stimulus because, in theory, a repeat could be detected as soon as the final tone of a sequence started.

To ensure children's engagement, the task and instructions were gamified. Participants saw a spaceship at the center of the screen, and the background mimicked a space environment. They were told that the sounds were produced by the ship's radar and that they needed to listen to them to detect asteroids that were approaching from above (attend high band) or from below (attend low band) the spaceship. An approaching asteroid was signaled by the repeated sequences. Feedback for correct and incorrect responses was given at the center of the screen (Dutch: "Raak/Fout"; English: "Hit/Wrong") along with a cumulative performance score in the top right corner of the screen. Children received an increase of 20 points for each identified target, a decrease of 2 points for each missed target, and a decrease of 5 points for each false alarm. The *d*-prime measure (Stanislaw & Todorov, 1999) was taken as a comprehensive measure of behavioral performance.

Before the task, children underwent a short practice with the experimenter to familiarize themselves with the stimuli. This included attending to single-stream stimuli and identifying targets and dual-stream stimuli for each active condition (attend high band and attend low band). During the task,

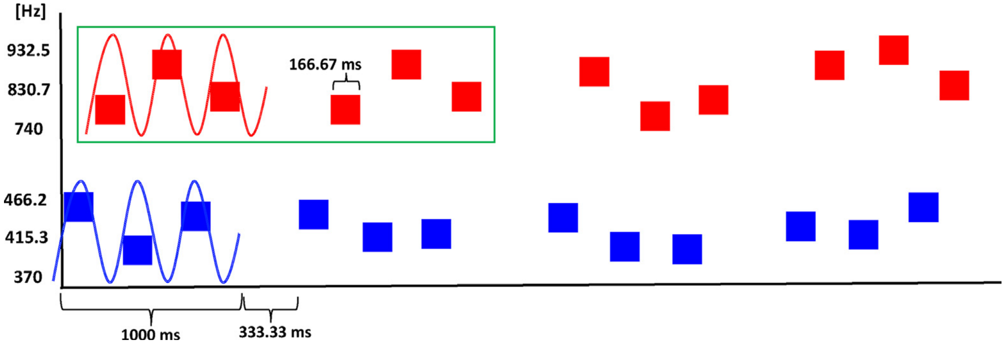

Fig. 2. Schematic of the selective attention task. The tones in the high and low bands were interleaved. Participants were asked to detect repetitions of sequences of three tones such as the one in the green rectangle (upper left). These repetitions occurred five times within each block of 30 three-tone sequences.

children sat in front of an Ilyama 21.5-inch computer monitor. ER-3C insert earphones (Etymotic Research, Elk Grove Village, IL, USA) were used for sound presentation at 72 to 73 dB SPL, as measured using a RION NA-27 Sound Level Meter with an NH-20 microphone.

Interference control

Interference control was tested with an auditory version (Green & Barber, 1981) of the Stroop task (Stroop, 1935). Similar to the original Stroop test, it requires the listener to ignore lexical information and to respond on the basis of a perceptual feature. The stimuli consisted of the words "boy" and "girl" ("jongen" and "meisje" in Dutch) spoken by two female and two male Dutch native speakers. On congruent trials, the word "boy" and the word "girl" were spoken by a male and female talker, respectively. On incongruent trials, the word "boy" was spoken by a female talker and the word "girl" was spoken by a male talker. Participants were asked to ignore the meanings of the words and to respond to the gender of the talker by pressing one of two keys. One key was on the left side and one on the right side of the keyboard, each marked by a yellow sticker to guide the children to the correct key.

The button-press was indicated by a light blue circle at the center of the screen. If the button-press occurred later than 4000 ms, a cartoon character with the text "Faster!" appeared on the screen. The interstimulus interval (ISI) was either 100, 250, 500, 750, or 900 ms with equal probability. There were 75 trials per condition, with presentation order randomized. Before the start, children had a brief practice of 8 or 16 trials (16 if they did not respond correctly to 6 of 8 trials in the first training set); the practice included both congruent and incongruent trials. During practice trials only, response feedback (happy/sad cartoon face) was displayed. Both accuracy and median reaction time (RT) to correct trials only were used for analysis.

Reading and reading-related abilities

Reading fluency. Children's reading level was assessed with the standardized EMT (Brus & Voeten, 1973) and the 3DM reading task (Blomert & Vaessen, 2009). The EMT includes 116 words (both low- and high-frequency words) that vary from one to four syllables presented in four columns of 29 words. The score was calculated as the number of words read correctly in 1 min. The 3DM reading task includes three subtasks: one with high-frequency words, one with low-frequency words, and one with pseudowords. Children are instructed to correctly read as many (pseudo)words as possible within the time limit (30 s per subtask). The words of each subtask increase in the number of syllables and syllabic complexity. Reading fluency is measured as the number of (pseudo)words read correctly within the time limit. The test–retest reliability coefficient of the EMT was .87, and those of the three 3DM reading fluency subtasks were .91, .93, and .92 for high-frequency words, low-frequency words, and pseudowords, respectively (reported in the test manuals).

Letter–speech sound identification and discrimination tasks (3DM battery subtests). In the identification task, a Dutch phoneme is presented via headphones simultaneously with four Roman letters or letter combinations appearing on the computer screen. Children identify the letter–speech sound pair by pressing the button corresponding to the correct letter in a response box. In the discrimination task, a speech sound is presented via headphones simultaneously with one letter or letter combination. Children indicate whether the letter(s) and the sound match or mismatch. Accuracy (percentage of correct responses) and RTs were measured for both tasks. These tests were only administered to children with dyslexia during the diagnostic assessment. The accuracy and speed scores of the letter–speech sound identification task had internal consistencies of .72 and .90, respectively, and the accuracy and speed scores of the letter–speech sound discrimination task had internal consistencies of .82 and .96, respectively (reported in the 3DM test manual).

Rapid automatized naming (3DM battery subtest). The rapid naming task of the 3DM battery consists of two subtasks: letter naming and digit naming (Blomert & Vaessen, 2009). In each subtask, 15 items are presented on the screen (5 letters or digits repeated three times). Each set of 15 items is presented twice on the screen, with the items presented in a different order. Participants are instructed to name the items as quickly and accurately as possible. Performance is measured as the response time obtained by averaging the response times of the two screen presentations. The correlations (with Spearman–Brown correction) between the speed scores on the first and second screens were .80 and .83 for letters and digits, respectively (reported in the 3DM test manual).

Phonological awareness (phoneme deletion; 3DM battery subtest). The phoneme deletion task contains 23 pseudowords (CVC or CCVCC structure) presented orally. Participants are asked to leave out the first consonant, the last consonant, or a consonant within a consonant cluster and to pronounce the remaining pseudoword (e.g., "/dauk/–/d/, what is left?"). Here, we report only the accuracy scores because RTs are not generated if accuracy is below 21.8% (i.e., <5 correct pseudowords); this was the case for 17 of 60 children with dyslexia. The task has an internal consistency of .85 for accuracy scores (reported in the 3DM test manual).

Statistical analyses

Symbol–speech sound learning

Learning trajectories. To characterize learning trajectories, we divided each block into three equal-sized bins (16 trials per bin for Blocks 1 and 2 and 18/19 trials per bin for Block 3 and 4). Then, for each participant, we calculated average accuracy and RT for correct responses only. Prior to averaging RTs, outlier responses (±3 *z* scores) in each bin were removed, and remaining RTs were log-transformed to normalize the underlying distribution. We then determined whether, and at what point, the learning trajectory of children with dyslexia significantly diverged from that of typical readers using two repeated-measures analyses of variance (ANOVAs) with (a) accuracy and (b) mean RTs at each bin as dependent variables. For both ANOVAs, block (1, 2, 3, or 4) and time bin (1, 2, or 3) were included as within-participants factors, and dyslexia diagnosis (yes or no) was included as a between-participants factor. To understand whether learning trajectories differed between younger and older children, and whether age interacted with diagnosis (e.g., whether there were differences between older children with and without dyslexia but not between younger children with and without dyslexia), we used a median split of age (younger children: *M* = 103.04 months, *SD* = 5.43; older children: *M* = 126.59 months, *SD* = 10.18) as a second categorical between-participants factor along with diagnosis.

Sensitivity to symbol–speech sound pair congruence in the match/mismatch task. We explored whether the (in)congruence of the S-SS pairs affected children's performance in the match/mismatch task (Block 4) and whether the congruence effect differentially affected children with dyslexia. To do so, we separately computed accuracy and RTs for matching and nonmatching trials. Repeated-measures ANOVAs were then carried out with congruence as the within-participants factor and diagnosis as the between-participants factor.

Transfer of symbol–speech sound learning to artificial orthography reading. Next, we investigated whether individual differences in S-SS learning measures of Blocks 3 and 4 (including all eight symbol–sound pairs) generalized to the ability to read (pseudo)words in the artificial orthography and whether this was affected by diagnosis. We carried out two regression analyses with word and pseudoword test performance as dependent variables. A total of 106 children were included in the analyses (4 children did not complete these reading tests). To reduce the number of predictor variables, a principal component analysis (PCA) with oblique rotation (direct oblimin) was carried out on the S-SS learning task measures of Blocks 3 and 4 (accuracy and mean RTs). The extracted PCA scores were then entered in the regression models along with age (in months) and dyslexia diagnosis (yes or no).

Predicting individual differences in reading fluency and reading-related abilities. Multiple hierarchical regression analyses were used to test whether the measures of the S-SS learning task (PCA scores) and performance in the reading tests within the artificial orthography predicted alphabetic reading fluency abilities (raw 3DM scores) independently from phonological awareness, vocabulary, and naming speed abilities. In the first step, S-SS learning task (PCA scores), age (in months), and diagnosis were entered in the models. In the second step, phonological awareness, vocabulary, and RAN measures (RAN digits and letters) were entered.

Finally, in dyslexic readers only, we explored the relation between S-SS learning measures and (alphabetic) letter–speech sound association skills (as assessed with 3DM letter–speech sound tasks). Because 3DM scores were taken from the RID database, analyses were carried out only for the 55 of 60 children with dyslexia whose data were available. Using a one-sample *t* test, we compared children's standardized scores (*t* scores; i.e., *M* = 50, *SD* = 10) with the normative population mean (because typical readers were not administered these tasks). We then used partial Spearman correlations (controlling for age) to test the association between 3DM raw scores of letter–speech sound association and the measures of the S-SS learning paradigm.

The relationship between auditory attention and symbol–speech sound learning

We investigated the contribution of auditory attention skills to S-SS learning in the subset of participants (*n* = 94) who had completed both active conditions of the nonspeech selective attention task and the interference control task. Multiple hierarchical regression analyses were carried out with the auditory attention measures and age (in months) as predictors of S-SS learning performance (task and reading test measures) in the first step. In the second step, phonological awareness, vocabulary, and naming speed (RAN digits and letters) abilities were also included.

For each statistical model, outliers were identified based on model standardized residuals, and data points with values ±3 were excluded from analyses (Osborne & Overbay, 2004). Following this method, the number of data points excluded is indicated in the Results section for each statistical analysis.

Results

Symbol–speech sound learning

Children's overall learning achievement varied considerably between participants (*SD* = 12.96%, range = 44.7%–93.8%), but on average participants reached a total accuracy of 72.93%, showing

Table 3
Descriptive statistics and group comparisons of the symbol–speech sound learning task

	Dyslexic readers (*n* = 60)			Typical readers (*n* = 50)			Dyslexic vs. typical readers	
Task accuracy (%)								
	M	*SD*	Range	*M*	*SD*	Range	*t*(108)	*p*
Total average	70.4	13.0	46.6–92.6	74.8	12.6	44.6–93.6	1.785	.077
Block 1[a]	61.1	14.5	20.9–93.8	63.2	15.1	31.3–93.8	0.740	.471
Block 2[a]	67.7	15.2	37.5–100	72.3	14.5	38.6–95.8	1.623	.107
Block 3[a]	76.6	15.4	39.3–98.2	80.6	14.3	41.1–100	1.408	.162
Block 4[b] (overall)	76.3	14.3	44.6–98.2	83.0	13.2	48.2–96.4	2.544	.012
Block 4[b] (matching)	74.2	14.7	39.1–100	80.1	14.9	39.1–100	2.093	.039
Block 4[b] (nonmatching)	77.9	16.5	39.4–100	85.2	13.2	48.5–100	2.558	.012
Task RTs (ms)								
	M	*SD*	Range	*M*	*SD*	Range	*U*[c]	*p*
Block 1[a]	1337.5	313.2	999.9–2238.9	1205.6	199.83	1016.5–1722.3	1150	.036
Block 2[a]	1221.2	251.2	1003.6–2089.4	1117.5	109.5	999.8–1513.2	1145	.033
Block 3[a]	1192.8	176.9	998.7–1789.0	1139.1	152.5	1000.8–1634.9	1140	.031
Block 4[b] (overall)	1133.6	326.3	628.7–2072.0	1032.9	264.3	576.1–1726.1	1258	.146
Block 4[b] (matching)	1044.6	360.0	469.7–2158.1	932.3	255.6	507.3–1710.2	1316	.269
Block 4[b] (nonmatching)	1153.1	334.8	608.3–2199.7	1069.7	275.6	538.3–1729.6	1219	.092

[a] Discrimination task.
[b] Match/mismatch task.
[c] Mann–Whitney *U* test.

learning of the novel S-SS pairs. Table 3 reports descriptive and group comparison statistics of S-SS learning paradigm measures per block for children with and without dyslexia.

Learning trajectories

Symbol–speech sound learning accuracy. Binned accuracy values indicate similar learning progress in typical and dyslexic readers in the first two blocks, with continued improvements in Blocks 3 and 4 for typical but not dyslexic readers (Fig. 3). This pattern was confirmed by results of the repeated-measures ANOVA, with significant main effects of block, $F(2.63, 273.81) = 109.635$, $p < .001$, $\eta_p^2 = .513$, and time bin, $F(2, 208) = 85.469$, $p < .001$, $\eta_p^2 = .451$, and significant interactions of time bin by diagnosis, $F(2, 208) = 6.06$, $p = .003$, $\eta_p^2 = .055$, and block by time bin, $F(2, 208) = 24.617$, $p < .001$, $\eta_p^2 = .191$. All the other effects were found to be nonsignificant ($p > .05$). (Two participants were excluded from the analysis for having standardized residuals below −3; remaining $N = 108$.)

The significant time bin-by-diagnosis and block-by-time bin interactions were further investigated with post hoc pairwise comparisons. First, children's response accuracy significantly improved across the three time bins in Blocks 1 and 2 but not in Blocks 3 and 4, where their performance remained stable at an asymptote of ~80% (Fig. 4A). Second, children with dyslexia responded significantly less accurately than typical readers in the last two time bins of each block (Blocks 1–4; Fig. 4B).

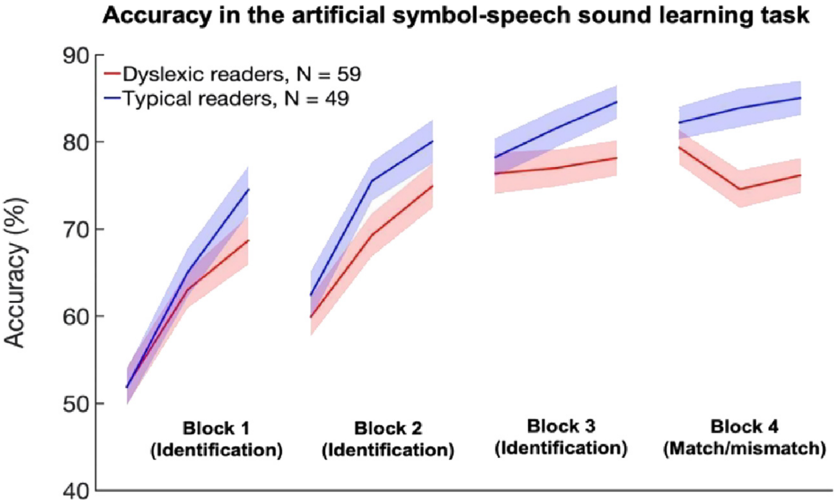

Fig. 3. Percentage of correct trials (accuracy) displayed per block of the symbol–speech sound learning for typical and dyslexic readers. For each block, trials were divided into three time bins.

Reaction times. Binned RT values indicate similar speed of responses in typical and dyslexic readers across the learning task, with results of the repeated-measures ANOVA showing no significant main effect of diagnosis or interaction with diagnosis ($p > .05$; Fig. 5A). We found significant main effects of block, $F(1.641, 155.924) = 29.977$, $p < .001$, $\eta_p^2 = .240$, and time bin, $F(1.682, 159.824) = 26.161$, $p < .001$, $\eta_p^2 = .216$, and significant interactions of block by age, $F(1.641, 155.92) = 4.327$, $p = .021$, $\eta_p^2 = .044$, and block by time bin, $F(4.524, 429.812) = 11.023$, $p < .001$, $\eta_p^2 = .104$. All other effects were nonsignificant ($p > .05$). (Ten participants' data points were removed from the model for having standardized residuals above 3 or below −3; remaining $N = 100$.)

We further investigated the block-by-time bin and block-by-age interactions with post hoc pairwise comparisons. These showed that children's RTs dropped from the first to the second time bin

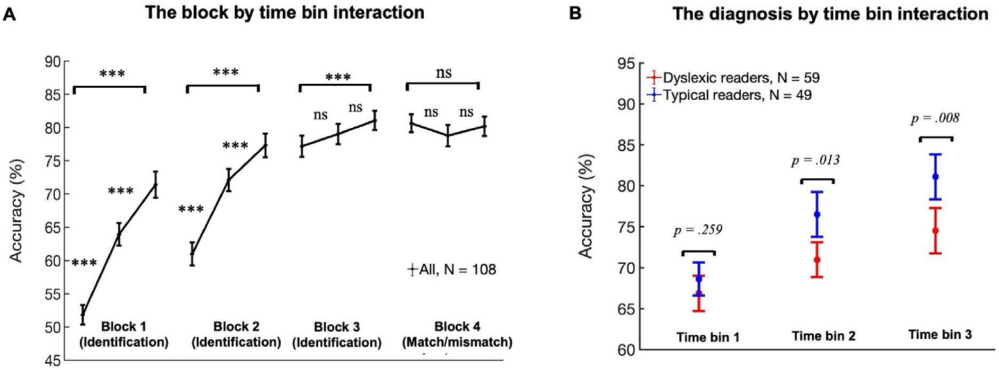

Fig. 4. (A) Across the groups, the accuracy increased from one time bin to the following one in Blocks 1 and 2, but not in Blocks 3 and 4. (B) Dyslexic readers' performance diverged from typical readers in the second and third time bins of each block. Error bars/shades: ±1 standard error. ***$p < .001$; ns, nonsignificant ($p > .05$).

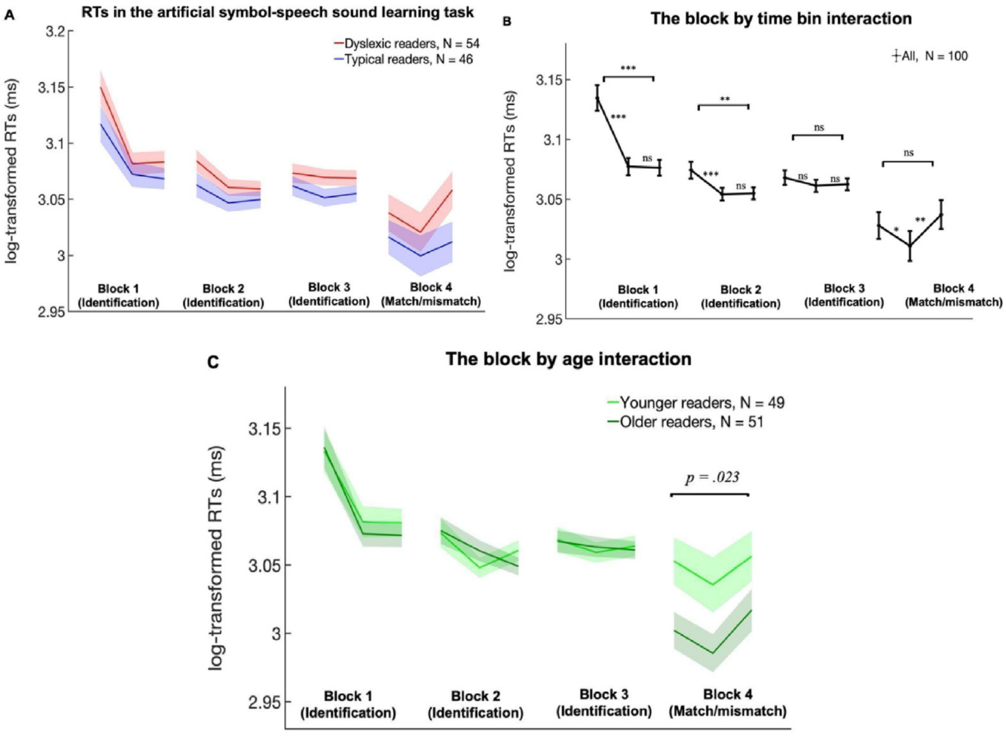

Fig. 5. (A) Mean reaction times (RTs; log-transformed) of the correct trials displayed per task block divided in three time bins for dyslexic and typical readers. (B) Children's RTs changed throughout the task. (C) Younger children gave slower responses in the match/mismatch task (Block 4). Error bars/shades: ±1 standard error. *$p < .05$; **$p < .01$; ***$p < .001$; ns, nonsignificant ($p > .05$).

of Blocks 1 and 2. In Block 3 RTs remained stable, and in Block 4 RTs initially dropped and then increased in the last time bin (Fig. 5B). Finally, younger children were significantly slower in responding in the match/mismatch task of Block 4 than older children (Fig. 5C).

Sensitivity to symbol–speech sound pair congruence in the match/mismatch task

Next, we examined whether the (in)congruence of the S-SS pairs presented in the match/mismatch task affected children's performance and whether this differed in children with and without dyslexia.

Both accuracy and RTs were significantly related to congruence [accuracy: $F(1, 108) = 13.923$, $p < .001$, $\eta_p^2 = .114$; RTs: $F(1, 108) = 57.888$, $p < .001$, $\eta_p^2 = .349$]. Children responded more accurately but more slowly when the presented speech sound and symbol did not match. Congruency effects on accuracy and RT were not significantly modulated by reading ability, as indicated by a nonsignificant congruence-by-diagnosis interaction [accuracy: $F(1, 108) = 0.304$, $p = .582$, $\eta_p^2 = .003$; RTs: $F(1, 108) = 0.615$, $p = .435$, $\eta_p^2 = .006$] (Fig. 6).

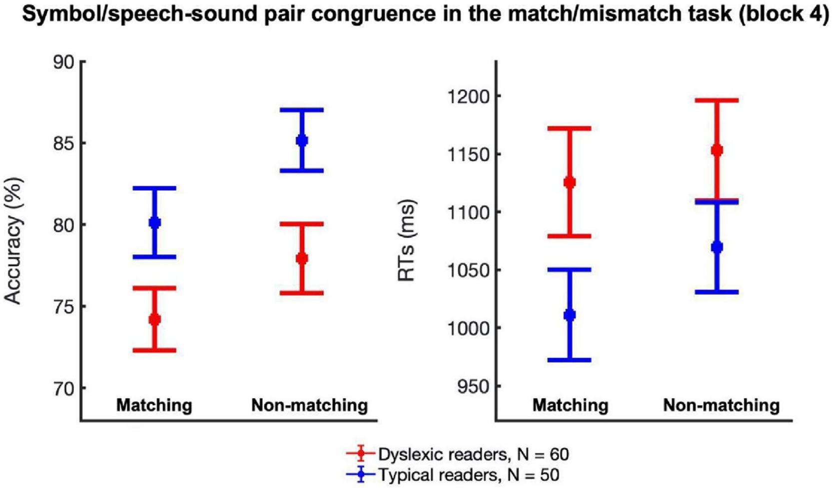

Fig. 6. Percentage of correct trials (accuracy) and mean reaction times (RTs) on the matching and nonmatching trials of the match/mismatch task displayed for children with and without dyslexia. Error bars: ±1 standard error.

Transfer of symbol–speech sound learning to artificial orthography reading abilities

After the learning tasks, on average, dyslexic and typical readers were equally able to read correct words (dyslexic readers: $M = 4.6$, $SD = 4.4$; typical readers: $M = 5.2$, $SD = 4.4$), $t(104) = -0.714$, $p = .477$, and pseudowords (dyslexic readers: $M = 4.2$, $SD = 4.3$; typical readers: $M = 4.9$, $SD = 4.7$), $t(104) = -0.844$, $p = .401$, in the 1-min artificial orthography reading tests.

A PCA on accuracy and mean RT measures of Blocks 3 and 4 yielded two factors with eigenvalues above 1, explaining cumulative variance of 85.84%. Accuracy measures loaded on the first component, and the RT measures loaded on the second component. Factor loadings and proportion of variance accounted for by each of the components are presented in Table S1 of the supplementary material. The extracted PCA scores, hereafter referred to as the accuracy and speed scores of the S-SS learning task, were used in the following analyses.

Multiple regression analyses showed that children's S-SS learning abilities during the task predicted their ability to read words and pseudowords in the newly learned artificial script (Table 4 and Fig. 7).

Table 4
Multiple regression results: Diagnosis, age, and symbol–speech sound learning accuracy and speed scores (PCA components) as predictors of (pseudo)word reading within artificial orthography

(Pseudo)word reading within artificial orthography	*β*	*p*	Lower CI	Upper CI
Diagnosis	.106	.206	−1.181	1.244
Age (in months)	−.062	.473	−0.137	0.064
S-SS learning accuracy score	.617	<.001	−3.932	7.050
S-SS learning speed score	−.277	.001	−3.781	−0.993
Model statistics	R^2	*df*	*F*	*p*
	.373	4, 101	15.017	<.001

Note. PCA, principal component analysis; CI, confidence interval; S-SS, symbol–speech sound.

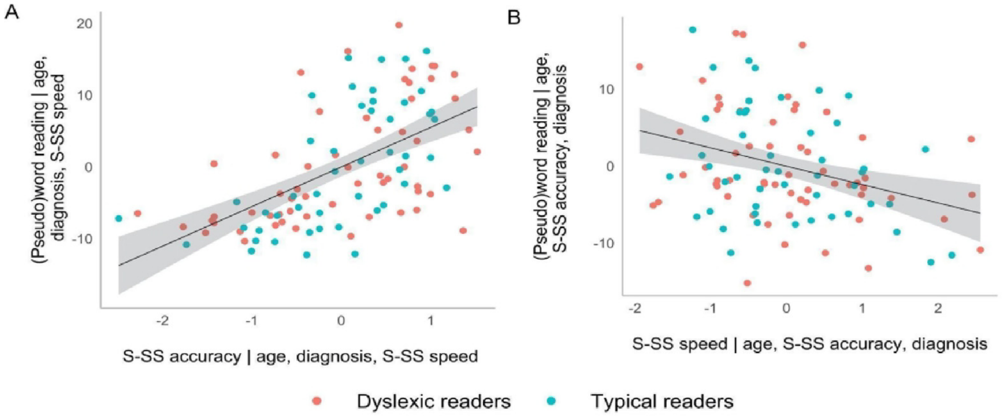

Fig. 7. Added variable plots showing that performance during the symbol–speech sound (S-SS) learning task (A: accuracy; B: speed scores) predicted subsequent performance on (pseudo)word reading tests within the artificial orthography when controlling for the effects of other predictors (age, diagnosis, and either symbol–speech sound accuracy or speed score).

Predicting individual differences in reading fluency and reading-related abilities

Here, we examined whether children's S-SS learning and pseudoword reading scores predicted alphabetic reading fluency skills—measured with a standardized reading task—independently from the contribution of phonological awareness, vocabulary, and rapid naming skills. Results of the multiple regression analysis including 104 participants, with S-SS learning accuracy and speed scores as predictors, showed that children who responded faster and more accurately in the S-SS learning task were more fluent readers (Table 5 and Fig. 8A). Adding phonological awareness, vocabulary, and rapid naming skills did not change the statistical significance of S-SS learning accuracy and speed scores. In contrast, once we controlled for the effect of dyslexia diagnosis, the learning scores were no longer significantly associated with reading fluency (Table 5 and Fig. 8B), indicating that the relationship was due to the lower scores of dyslexic readers for both associative learning and reading fluency.

When using reading in the artificial orthography as a predictor of alphabetic reading fluency including 100 participants, multiple hierarchical regression analysis showed that children who were more able to correctly read (pseudo)words written with the symbols were also more fluent readers, as measured with a standardized word reading task. When phonological awareness, vocabulary, and rapid naming skills were added in the model, (pseudo)word reading within artificial orthography was associated with reading fluency skills with a nonsignificant trend. When diagnosis was also added in the model, (pseudo)word reading within artificial orthography was significantly associated with reading fluency skills (Table 6 and Fig. 8C).

Table 5
Multiple regression results: S-SS learning accuracy and speed scores (PCA components) as predictors of (alphabetic) reading fluency

Step	Predictors	β	p	Lower CI	Upper CI
1	S-SS learning accuracy score	.269	.003	3.66	16.90
	S-SS learning speed score	−.253	.003	−15.74	−3.39
	Age	.375	<.001	0.533	1.437
2	S-SS learning accuracy score	.150	.036	0.38	11.039
	S-SS learning speed score	−.159	.014	−10.75	−1.258
	Age	.167	.038	0.024	0.852
	RAN letters	−.312	<.001	−5.75	−1.865
	RAN digits	−.047	.578	−3.53	1.983
	Vocabulary	.026	.750	−0.62	0.851
	Phonological awareness	.390	<.001	0.36	0.752
3	S-SS learning accuracy score	.047	.444	−2.81	6.356
	S-SS learning speed score	−.077	.159	−6.95	1.153
	Age	.282	<.001	0.39	1.097
	RAN letters	−.157	.029	−3.62	−0.204
	RAN digits	−.071	.312	−3.47	1.119
	Vocabulary	.045	.515	−0.41	0.810
	Phonological awareness	.232	<.001	0.154	0.508
	Diagnosis	−.431	<.001	−21.303	−11.530

Step	R^2 change	F change ($df1$,$df2$)	p	R^2	F($df1$,$df2$)	p
1	–	–	–	.316	17.05(3,101)	<.001
2	.315	21.89 (4,97)	<.001	.626	25.86(7,97)	<.001
3	.110	44.47 (1,96)	<.001	.742	38.32(8,96)	<.001

Note. S-SS, symbol–speech sound; PCA, principal component analysis; CI, confidence interval; RAN, rapid automatized naming.

Table 6
Multiple regression results: (Pseudo)word reading within artificial orthography as predictor of alphabetic reading fluency

Step	Predictors	β	p	Lower CI	Upper CI
1	(Pseudo)word reading within artificial orthography	.224	.012	0.223	1.753
	Age	.434	<.001	0.680	1.587
2	(Pseudo)word reading within artificial orthography	.120	.064	−0.031	1.091
	Age	.157	.056	−0.011	0.832
	RAN letters	−.316	<.001	−6.155	−1.970
	RAN digits	−.088	.296	−4.187	1.290
	Vocabulary	.083	.307	−0.348	1.091
	Phonological awareness	.386	<.001	0.348	0.754
3	(Pseudo)word reading within artificial orthography	.107	.040	0.023	0.918
	Age	.281	<.001	0.386	1.081
	RAN letters	−.166	.017	−3.877	−0.382
	RAN digits	−.075	.266	−3.417	0.954
	Vocabulary	.061	.351	−0.303	0.846
	Phonological awareness	.221	.001	0.141	0.489
	Diagnosis	−.448	<.001	−21.856	−12.609

Step	R^2 change	F change ($df1$,$df2$)	p	R^2	F($df1$,$df2$)	p
1	–	–	–	.261	18.64(2,98)	<.001
2	.366	23.98 (4,94)	<.001	.619	28.03(6,94)	<.001
3	.133	54.78 (1,93)	<.001	.757	45.60(7,9)	<.001

Note. CI, confidence interval; RAN, rapid automatized naming.

Finally, after observing the lower response accuracy of children with dyslexia in the S-SS learning task, we were interested in relating the artificial symbol learning task performance with their alphabetic letter–speech sound association skills. Compared with the normative population mean, as would be expected, children with dyslexia (n = 55) showed deficits in identifying and discriminating real let-

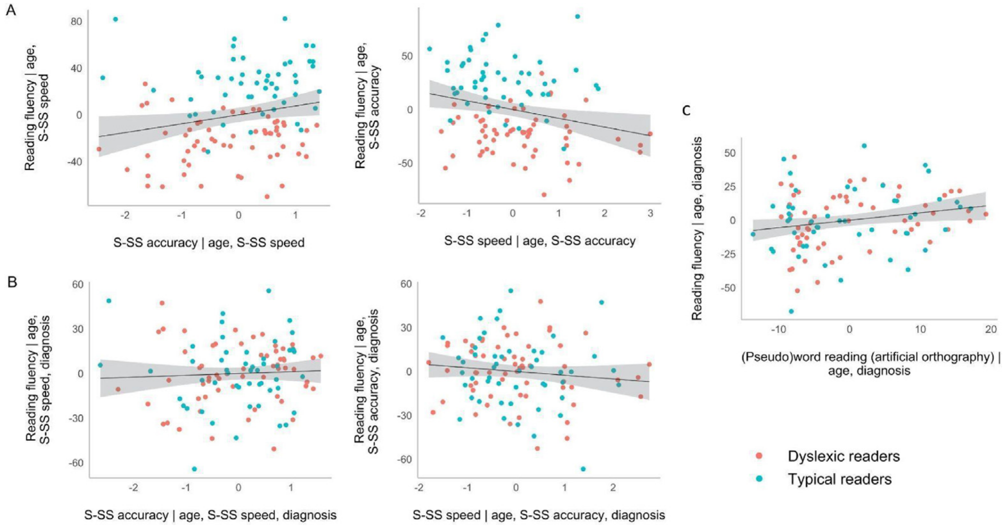

Fig. 8. (A, B) Added variable plots showing that the performance during the symbol–speech sound (S-SS) learning task (accuracy and speed) was related to (alphabetic) reading fluency (A), but not once diagnosis was entered in the model (B). (C) Reading within the artificial orthography (sum of words and pseudowords) predicted (alphabetic) reading fluency even when the effects of age and diagnosis were partialed out.

ter–speech sound correspondences (3DM standardized scores) in terms of both low accuracy and slow responses ($p < .001$; see Table S2 in supplementary material). Spearman partial correlation analyses revealed that only the S-SS learning accuracy of the identification task (Block 3) was correlated with dyslexic readers' alphabetic letter–speech sound identification accuracy (rho = .338, $p < .05$) and discrimination accuracy (rho = .376, $p < .01$) (3DM subtests). Correlations of S-SS learning speed of the identification task (Block 3) and accuracy and speed of the match/mismatch task (Block 4) with alphabetic letter–speech sound learning measures were nonsignificant (see Table S3 in supplementary material).

Interference control and selective attention predict symbol–speech sound learning abilities and artificial orthography reading

We first tested potential differences between children with and without dyslexia in the attentional measures. Results revealed no significant group differences in nonspeech sustained auditory selective attention (d-prime) or interference control as measured with the magnitude of the Stroop effect in accuracy and RTs ($p > .05$; see supplementary material). Therefore, diagnosis was not included as a factor in the following analyses.

We then used hierarchical multiple regression to investigate the association of auditory attentional measures with S-SS learning accuracy and speed scores and (pseudo)word reading (summed word and pseudoword scores) within the artificial orthography, also when controlling for phonological awareness, vocabulary, and rapid naming skills. A total of 89 children were included in the analysis. We found that children with greater nonspeech selective sustained attention (Fig. 9A) and interference control (Fig. 9B) responded more accurately (Table 7A) but not faster in the S-SS learning task (Table 7B). Adding phonological awareness, vocabulary, and rapid naming skills did not change the statistical significance and predictive values of auditory attentional measures. Given the significant relationship between attentional measures and accuracy in the learning task, we investigated whether attentional abilities predicted (pseudo)word reading in the artificial script independently of the contribution of attention to response accuracy in the learning task. A total of 86 participants were included in the analysis. We found that children with better nonspeech selective attention skills

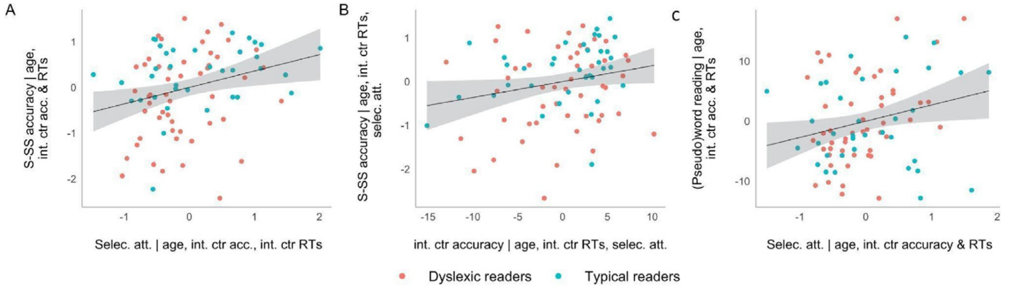

Fig. 9. (A, B) Added variable (partial regression) plots displaying the relationship of sustained selective attention (A) and interference control accuracy (B) with response accuracy in the symbol–speech sound (S-SS) learning task while controlling for the effects of the other predictors (age, interference control reaction times [RTs], and either selective attention or interference control RTs). (C) Sustained selective attention predicted the number of correctly read (pseudo)words written in the artificial symbols when controlling for the effect of response accuracy in the learning task (and of the other predictors). Selec. att., selective attention; int. ctr, interference control; acc., accuracy.

Table 7A

Multiple regression results: Nonverbal sustained selective attention and interference control predicting response accuracy during the learning task

Step	Predictors	β	p	Lower CI	Upper CI
1	Nonspeech selective attention	.251	.015	0.066	0.601
	Interference control accuracy	.219	.026	0.004	0.068
	Interference control RTs	−.113	.238	−3.995	1.006
	Age	.273	.008	0.005	0.031
2	Nonspeech selective attention	.214	.040	0.013	1.371
	Interference control accuracy	.197	.044	0.001	0.555
	Interference control RTs	−.136	.148	−4.231	0.064
	Age	.072	.562	−0.011	0.650
	RAN letters	.110	.395	−0.045	0.021
	RAN digits	−.322	.016	−0.233	0.113
	Vocabulary	.198	.107	−0.005	−0.024
	Phonological awareness	.003	.978	−0.008	0.049

Step	R^2 change	F change ($df1$,$df2$)	p	R^2	F($df1$,$df2$)	p
1	–	–	–	.218	7.19(4,85)	<.001
2	.087	2.68 (4,81)	.037	.275	5.22(8,81)	<.001

Table 7B

Multiple regression results: Nonverbal sustained selective attention and interference control predicting response speed during the learning task

Step	Predictors	β	p	Lower CI	Upper CI
1	Nonspeech selective attention	.067	.562	−0.228	0.416
	Interference control accuracy	.090	.411	−0.022	0.054
	Interference control RTs	−.148	.173	−5.089	0.932
	Age	−.124	.277	−0.025	0.007
2	Nonspeech selective attention	.119	.327	−0.171	0.508
	Interference control accuracy	.126	.271	−0.018	0.062
	Interference control RTs	−.149	.177	−5.149	0.967
	Age	.017	.909	−0.019	0.021
	RAN letters	−.010	.947	−0.102	0.096
	RAN digits	.152	.328	−0.066	0.195
	Vocabulary	−.095	.507	−0.045	0.022
	Phonological awareness	−.108	.429	−0.014	0.006

Step	R^2 change	F change ($df1$,$df2$)	p	R^2	F($df1$,$df2$)	p
1	–	–	–	−.002	0.96(4,85)	.433
2	.042	0.94.446 (4,81)	.446	−.005	0.95(8,81)	.482

Table 7C
Multiple regression results: Nonverbal sustained selective attention and interference control predicting reading within the artificial orthography

Step	Predictors	β	p	Lower CI	Upper CI
1	Nonspeech selective attention	.217	.033	0.219	5.118
	Interference control accuracy	.170	.074	−0.026	0.544
	Interference control RTs	−.027	.774	−25.451	19.014
	S-SS learning accuracy score	.436	<.001	2.148	5.965
	Age	−.081	.425	−0.169	0.072
2	Nonspeech selective attention	.235	.030	0.287	5.503
	Interference control accuracy	.194	.053	−0.004	0.593
	Interference control RTs	−.021	.827	−25.509	20.435
	S-SS learning accuracy score	.448	<.001	2.106	6.233
	Age	.002	.990	−0.147	0.149
	RAN letters	−.042	.752	−0.906	0.657
	RAN digits	−.042	.759	−1.146	0.839
	Vocabulary	−.167	.183	−0.417	0.081
	Phonological awareness	−.044	.703	−0.087	0.059

Step	R^2 change	F change ($df1$,$df2$)	p	R^2	F($df1$,$df2$)	p
1	–	–	–	.302	8.45(5,81)	<.001
2	.019	0.577 (4,77)	.680	.287	4.85(9,77)	<.001

Note. CI, confidence interval; RTs, reaction times; RAN, rapid automatized naming; S-SS, symbol–speech sound.

showed higher word and pseudoword artificial orthography reading scores (Table 7C and Fig. 9C). Results remained unchanged when phonological awareness, vocabulary, and rapid naming measures were entered in the model.

Discussion

In the current study, we examined the unfolding of children's letter–speech sound association learning, simulating one of the first steps of reading acquisition. The participants, 7- to 12-year-old children with and without dyslexia, learned the associations between eight novel symbols and familiar native (Dutch) speech sounds. Then, children read out loud words and pseudowords written within the artificial orthography. To identify factors influencing children's ability to learn symbol–speech sound correspondences, we also measured auditory nonspeech sustained selective attention and interference control abilities. We found that S-SS learning trajectories were modulated by reading ability, with children with dyslexia showing shallower learning curves. No group differences were observed for reading out loud in the artificial orthography. Importantly, nonspeech sustained selective attention and interference control predicted children's accuracy during S-SS learning. Sustained selective attention also predicted the ability to read the artificial orthography.

Symbol–speech sound learning trajectories are modulated by dyslexia diagnosis

In our analyses of the S-SS learning data, we first focused on learning trajectories to detect individual differences across and between children with and without dyslexia. Interestingly, our findings revealed that the learning trajectories of children with dyslexia gradually diverged from those of typical readers, indicating the relevance of tracking behavioral changes *during* learning, next to previously used learning outcome measures such as behavioral scores on post-training tasks (e.g., Aravena et al., 2017; Law et al., 2018), total learning scores (Gellert & Elbro, 2017a, 2017b, 2018; Karipidis et al., 2017), and training duration (Karipidis et al., 2017; Pleisch et al., 2019). Specifically, response accuracy of children with dyslexia was significantly lower than that of typical readers in the last two thirds of each block. The difference compared with typical readers was particularly pronounced in the last block (as shown by a significant difference in Block 4 across time bins; Table 3), where the task design changed compared with previous blocks. Across the three time bins, children with dyslexia responded on average significantly less accurately in the match/mismatch task (Block 4). This suggests that once children with dyslexia were required to apply the newly learned pairs in a novel context, their difficulties became more evident, potentially indicating a reduced capacity to generalize across tasks. Alternatively, the match/mismatch task may tap into a specific impairment of dyslexia. Whereas in the identification task children were simultaneously presented with a sound and two visual characters and were asked to identify the correct symbol, in the match/mismatch task they were first presented with the visual symbol and then, after 1500 ms, with a matching/mismatching phoneme. Thus, the match/mismatch task may capture a difficulty in accessing the phonological information from print or may be driven by reduced short-term verbal memory skills (Ramus & Szenkovits, 2008). In particular, the asynchronous presentation between visual and auditory stimuli may have placed higher demands on working memory processes, which are often found to be impaired in dyslexic readers (e.g., Menghini et al., 2011; Swanson et al., 2009; Wang et al., 2022). In future studies, manipulating the temporal presentation of audio and visual stimuli could clarify the role of (a)synchronicity in audiovisual association learning in children with dyslexia. Another possibility is that the observed greater divergence of the learning trajectory of dyslexic readers in later learning phases is due to reduced benefit from continued practice with the S-SS correspondences. In other words, the longer the children with and without dyslexia are exposed to the pairs, the larger the differences between typical and dyslexic readers. This increasing divergence from typical readers' trajectories and the difficulty in applying the learned pairs in a novel context may underlie reported difficulties in consolidating or automatizing letter–speech sound associations after an initial audiovisual link is formed (Blomert, 2011; Blomert & Willems, 2010; Kronschnabel et al., 2014; for a review, see Romanovska & Bonte, 2021).

Across the match/mismatch task (Block 4), we also observed that younger children, both with and without dyslexia, gave slower responses. This finding may relate to younger pupils' difficulty in task switching (e.g., Diamond, 2013) or to developmental differences in attention and working memory processes (Cowan et al., 2018), such that younger children require more time to respond correctly despite being able to respond as accurately as the older participants. Alternatively, this result could be related to specific characteristics of the new task, for example, the interference created by the incongruence of the audiovisual units (Huizinga et al., 2006).

Observation of the learning trajectories did not reveal a difference with typical readers in the change of response times during learning, although in line with Aravena et al. (2017) dyslexic readers' responses were overall slower in the identification task (Blocks 1–3). In contrast to previous evidence, no differences were found in subsequent reading tests within the artificial orthography (Aravena et al., 2017; Law et al., 2018). However, our 14-min task was shorter than the 20-min training in Aravena et al. (2017) and Law et al. (2018). It is possible that extending the training duration may have increased response accuracy in both typical and dyslexic readers until learning curves of both groups reached similar high accuracy. Longer training may have instead revealed group differences at the level of changes in response speed or in making use of the learned correspondences to read words written with the symbols. Future studies may clarify this point, for example, by employing a longer learning task or a task with no time limit (e.g., as in Karipidis et al., 2017), which allows children to move to the reading tests once a predefined level of training performance is achieved.

Because previous neuroimaging studies showed a reduced sensitivity to letter–speech sound (in)congruency (Blau et al., 2009, 2010; Kronschnabel et al., 2014; Žarić et al., 2014), we also investigated whether (in)congruency of the symbol and subsequently presented speech sound influenced children's responses in the match/mismatch task. We observed that children were faster but less accurate for congruent S-SS pairs. Thus, after a brief learning phase, children processed the congruent and incongruent audiovisual pairs differently. Although this condition-related pattern of responses may appear to be counterintuitive, it is plausible that when starting to learn unfamiliar pairs, the rejection of an incorrect match (out of 7 incorrect matches) is slower but more accurate than the identification of the single correct match. The absence of a group difference in discriminating congruent and incongruent symbol–sound pairs concurs with previous behavioral evidence in priming tasks with congruent, baseline, and incongruent real letters and speech sounds (Clayton & Hulme, 2018).

Altogether, divergent learning trajectories in dyslexic readers as well as a lack of group differences in processing the incongruency of audiovisual pairs may explain contrasting behavioral findings from previous studies. These did not report dyslexia-related differences in discriminating congruent (real) letter–speech sound pairs (Clayton & Hulme, 2018; Nash et al., 2017) as compared with training studies that did find deficits in dyslexic readers' performance in post-training identification tasks (Aravena et al., 2013, 2017) or reading tasks within the trained orthography (Aravena et al., 2013, 2017; Law et al., 2018). Furthermore, dyslexic readers' shallower learning trajectories could indicate that the previously found lower ability to read the novel orthography stemmed from lower letter–speech sound learning abilities (Aravena et al., 2013, 2017) rather than mainly being the result of reduced reading experience (Law et al., 2018).

Finally, individual differences in reading fluency (measured with a standardized word reading task) were associated with performance in the letter–speech sound learning paradigm, also when controlling for established predictors of reading abilities such as phonological awareness, rapid naming, and vocabulary. This finding does not align with that of Law et al.'s (2018) study, where the contribution of audiovisual association learning to reading outcomes in 7- and 8-year-old children (20 with and 64 without dyslexia) was explained by previous phonological and orthographic knowledge. In our study, S-SS association learning no longer predicted reading fluency when controlling for dyslexia diagnosis, whereas phonological awareness and rapid naming of letters remained significant predictors, indicating that this relation was driven by the overall lower performance of children with dyslexia on both S-SS learning and reading tasks. On the contrary, the relationship between alphabetic reading fluency and reading in the artificial orthography remained significant also when diagnosis was entered in the model. Thus, considering also the limits of a correlational design, these results provide evidence for the use of an S-SS association learning paradigm as a model for critical processes underlying early fluent reading development (Schmalz et al., 2021). Notably, in the group of dyslexic readers, only accuracy values of the S-SS identification task correlated with measures of standardized (real) letter–speech sound. Measures of the match/mismatch task (Block 4), where dyslexic readers' overall accuracy scores diverged more from those of typical readers (Table 3), were not associated with any of those of the standardized tasks. These observations indicate that learning measures obtained in the match/mismatch task provide relevant unique information for (diagnostic) assessments of children's reading skills. Future investigations may clarify whether the match/mismatch task also taps into specific difficulties of dyslexic readers with diagnostic and prognostic value.

Auditory attention predicts symbol–speech sound learning abilities

At the group level, our study did not provide evidence of interference control or sustained selective attention deficits in children with dyslexia given that their target detection in the dual-stream paradigm and the magnitude of their Stroop congruency effects (in accuracy and RTs) were not different from those of typical readers (see supplementary material). These results are in contrast to previous evidence showing dyslexic readers' difficulties in orienting attention (Facoetti et al., 2006), inhibiting irrelevant information (Gabay et al., 2020; Facoetti et al., 2006) and sustaining attention (Menghini et al., 2010). However, and interestingly, individual differences in auditory sustained selective attention and interference control abilities predicted S-SS association learning, providing novel evidence supporting a potential role for top-down mechanisms such as auditory attention in letter–speech sound associative processes (Fraga González et al., 2017; Hämäläinen et al., 2019). Altogether, these findings align with those of a previous study that did not find differences in (visual) interference control skills between children with and without dyslexia but did find that dyslexic readers with poorer interference control had poorer performance on rapid naming tasks (Bexkens et al., 2015). The lack of group-level deficits in the current study could indicate that auditory attention deficits are characteristic of only some individuals with dyslexia, in line with a risk factor model of neurodevelopmental disorders. The model proposes that no single deficit is either necessary or sufficient to lead to (reading) deficits but rather several interacting factors are (e.g., Astle & Fletcher-Watson, 2020; Pennington, 2006; van Bergen et al., 2014). Given the significant association between attention and audiovisual learning, it is possible that along a continuum of attentional abilities, even mildly compromised attentional skills may influence children's ability to learn letter–speech sound correspondences. Longitudinal studies may be especially informative for clarifying the extent to which attention influences processes underlying reading acquisition over time as well as the role of attention in reading deficits (Goswami et al., 2014).

Our sustained selective attention task required participants to direct attention to sound streams by making use of the acoustic dimensions (temporal and spectral) that differentiated the to-be-attended and ignored tone melodies. The task also required participants to sustain attention over time and integrate information across the attended melody to successfully detect targets. Thus, better selective attention skills may facilitate attention toward relevant features of the audio and visual stimuli (Hämäläinen et al., 2019), resulting in better associative learning. Alternatively, the relationship may be driven by the sustained attention component of the task. Children who can maintain focus throughout the task may experience general benefits for learning across different domains. Nonspeech sustained selective attention also predicted the ability to apply the newly learned correspondences in subsequent reading tests. This relationship was independent from the contribution of attention to audiovisual learning abilities. This result supports previous findings demonstrating that selective attention to grapheme–phoneme mappings *during* learning facilitates later word reading (Yoncheva et al., 2015). Moreover, it could indicate that in beginner readers, attentional resources directly support accurate and fast decoding (Shaywitz & Shaywitz, 2008).

An association was also found between accuracy of children's responses in the S-SS learning paradigm and interference control, as measured by the difference in response accuracy between the congruent and incongruent conditions of the auditory Stroop task. This could indicate that better learners were more able to suppress attention toward the incorrect audiovisual pairs while learning the associations. More specifically, in the identification task, where two symbols are simultaneously presented with a sound, attention toward the nonmatching symbol may activate the speech sound corresponding to that symbol. This activation may more likely occur when audiovisual links are successfully formed. Consequently, suppression of competing audiovisual information may be increasingly required during learning. Having greater interference control skills may also support children in resolving the incongruence between the presented audio and visual information in the match/mismatch task. A previous study with prereaders found that inhibition control (as measured with a visual go/no-go task) played a minor role in the acquisition and retrieval of three symbol–syllable pair associations once working memory and phonological measures were taken into account (Ehm et al., 2019). The authors interpreted the lack of association between inhibition and audiovisual association skills in terms of the characteristics of the learning paradigm. In contrast to the task in the current study, the paired-associate learning (PAL) task in Ehm et al. (2019) did not require active suppression of irrelevant information. Nonetheless, findings of Ehm et al. (2019) suggest that other cognitive skills such as working memory may be required for successful audiovisual association learning. Follow-up studies including working memory and attentional measures may help to clarify the independent contribution of auditory attentional and working memory to audiovisual learning mechanisms relevant to reading acquisition.

Finally, in contrast to Ehm et al. (2019), we did not observe a significant contribution of phonological awareness to S-SS learning performance or to the ability to read the artificial orthography. Several differences between the studies may account for this contrasting finding. First, Ehm et al. (2019) included younger children in a more narrow age range (M = 5 years 7 months, SD = 0.4 years) as compared with the older children in our sample (M = 9 years 6 months, SD = 1.20 years), whose reading fluency (and reading-related skills such as letter–speech sound learning) may on average rely less strongly on phonological awareness (Powell & Atkinson, 2021). Second, Ehm et al. (2019) used a PAL task where children learned to associate three syllables (/ma/, /pa/, and /ta/) with basic geometric shapes (circle, square, and triangle). They received direct corrective feedback by the experimenter (30 learning trials), followed by a retrieval phase where feedback was not provided (maximum 12 trials). The relation between verbal–visual PAL tasks and reading skills has been shown to be more strongly driven by verbal demands (e.g., phonological awareness) than by cross-modal demands (Litt et al., 2013; Poulsen & Elbro, 2018) and to be associated with reading accuracy more than reading fluency development (Poulsen & Elbro, 2018). Our S-SS learning task, where children learned to associate eight individual phonemes with letter-like symbols without previous presentation of the associations by the experimenter, may tap more strongly into cross-modal learning abilities. Consequently, here the relation between S-SS learning performance and reading fluency scores was not accounted for by phonological awareness skills.

Conclusions

Our study mimicked the first steps of reading acquisition examining S-SS learning trajectories, next to measures of learning outcomes, in school-age children with and without dyslexia. Learning curves of children with reading deficits diverged from those of typical readers, suggesting an emerging difficulty during learning novel audiovisual correspondences. Poorer audiovisual learning is possibly due to difficulty in accessing phonological information from graphemes (Ramus & Szenkovits, 2008) or in automatizing and consolidating audiovisual relationships (Blomert, 2011). Furthermore, dyslexic readers' difficulties were independent of the ability to discriminate the novel congruent and incongruent audiovisual pairs, which was comparable to that of typical readers. Therefore, individual differences in the moment-to-moment process of learning may be crucial for understanding individual differences in reading (dis)fluency.

Importantly, the learning paradigm also allowed us to hone in on the factors affecting the acquisition of novel audiovisual associations. Here, we focused on auditory attention, revealing an association between nonspeech sustained selective auditory attention and interference control and children's symbol–sound association learning ability. Although with the limitation of a correlational design, this finding suggests that the ability to selectively direct the focus of attention to relevant auditory and visual units facilitates successful letter–speech sound integration and promotes phonological access from print and, later, automatic word recognition (Yoncheva et al., 2010, 2015). Further investigations aimed at identifying attentional processes relevant for different reading subskills may be key for understanding the contribution of domain-general factors to the large interindividual variations in reading abilities. Longitudinal studies in particular may be able to determine to what extent and at what stage of reading development attention plays a significant role, potentially providing new insight for targeted intervention.

From a clinical perspective, a brief artificial S-SS learning paradigm such as the one employed in the current study may be developed into a valuable and accessible tool for early screening and diagnostic assessment. In particular, combining learning tasks with existing assessments of (alphabetic) letter–speech sound knowledge may provide more insight into children's learning potential. Finally, our findings highlight the need to better define the contribution of attention and other domain-general skills to the development of fundamental processes for successful reading acquisition.

Data availability

Data will be made available on request.

Appendix A. Supplementary material

Supplementary material to this article can be found online at https://doi.org/10.1016/j.jecp.2023.105761.

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