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Phonemes, words, and phrases: Tracking phonological processing in pre-schoolers developing dyslexia

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HIGHLIGHTS

- Phonological processing in preschoolers with and without later literacy problems.
- Electrophysiological correlates of phoneme-, word-, and phrase-level phonology.
- Deficits at phoneme- and word-, but not at phrase-level in children with later literacy problems.

ABSTRACT

Objectives: Individuals with dyslexia often suffer from deficient segmental phonology, but the status of suprasegmental phonology (prosody) is still discussed.
Methods: In three passive-listening event-related brain potential (ERP) studies, we examined prosodic processing in literacy-impaired children for various prosodic units by contrasting the processing of word-level and phrase-level prosody, alongside segmental phonology. We retrospectively analysed school children's ERPs at preschool age for discrimination of vowel length (phoneme processing), discrimination of stress pattern (word-level prosody), and processing of prosodic boundaries (phrase-level prosody).
Results: We found differences between pre-schoolers with and without later literacy difficulties for phoneme and stress pattern discrimination, but not for prosodic boundary perception.
Conclusion: Our findings complement the picture of phonological processing in dyslexia by confirming difficulties in segmental phonology and showing that prosodic processing is affected for the smaller word level, but not the larger phrase level.
Significance: These findings might have implications for early interventions, considering both phonemic awareness and stress pattern training.

1. Introduction

Phonological processing comprises listeners' tracking of the sounds of a given language at *segmental* (i.e., targeting phonemes, as the most basic elements of sound) and *suprasegmental* levels (i.e., targeting words and phrases). At the segmental level, discrimination of phonemes is important to grasp the content of utterances (e.g., *rake* vs. *lake*). Phonemic awareness, the capability of phoneme detection and manipulation, is also relevant for spelling (Ziegler et al., 2010; Ziegler and Goswami, 2006) and reading (Coltheart et al., 2001; Ziegler et al., 2000), and an important indicator of resulting literacy skills (Caravolas et al., 2013; Moll et al., 2014; Seymour et al., 2003; Ziegler et al., 2010). In clinical studies, typical populations and those with literacy impairments, including developmental dyslexia (DD), differed in phonemic awareness (World Health Organization, 2009). In comparison to their typical peers, adults and school children with DD performed worse on phoneme discrimination tasks (Groth et al., 2011; Hämäläinen et al., 2009; Landerl, 2003; Steinbrink et al., 2014). Moreover, infants with a familial risk of developing DD already showed an impairment in discriminating lengths of vowels and consonants (Leppänen et al., 2002; Pihko et al., 1999), and longitudinal studies could show a relationship between infants' phoneme processing and perception abilities and later reading and spelling skills

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(Lohvansuu et al., 2018; Schaadt et al., 2015; van Zuijen et al., 2013). Thus, research so far has demonstrated a potentially causal outcome of literacy impairments from preceding poor perception of segmental phonology.

In addition to segmental phonology, suprasegmental phonology or prosody, the application of stress, intonation, and timing to words and phrases facilitates one's language comprehension. At the word level, stress placement can determine distinctions between verbs and nouns at the syntactic and lexical levels (e.g., *projéct* versus *prójectt*) and promote segmentation from sentence contexts (Cutler and Norris, 1988). At phrase level, sentence intonation quality indicates syntactic units (Nespor and Vogel, 1986; Selkirk, 1984), while ambiguous syntactic structures can be resolved by prosodic boundaries (Price et al., 1991; Speer et al., 2011; see also Bögels et al., 2011). Prosodic skills have also been related to literacy outcome (David et al., 2007; Gutierrez-Palma et al., 2009; Holliman et al., 2008, 2010a, 2010b; Whalley and Hansen, 2006). At the word level, prosodic skills explained children's spelling scores (Wood, 2006) and reading accuracy (Lochrin et al., 2015), independent of vocabulary and phonemic awareness. Furthermore, children's sensitivity to lexical stress predicted their reading achievement half to one year later (Calet et al., 2015; Holliman et al., 2010b). Primary evidence further suggests that suprasegmental features at phrase and sentence levels have an impact on reading progress (Holliman et al., 2014). Contrary to segmental phonology's compelling influence in DD, studies on literacy impairments report mixed evidence of the role of suprasegmental phonology in DD. For example, Spanish-speaking adolescents with DD were observed to have impaired word-level stress assignment along with impaired segmental awareness. On the contrary, English-speaking school children, diagnosed with DD were not observed to have difficulties with stress pattern discrimination at the word level (Anderson et al., 2013). For prosodic skills at the phrase level, children with reading difficulties were found to perform comparable to their typically developing peers while perceiving stress at the phrase level (Holliman et al., 2012), along with the intact use of prosodic phrase boundaries to solve syntactic ambiguities (Geiser et al., 2014). Thus, research on suprasegmental phonology reported both difficulties in prosodic abilities (Barry et al., 2012; Cuetos et al., 2018; Goswami et al., 2010; Goswami et al., 2013; Goswami et al., 2002; Leong et al., 2011) and, conversely, intact prosodic abilities (Anderson et al., 2013; Marshall et al., 2009; Mundy and Carroll, 2013) in impaired literacy, delivering an equivocal picture.

Given these differing outcomes of prosody's influence on literacy impairments, we recently investigated how German school children with typical and poor spelling abilities process segmental and suprasegmental phonology (Männel et al., 2017). In the following behaviour-independent experimental paradigms, we recorded children's event-related brain potentials (ERPs): Mismatch Negativity (MMN; i.e., automatic auditory detection of a violation of an established prediction; Näätänen et al., 1978) and Closure Positive Shift (CPS). Using MMN to measure segmental phonological processing, we examined children's vowel length discrimination, because this phonological feature is orthographically relevant in German. Specifically, vowel lengthening can indicate lexical distinctions in German (e.g., *Bann /ban/, [engl. ban]* versus *Bahn /ba:n/, [engl. train]*), yet the acquisition of the corresponding orthographic representation is challenging, because lengthening can take different forms (e.g., *Bahn [engl. train], Bad [engl. bath]*, or *Boot [engl. boat]*) (see Klicpera et al., 1993; Klicpera and Gasteiger-Klicpera, 2000; Landerl, 2003).

Using the CPS component to measure suprasegmental phonological processing, we evaluated children's prosodic boundary (PB) perception, which occurs in response to sentence-level PBs in pre-schoolers (Männel and Friederici, 2011) and adults (Steinhauer et al., 1999; for a review, see Bögels et al., 2011). Our results revealed that those school children (aged 11 years) that showed difficulties in their spelling abilities had deficient segmental phonology in comparison to school children without such difficulties (see also Corbera et al., 2006; Lachmann et al., 2005; Lovio et al., 2010; Paul et al., 2006). However, intact phonology at the suprasegmental level (i.e., prosody) was found at the phrase level (Männel et al., 2017). The latter result contradicts findings that individuals with DD have difficulties in prosodic processing (Barry et al., 2012; Goswami et al., 2010; Goswami et al., 2013; Leong et al., 2011), but might be explained by the specific type of prosodic unit being studied. Specifically, intact phrase-level prosody is often exhibited in individuals with DD (Geiser et al., 2014; Holliman et al., 2012), but deficient word-level stress assignment is not (Barry et al., 2012; Cuetos et al., 2018; Goswami et al., 2013; Holliman et al., 2012). The larger prosodic units have a more prominent acoustic marking, as evident in phrase- and sentence-level prosody (Nespor and Vogel, 1986; Peters et al., 2005) compared to word-level prosody (Dogil, 1995), which might lead to this processing advantage. A second explanation for these inconsistent findings on prosodic abilities in individuals with DD may be differences in task demands across experiments. It was shown that individuals with DD do not have problems performing implicit tasks (e.g., priming tasks, see Mundy and Carroll, 2012; 2013), however, they do struggle with performing explicit tasks (e.g., production tasks, see Goswami et al., 2010; Leong et al., 2011; Mundy and Carroll, 2012). Thus, an advantage for processing larger prosodic segments and/or recording ERPs during passive listening may elicit the intact PB processing in children with DD.

Complementing the picture of prosody processing in individuals with DD, the current study targets the thus far unexplored prosodic level, namely the word-level prosody in a behaviour-independent, passive-listening ERP study. We investigated stress pattern discrimination implemented by a vowel length contrast in pseudowords (i.e., ba:ba vs. baba:) by evaluating the MMN in a longitudinal sample of children at age 4.6 years. Importantly, we compared pre-schoolers at risk of DD, defined by preschool phonological deficits, who developed literacy problems at school age (i.e., children with later literacy difficulties) with pre-schoolers who were not at risk of DD and did not develop literacy problems at school age (i.e., children without later literacy difficulties). To affirm our previous findings on segmental difficulties in literacy-impaired children (see Männel et al., 2017), we also evaluated vowel length discrimination (i.e., MMN) when the children of our longitudinal sample were 4.4 years old. In the same sample of children, we again analysed phrase-level prosodic processing, testing their PB processing (i.e., CPS) when they were 6-years-old. Consistent with our previous results, we expected deficient segmental phonological processing (i.e., reduced MMN amplitudes to changes in vowel length information) in children with later literacy difficulties. In contrast, we expected comparable suprasegmental phonological processing at phrase level (i.e., no reduced CPS amplitudes to PB processing in children with later literacy difficulties) of children with and without later literacy difficulties. Importantly, our new experiment on stress pattern discrimination of pseudowords will reveal whether literacy-impaired children generally show intact suprasegmental phonology, or whether the prosodic unit (i.e., word vs. phrase) under consideration is the driving element differentiating intact and deficient suprasegmental phonological processing in DD.

2. Materials and methods

2.1. Participants

Participating children formerly took part in the longitudinal "*German Language Developmental Study* (GLAD-study)". Originally

198 participants were engaged who were tested repeatedly on their language perception and production skills, beginning at birth until school age. In the current study, we were thus able to retrospectively consider ERP data recorded during preschool age for groups of children with and without later literacy difficulties, determined by children's preschool and school performance.

Prior to school enrolment at 5.02 years of age [*Standard Deviation (SD)* = 0.06], children were tested using the standardized Bielefeld Screening for the Early Recognition of Reading and Spelling difficulties ("***BI****elefelder* ***SC****reening zur Früherkennung von Lese-Rechtschreibschwierigkeiten*"; *BISC*, Jansen et al., 2002), assessing prerequisites of literacy (i.e. phonological awareness, attention, phonetic recoding in short-term memory, and recall from long-term memory). In accordance to the test standards, children scoring below the 16th percentile in at least four of the eight subtests were considered at risk of later literacy problems, in comparison to the standard sample (see Jansen et al., 2002 for test standards). At ten years of age [*Mean (M)* = 9.80, *SD* = 0.40], 67 children of the original sample were re-invited to test their spelling abilities using the standardized German spelling test ("***DE****utscher* ***RE****chtschreib****T****est*"; *DERET*; Stock and Schneider, 2008). Children were tested individually and they had to write down ten sentences without time limit that were dictated to them in consecutive order by the experimenter. Spelling errors, defined as at least one spelling error within one word, were judged based on their comparison to age-normed percentile ranks (PRs; Stock and Schneider, 2008). In the current study, the ERP data were taken into consideration of those children who were at risk of developing literacy problems at preschool age (i.e., according to the BISC's test norms; Jansen et al., 2002) and who showed spelling problems at school age (PR $\leq$ 25, according to the DERET's test norms; Stock, and Schneider, 2008). These children were grouped to the sample with later literacy difficulties (*N* = 15), whereas children with a spelling test PR > 25 and who were not at risk of later literacy problems at preschool age (i.e., according to the BISC's test norms; Jansen et al., 2002) were categorized as children without later literacy difficulties (*N* = 14) (see Table 1)[1]. Preceding the first ERP experiment, we considered children's non-verbal intelligence to ensure that their differences in performance cannot be attributed to differences in general intelligence (i.e., at age 4 years; *M* = 4.15 years, *SD* = 0.05). Utilizing the nonverbal scale (i.e., consisting of five subtests; e.g.: *Spatial working memory*) of the German version of the "***K****aufman-****A****ssessment* ***B****attery for* ***C****hildren*" (*K-ABC*; Kaufman et al., 2009), their performance was translated into age-normed standard scores (*M* = 100, *SD* = 15). Shown in Table 1, no differences were seen between groups in non-verbal intelligence. That we found more boys to be affected by literacy problems than girls reflects the typically observed sex ratio for literacy disorders.

All participants were German monolinguals who did not report any hearing deficiencies or neurological impairments. The ethics committee of Leipzig University approved the study, which adhered to American Psychological Association (APA) standards according to Helsinki's declaration from 1964 (World Medical Association, 2013). Parental written consent to participate was collected before the experiment and after we had informed parents and their children about the study details.

2.2. Additional behavioural tests

At school age (*M* = 9.80 years, *SD* = 0.40), all participants were tested on their phonemic awareness abilities by applying the German test for reading and spelling skills ("***BA****sis****KO****mpetenzen für Lese- Rechtschreibleistungen 1–4*"; *BAKO 1–4;* Stock et al., 2003). The test assesses phonemic manipulation skills with seven subtests (e.g., phoneme deletion). Age-specific norms serve to calculate PRs.

Three years later (*M* = 12.99 years; *SD* = 0.52), a standardized German test, assessing reading speed and comprehension ("***L****ese****G****eschwindigkeits- und –****V****erständnis****T****est*"; *LGVT*; Schneider et al., 2007), was administered testing participants' text reading. Children had four minutes to silently read as much of a cloze text as possible, while they had to pick one of three semantically different options into the missing word spaces. Comprehension (i.e., total of semantically correct insertions) and reading speed (i.e., total of read words) are translated into PRs based on school children's grade-specific norms.

2.3. Segmental phonology: MMN experiment on vowel length discrimination

Vowel length discrimination, tested when participants were 4.4 years old (*SD* = 0.18), was presented using a passive-listening oddball paradigm, in which a standard stimulus gets repeatedly presented and only occasionally replaced by a deviant stimulus. Stimuli consisted of two syllables that differed in terms of the length of the vowel /a/ (i.e., one with a short vowel: /ba/, 202 ms; one with a long vowel: /ba:/, 431 ms). A female German native speaker recorded the short-vowel syllable (i.e., /ba/) in a soundproof booth, while digitization at 44.1 kHz/16-bit sampling rate, mono was used. The long-vowel syllable /ba:/ was created by digitally lengthening the steady-state part of the short-vowel syllable (PRAAT; Boersma, 2001; see Friedrich et al., 2004 for more details). The experiment was comprised of two experimental blocks, each consisting of 525 syllables. Within one block, we presented 420 standard (80%) and 105 deviant syllables (20%). The inter-stimulus interval (offset to onset) was 855 ms. In the first block, the short syllable /ba/ was used as the standard and the long syllable /ba:/ as the deviant, and in reverse in the second block. Across participants, the block order was counterbalanced. Loudspeakers were used for stimulus presentation and the total experiment time was about 20 minutes.

2.4. Word-level prosody: MMN experiment on stress pattern discrimination

For stress pattern discrimination, tested when participants were 4.6 years old (*SD* = 0.04), a passive-listening oddball paradigm was applied with the pseudoword *baba*. Specifically, the pseudoword could be stressed on the first syllable (*ba:ba*) or on the second syllable (*baba:*), which was implemented by a vowel length contrast. Thus, the first stimulus consisted of a long vowel syllable followed by a short vowel syllable (ba:ba, offset first syllable: 355 ms, onset second syllable: 405 ms, total duration 750 ms), and the second stimulus consisted of a short vowel syllable followed by a long vowel syllable (baba:, offset first syllable: 138 ms, onset second syllable: 278 ms, total duration: 750 ms) (see Friederici et al., 2007). A female German native speaker recorded both pseudowords in a soundproof booth, while digitization at 44.1 kHz/16-bit sampling rate, mono was used. The pseudowords were then manipulated as follows: The first 100 ms of both pseudowords were taken and replaced by the other, such that acoustic differences began after 100 ms (see Weber et al., 2004 for more details). The experiment was comprised of two experimental blocks, each consisting of 500 pseudowords. Within one block, we presented 400 standard pseudowords (80%) and 100 deviant pseudowords (20%). The inter-stimulus interval (offset to onset) was 855 ms. In the first block, the pseudoword /ba:ba/ was used as

[1] Note that the classification of literacy-impairments in German individuals is more reliable when spelling is used (see Cantiani et al., 2013; Landerl et al., 1997; Männel et al., 2015; Neuhoff et al., 2012; Wimmer, 1996) due to the properties of German orthography (Landerl and Wimmer, 2008).

Table 1
Demographic and literacy variables of children with and without (later) literacy difficulties.

	Children with (later) literacy difficulties	Children without (later) literacy difficulties	Inference statistics	p-value
Participant numbers	15	14		
Sex: male:female	12:3	5:9	χ^2 = 5.86	**.02**
Non-verbal IQ testing at preschool age				
Age (years)	4.14 (0.05)	4.16 (0.04)	*t* = 1.04	.31
Non-verbal IQ (SSc)	94.50 (10.25)	95.79 (8.28)	*t* = 0.35	.73
At-risk group assignment for literacy difficulties at preschool age				
Age (years)	5.02 (0.07)	5.02 (0.04)	*t* = 0.33	.74
Number of risk points for literacy difficulties (BISC)	4.33 (0.90)	0.79 (0.89)	*U* = 0.00	**.001**
Age of participants at ERP experiments at preschool age				
Age (years): MMN experiment on vowel length discrimination	4.40 (0.25)	4.48 (0.04)	*t* = 1.20	.24
Age (years): MMN experiment on word stress discrimination	4.64 (0.04)	4.63 (0.04)	*t* = -0.51	.61
Age (years): CPS experiment on PB processing*	5.99 (0.05)	6.01 (0.03)	*t* = 0.81	.43
Literacy group assignment at school age				
Age (years)	9.74 (0.48)	9.85 (0.30)	*t* = 0.71	.48
Spelling from dictation (PR)	9.74 (7.54)	64.00 (20.82)	*t* = 9.17	**.001**
Phonemic awareness test battery (PR)	19.33 (18.52)	70.43 (28.31)	*t* = 5.79	**.001**
Additional testing of reading abilities at school age				
Age (years)	12.93 (0.55)	13.06 (0.50)	*t* = 0.63	.53
Text reading speed (PR)	26.92 (21.46)	43.54 (22.39)	*t* = 2.40	**.02**
Text reading comprehension (PR)	27.69 (21.33)	52.77 (28.48)	*t* = 1.93	**.05**

Note. Number in parenthesis are standard deviations; SSc = standard score; PR = percentile rank; *p*-values presented in bold indicate significant differences; * number of children with later literacy difficulties = 11; number of children without later literacy difficulties = 10.

the standard, while the pseudoword /baba:/ was used as the deviant, and the other way around in the second block. Across participants, the order of the blocks was counterbalanced. Loudspeakers were used for stimulus presentation and the total experiment time was about 24 minutes.

2.5. Phrase-level prosody: CPS experiment

In the CPS experiment, tested when participants were 6.0 years old (*SD* = 0.04), children were auditorily presented via loudspeaker with a total of 100 sentences. Half of these sentences had a PB, while the other half did not (Fig. 1; for more detail, see Männel and Friederici, 2009; 2011). Sentences were presented in a pseudo-random order (i.e., $\leq$ three succeeding sentences of one prosodic type). Each sentence was followed by an inter-stimulus interval of 1.5 s, with an overall experiment duration of 8 minutes. A female German native speaker recorded the sentences in a soundproof booth at a digitization of 44.1 kHz/16-bit sampling rate, mono; and normalized in amplitude to 70%.

The current experimental manipulation, using sentences with and without PBs, targets participant's prosodic and syntactic processing. Both sentences types were paired and identically worded up until the verb concluding the sentence. The induced structural ambiguity (i.e., early or late closure) can solely be solved when the ending verb appears. However, prosodic characteristics of the sentence can already help determining the correct sentence structure. The different syntactic units from sentence onset are signalled by intonation and duration characteristics, producing sentences with PBs (early closure) and without PBs (late closure). Fig. 1 illustrates the different prosodic structures, showing that PBs were realized by pronounced pre-boundary lengthening, boundary-related pitch changes and pausing. Acoustic analyses showed sentences with PBs to be longer (2890 ms; *SD* = 136) than sentences without PBs (2200 ms, *SD* = 145; $t(98) = -24.71$, $p \leq 0.001$), which could especially be accounted for by the first sentence part (i.e., sentence onset to boundary pause onset; 1078 ms, *SD* = 109 versus 838 ms, *SD* = 114; $t(98) = -10.78$, $p \leq 0.001$), driven by the longer pre-boundary syllable in sentences with PBs ($t(98) = -22.99$, $p \leq 0.001$). In addition, sentences with PBs had a larger pre-boundary pitch rise (237.00 Hz, *SD* = 49.81 versus 32.42 Hz, *SD* = 21.84; $t(98) = -36.22$, $p \leq 0.001$) and a longer pause following the first sentence part (560 ms, *SD* = 26 versus 45 ms, *SD* = 22; $t(98) = -100.38$, $p \leq 0.001$) than sentences without PBs.

2.6. EEG recordings and analysis

For all three experiments, an EEG was recorded during the presentation of the auditory stimuli. Children were seated in a comfortable chair in a sound-attenuating booth. In order to engage the children and to prevent their body movement, we presented them with a silent children's video of their choice (for a similar procedure in preschool and school children, see Männel and Friederici, 2011, 2013; Männel et al., 2013; Schaadt et al., 2015).

QRefa Acquisition Software was used for EEG recording (Version 1.0 beta; MPI-CBS, Leipzig, Germany), for which we used 23 Ag/AgCl installed in an electrode cap (Easy Cap GmbH, Germany) using standard positions (see Fig. 2), identical across experiments. Additional electrodes were positioned above and below the right eye and at the outer canthi of each eye to record electrooculograms. The online reference was CZ and the ground electrode was located at FP1. Impedances were < 10 kΩ (at least < 20 kΩ). The Refa system (Twente Medical Systems International B.V.) was used for EEG signal amplification, which was digitized online at 500 Hz (anti-aliasing low-pass filter of 135 Hz). Offline, we re-referenced the EEG signal algebraically from CZ to the linked mastoids.

For the MMN experiments, we then used a band-pass filter at 0.5–20 Hz (-3dB–cut-off frequencies of 0.59 Hz and 19.91 Hz), while we used a band-pass filter at 0.2–20 Hz (-3dB–cut-off frequencies of 0.25 Hz and 19.91 Hz) for the CPS experiment. This procedure could be justified by the different ERP components under investigation. Specifically, the high-pass filter was less restrictive for the slower CPS component (at 0.2 Hz) than for the faster MMN component (at 0.5 Hz) (see Männel and Friederici, 2009; 2011; 2013; Schaadt et al., 2016; Schaadt et al., 2015). For the MMN vowel length discrimination experiment, EEG epochs of 900 ms post-syllable onset were obtained with a 200 ms pre-syllable baseline (see also Friedrich et al., 2004). For the MMN experiment on stress pattern discrimination, epochs of 1000 ms

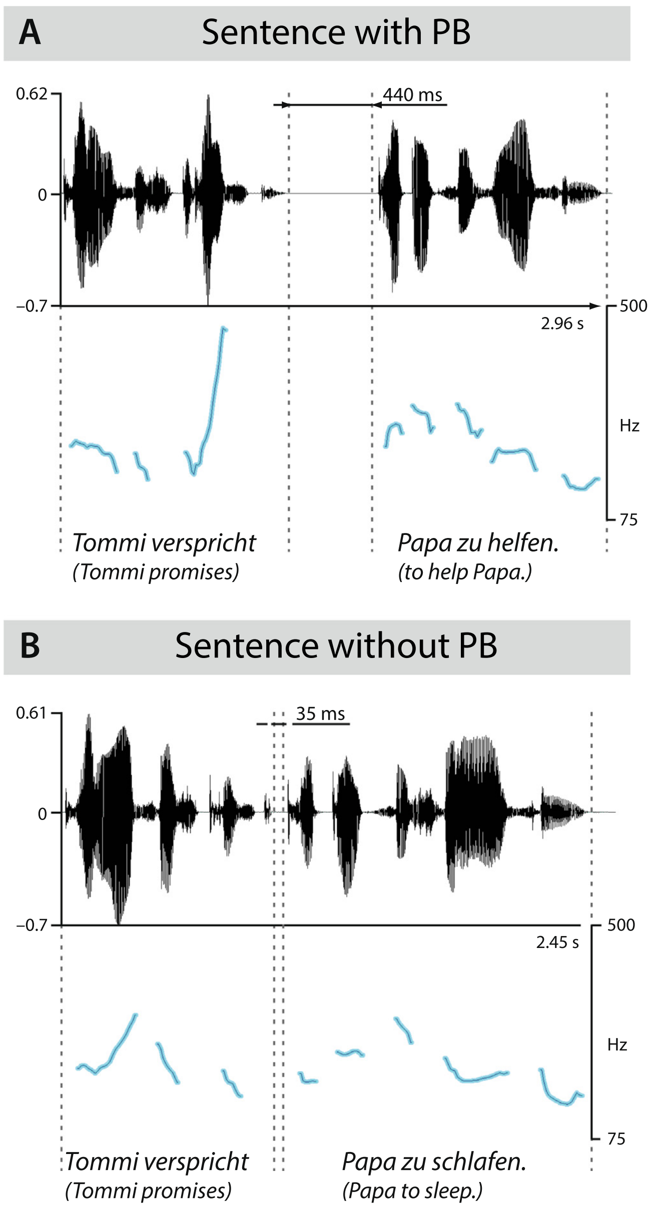

Fig. 1. Example for sentences used for the CPS paradigm testing the perception of prosodic boundaries. Depicted are waveform (normalized values) and pitch track (F0 contour in Hz) of a sentence (A) with and a sentence (B) without prosodic boundary (adapted from Männel and Friederici, 2011).

post-pseudoword onset were obtained with a 200 ms pre-pseudoword baseline (see also Friederici et al., 2007). For the CPS experiment, epochs of 3000 ms relative to sentence onsets were obtained with a 200 ms pre-sentence baseline (see also Männel and Friederici, 2009; 2011; Männel et al., 2013). We identified prototypical blinks and eye-movements separately for each experiment and each participant. These identified blinks and eye-movements then served as an individual correction template to clean those epochs containing the respective artefacts (correlation-based correction algorithm implemented in EEP 3.3, MPI-CBS, Germany). In addition, epochs with a standard deviation exceeding 80 μV within a 200 ms-sliding window were defined as containing artefacts and excluded from further analyse. Notably, for the MMN experiments, those standard epochs directly following a deviant epoch were not included in further analyses. Please note that four children without later literacy difficulties (resulting in $n = 10$) and four children with later literacy difficulties (resulting in $n = 11$) did not participate in the CPS experiment.

For all three experiments, we did not find any significant groups differences (i.e., between children with and without later literacy difficulties) concerning the number of artefact-free trials included in the analyses (see Table 2 for statistical details).

2.7. Statistical analyses

Statistical analyses were run across participants' individual ERP averages (mean amplitude). Across defined time windows (TWs), separate analyses were performed for midline electrodes and lateral electrodes. We defined six regions of interest (ROIs) to analyse effects at lateral electrodes, including hemisphere (left, right) and region information (anterior, central, posterior) (see Figs. 2–4).

To analyse the MMN experiments, we visually inspected the difference wave (deviant–standard) averaged across both literacy groups, but separately for each condition (i.e., long vowel deviant, short vowel deviant, first syllable stressed as deviant, second syllable stressed as deviant), because ERP effects were shown to differ depending on deviancy condition (see Friederici et al., 2007; Männel et al., 2017). For the long vowel deviant, visual inspection revealed two ERP effects: a positive deflection at 300–450 ms and a negative deflection at 450–800 ms (see Fig. 2). For the short vowel deviant, visual inspection also revealed two ERP effects: a negative deflection at 300–400 ms and a second negative deflection at 600–800 ms (see Fig. 2). For the pseudoword with the first syllable stressed as deviant, two negative deflections were found, one at 250–400 ms and one at 500–900 ms. For the pseudoword with the second syllable stressed as deviant, one negative deflection was found at 350–550 ms (see Fig. 2). Mixed-model design analyses of variance (ANOVAs) were then calculated separately for each contrast. For midline electrodes, we performed a three-factorial ANOVA with the factors condition, electrode site (Fz, Cz, Pz) and group (i.e., with and without later literacy difficulties). For lateral ROIs, we performed a four-factorial ANOVA including the factors condition, region, hemisphere, and group. All significant effects (Greenhouse-Geisser-corrected) involving the factor condition are reported, and we analysed significant interactions including the factor condition step-down (Bonferroni-corrected). The interactions that involved factors condition and group were further analysed by performing post-hoc *t*-tests on the MMN difference wave (i.e., deviant–standard) comparing the MMN amplitude of children with and without later literacy difficulties.

For the CPS experiment, we analysed mean ERP amplitudes across the whole sentence by defining TWs of 500 ms each (i.e., relative to sentence onset: TW 0–500, TW 500–1000, TW 1000–1500, TW 1500–2000, TW 2000–2500, and TW 2500–3000 (see Männel and Friederici, 2009; 2011; Männel et al., 2013). For each TW, we performed a three-factorial ANOVA at midline electrodes including the following factors: sentence type (with PBs, without PBs), electrode site, and literacy group; and a four-factorial ANOVA at lateral ROIs including the following factors: sentence type, region, hemisphere, and literacy group. We report those significant effects and significant interactions (Greenhouse-Geisser-corrected) involving sentence type as a factor. Significant interactions involving the factor sentence type were further analysed step-down (Bonferroni-corrected).

3. Results

3.1. Behavioural tests

As Table 1 documents, children with and without literacy difficulties differed in their spelling performance, text reading (i.e., comprehension and speed), and phonemic awareness. Specifically, we found significantly lower phonemic awareness abilities, lower

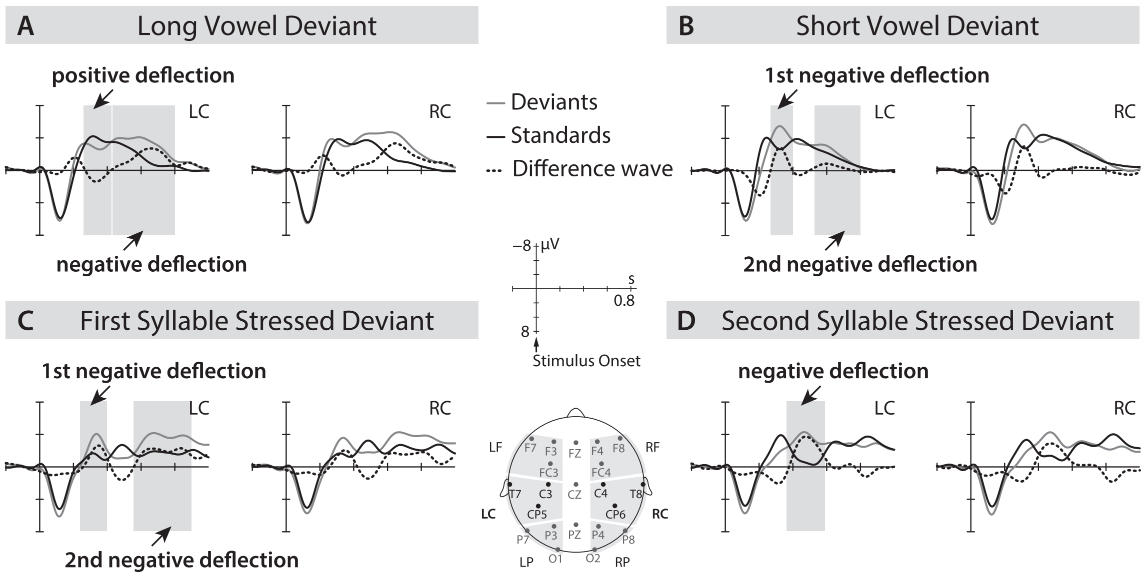

Fig. 2. MMN paradigms on vowel length and stress pattern discrimination across both groups of participants. Depicted are the grand-average ERP responses separately for the standard and for the deviant stimuli, as well as the ERP difference waves (deviant–standard) relative to the onset of the stimulus for (A) the vowel length contrast long vowel deviant /ba:/ – short vowel standard /ba/, (B) the vowel length contrast short vowel deviant /ba/ – long vowel standard /ba:/, (C) the stress pattern contrast first syllable stressed deviant /ba:ba/ – second syllable stressed standard /baba:/, and (D) the stress pattern contrast second syllable stressed deviant /baba:/ – first syllable stressed standard /ba:ba/ across children with and without later literacy difficulties. Grey-shaded areas indicate those time windows with significant effects including the factor condition (exemplified at one region of interest).

Table 2
Information on the number of artefact-free trials for all three experiments.

	Children with (later) literacy difficulties	Children without (later) literacy difficulties
MMN deviant trials short syllable /ba/	88.06% (7.63)	90.61% (4.78)
MMN deviant trials long syllable /ba:/	89.27% (7.19)	89.72% (5.38)
MMN deviant trials first syllable stressed /ba:ba/	91.42% (5.81)	91.21% (7.61)
MMN deviant trials second syllable stressed /baba:/	90.41% (7.95)	88.93% (9.20)
Sentences with PBs	76.54% (13.84)	78.00% (10.88)
Sentences without PBs	76.54% (15.82)	76.40% (12.88)

Note. Number in parenthesis are standard deviations.

reading accuracy, and slower reading speed in children with in comparison to children without literacy difficulties. Note that all behavioural data analyses were rerun without the children whose data were missing in the CPS experiment, however, without revealing any changes in the result and significance patterns.

3.2. Segmental phonology: MMN experiment on vowel length discrimination

3.2.1. Long vowel as deviant

Regarding the defined TWs, the ANOVA did not reveal any significant condition effects for the TW 300–450 ms, but for the TW 450–800 ms, with a significant main effect of condition at lateral regions [$F(1,27) = 26.95$; $p < .001$; $\eta_p^2 = 0.51$] and at midline electrodes [$F(1,27) = 40.42$; $p < .001$; $\eta_p^2 = 0.61$], indicating a more negative response to the deviant compared to the standard stimuli. No interactions were found for the factors group and condition (see Fig. 3).

3.2.2. Short vowel as deviant

For the TW 300–400 ms, the ANOVA showed a significant main effect of condition [$F(1,27) = 17.92$; $p < .001$; $\eta_p^2 = 0.40$] and a significant interaction between condition, region, and hemisphere [$F(2,54) = 4.81$; $p < .03$; $\eta_p^2 = 0.15$] at lateral regions. This interaction was driven by a more negative response to the deviant compared to the standard across all regions, except at the right parietal region ($p = .332$). Additionally, a significant interaction was found between condition and group [$F(1,27) = 3.12$; $p < .05$; $\eta_p^2 = 0.10$]. Step-down analyses revealed that children without later literacy difficulties showed a more negative response to the deviant compared to the standard, but children with later literacy difficulties did not show this difference (for detailed statistics, see Table 3). Importantly, post-hoc *t*-test on the MMN difference wave (deviant – standard) between literacy groups revealed that the MMN amplitudes of children with and without later literacy difficulties differed significantly (see Table 3). At midline electrodes, we also found a significant main effect of condition [$F(1,27) = 23.97$; $p < .001$; $\eta_p^2 = 0.47$] and a significant interaction between condition and group [$F(1,27) = 5.96$; $p < .01$; $\eta_p^2 = 0.18$]. Step-down analyses showed that children without later literacy difficulties showed a more negative response to the deviant compared to the standard, but children with later literacy difficulties did not show this difference (see Table 3). Post-hoc *t*-test on the MMN difference wave (deviant – standard) between groups showed that

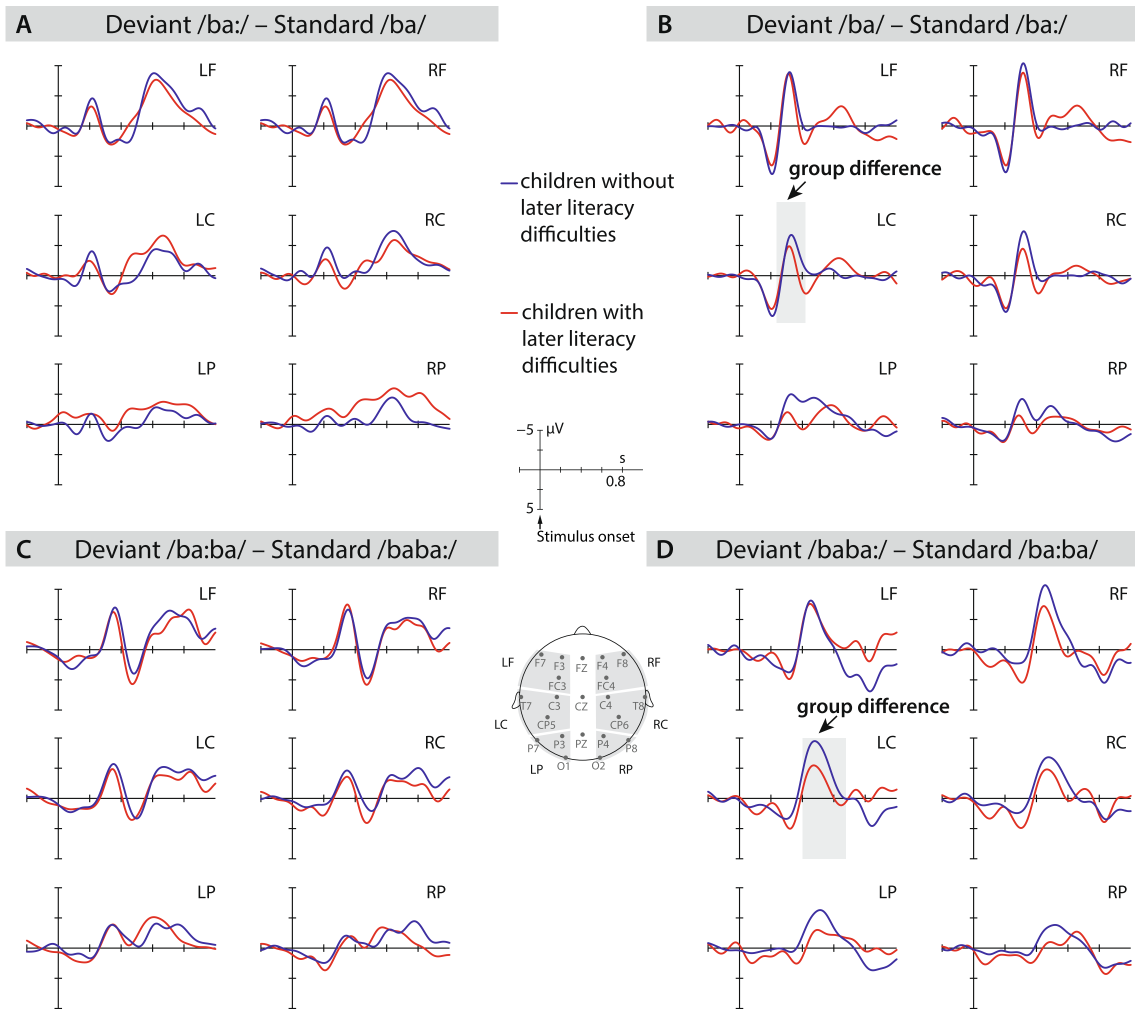

Fig. 3. MMN paradigms on vowel length and stress pattern discrimination separately for children with and without later literacy difficulties. Depicted are the grand-average ERP difference waves (deviant–standard) of children with and without later literacy difficulties relative to the onset of the stimulus for (A) the contrast long vowel deviant /ba:/ – short vowel standard /ba/, (B) the contrast short vowel deviant /ba/ – long vowel standard /ba:/, (C) the contrast first syllable stressed deviant /ba:ba/ – second syllable stressed standard /baba:/, and (D) the contrast second syllable stressed deviant /baba:/ – first syllable stressed standard /ba:ba/. Grey-shaded areas indicate those time windows with significant differences between children with and without later literacy difficulties (exemplified at one region of interest). For the contrast with the short vowel deviant /ba/ (3B) and the second syllable stressed deviant /baba:/ (3D), the MMN of children with later literacy difficulties is less pronounced compared to the MMN of children without later literacy difficulties. No differences between groups were found for the contrast with the long vowel deviant /ba:/ (3A) and for the contrast with the first syllable stressed deviant /ba:ba/ (3C).

the MMN amplitudes of children with and without later literacy difficulties differed significantly (see Table 3 and Fig. 3).

For the TW 400–600 ms, a significant interaction was found between condition and region [$F(2,54) = 4.33$; $p < .04$; $\eta_p^2 = 0.14$] at lateral regions, which could be explained by a more negative response to the deviant compared to the standard at parietal regions, compared to frontal and central regions across both groups. At the midline electrodes, a significant interaction was found between condition and region [$F(2,54) = 6.49$; $p < .01$; $\eta_p^2 = 0.19$], which could be explained by a more negative response to the deviant compared to the standard at Cz and Pz, compared to Fz across both groups. Here, no significant interactions were found for factors condition and group (see Fig. 3).

Taken together, we found significant differences between children with and without later literacy difficulties when analysing the short vowel deviant in contrast to the long vowel standard. Children without later literacy difficulties showed significantly stronger negative responses to the short vowel deviant in contrast to the long vowel standard compared to children with later literacy difficulties between 300 to 400 ms. Neither when analysing the TW 400–600 ms, nor when analysing the long vowel deviant compared to the short vowel standard, we found any group differences.

3.3. Word-level prosody: MMN experiment on stress discrimination

3.3.1. First syllable stressed as deviant

For the TW 250–400 ms, the ANOVA revealed a significant main effect of condition [$F(1,27) = 10.38$; $p < .01$; $\eta_p^2 = 0.29$] and a significant interaction between condition and region [$F(2,54) = 7.54$; $p < .01$; $\eta_p^2 = 0.23$] at lateral regions. The interaction could be explained by a more negative response to the deviant compared to the standard that was broadly distributed, with more enhanced amplitudes at frontal and central regions compared to parietal regions across both groups. At midline electrodes, we also found a significant main effect of condition [$F(1,27) = 9.74$; $p < .01$; $\eta_p^2 = 0.28$], but no interactions involving the factors group and condition. For the TW 550–900 ms, we found a significant main effect of condition at lateral regions [$F(1,27) = 14.17$; $p < .01$; $\eta_p^2 = 0.36$] and midline electrodes [$F(1,27) = 11.12$; $p < .01$; $\eta_p^2 = 0.31$], due to a more negative response to the deviant compared to the standard

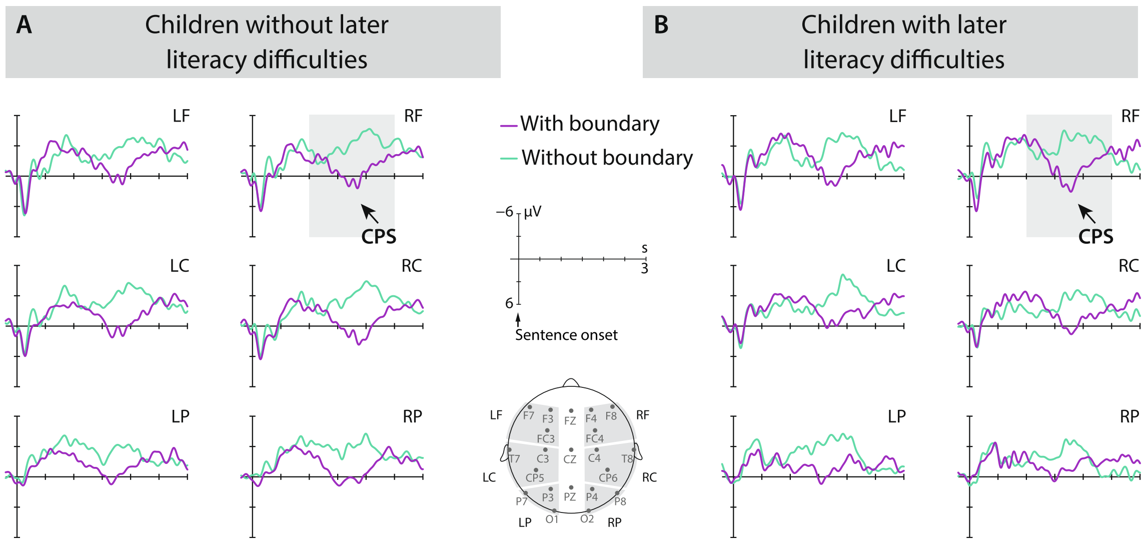

Fig. 4. CPS paradigm on prosodic boundary perception separately for children with and without later literacy difficulties. Depicted are the grand-average ERPs of (A) children without later literacy difficulties and (B) children with later literacy difficulties relative to the onset of the sentences with and without prosodic boundaries (PBs). Grey-shaded areas indicate those time windows with significant effects including the factor sentence type (exemplified at one region of interest). Both groups show CPS in responses to PBs, while children with and without later literacy difficulties did not differ significantly.

Table 3
Step-down analyses of the MMN difference wave of children with and without later literacy difficulties in response to the short vowel deviant /ba/.

Children with later literacy difficulties	Children without later literacy difficulties	Post-hoc *t*-test on difference wave
Lateral regions		
$F(1,27) = 3.25$; $p = .08$; $\eta_p^2 = 0.11$ ($M = -1.00$ µV; $SD = 2.37$)	$F(1,27) = 17.19$; $p < .001$; $\eta_p^2 = 0.39$ ($M = -2.40$ µV; $SD = 1.91$)	$t(27) = -1.73$; $p^1 < .05$
Midline electrodes		
$F(1,27) = 3.12$; $p = .089$; $\eta_p^2 = 0.10$; $M = -1.19$ µV; $SD = 2.83$	$F(1,27) = 26.02$; $p < .001$; $\eta_p^2 = 0.49$ ($M = -3.54$ µV; $SD = 2.33$)	$t(27) = -2.44$; $p^1 < .01$

Note. Difference wave = deviant – standard; Mean (M) and Standard Deviation (SD) are from the differences wave; 1 = p-values are one-sided.

Table 4
Step-down analyses of the MMN difference wave of children with and without later literacy difficulties in response to the second syllable stressed deviant /baba:/.

Children with later literacy difficulties	Children without later literacy difficulties	Post-hoc *t*-test on difference wave
*Condition * Group at later regions*		
$F(1,27) = 7.11$; $p < .02$; $\eta_p^2 = 0.22$ ($M = -1.33$ µV; $SD = 1.96$)	$F(1,27) = 26.94$; $p < .001$; $\eta_p^2 = 0.52$ ($M = -2.49$ µV; $SD = 1.62$)	$t(27) = -2.44$; $p^1 < .02$
*Condition*Region*Hemisphere*Group*		
LC $M = -1.73$ µV; $SD = 2.91$	$M = -3.35$ µV; $SD = 2.74$	$t(27) = -1.68$ $p^1 < .05$
LP $M = -0.18$ µV; $SD = 1.59$	$M = -2.24$ µV; $SD = 1.33$	$t(27) = -3.67$ $p^1 < .001$
RP $M = 0.33$ µV; $SD = 2.14$	$M = -1.09$ µV; $SD = 1.41$	$t(27) = -2.04$; $p^1 < .03$

Note. Difference wave = deviant – standard; Mean (M) and Standard Deviation (SD) are from the differences wave; 1 = p-values are one-sided; LC = left-central; LP = left-parietal; RP = right-parietal.

that was broadly distributed across all regions. Again, no significant interactions were found for factors group and condition (see Fig. 3).

3.3.2. Second syllable stressed as deviant

For the TW 350–550 ms, the ANOVA revealed a significant main effect of condition [$F(1,27) = 30.49$; $p < .001$; $\eta_p^2 = 0.55$] and a marginally significant interaction between condition and group [$F(1,27) = 2.83$; $p = .09$; $\eta_p^2 = 0.10$] at lateral regions. Step-down analyses showed that both, children with and without later literacy difficulties showed a more negative response to the deviant compared to the standard. A post-hoc *t*-test on the MMN difference wave (deviant – standard) showed that the MMN amplitude was significantly larger in children without later literacy difficulties in comparison to those with later literacy difficulties (see Table 4). In addition, we found a significant interaction between condition, region, hemisphere, and group [$F(2,54) = 2.84$; $p < .04$; $\eta_p^2 = 0.12$]. As can be seen from Table 4, this interaction was mainly driven

Table 5
CPS experiment: ANOVAs for mean amplitudes at lateral regions and midline electrodes across the time range of 0–3000 ms relative to sentence onset.

TW (ms)	Lateral regions	Midline electrodes
0–500	#	
1000–1500	*Sentence*Region* $F(2,38) = 4.42$; $p < .04$; $\eta_p^2 = 0.19$ *Posterior* $F(1,20) = 9.40$; $p < .006$; $\eta_p^2 = 0.32$ ($M = 2.30$ µV; $SD = 3.43$)	*Sentence* $F(1,19) = 5.08$; $p < .04$; $\eta_p^2 = 0.21$ ($M = 2.17$ µV; $SD = 4.39$)
1500–2000	*Sentence* $F(1,19) = 32.51$; $p < .001$; $\eta_p^2 = 0.63$ ($M = 4.17$ µV; $SD = 3.27$)	*Sentence* $F(1,19) = 38.33$; $p < .001$; $\eta_p^2 = 0.67$ ($M = 5.72$ µV; $SD = 4.15$)
2000–2500	*Sentence* $F(1,19) = 10.35$; $p < .005$; $\eta_p^2 = 0.35$ ($M = 1.60$ µV; $SD = 2.31$) *Sentence*Region* $F(2,38) = 7.27$; $p < .005$; $\eta_p^2 = 0.28$ *Anterior* $F(1,20) = 9.75$; $p < .005$; $\eta_p^2 = 0.33$ ($M = 2.06$ µV; $SD = 3.03$) *Central* $F(1,20) = 17.88$; $p < .001$; $\eta_p^2 = 0.47$ ($M = 2.50$ µV; $SD = 2.71$)	
2500–3000	*Sentence* $F(1,19) = 6.81$; $p < .02$; $\eta_p^2 = 0.26$ ($M = -1.02$ µV; $SD = 1.83$)	*Sentence* $F(1,19) = 10.13$; $p < .005$; $\eta_p^2 = 0.35$ ($M = -2.16$ µV; $SD = 3.02$)

Note. Sentence = sentence type; Mean (M) and Standard Deviation (SD) reflect the sentence condition difference; # The interaction Sentence*Region*Hemisphere F(2,38) = 5.59; p < .01; ηp2 = 0.23, because follow-up analyses did not reveal a significant Sentence effect in any ROI.

by MMN amplitude differences between children with and without later literacy difficulties at left-central, left-parietal, and right-parietal regions (see also Fig. 3).

At midline electrodes, no significant effects were found for children with nor for children without later literacy difficulties.

Taken together, we found significant differences between children with and without later literacy difficulties when analysing the pseudoword with the second syllable stressed as deviant compared to the pseudowords with the first syllable stressed as standard. Children without later literacy difficulties showed significantly stronger negative responses to the pseudoword with the second syllable stressed as deviant in contrast to the first syllable stressed as standard compared to children with later literacy difficulties between 350 and 550 ms. When analysing the pseudowords with the first syllable stressed as deviant compared to the second syllable stressed as standard, we did not find significant differences between children with and without later literacy difficulties, neither between 250 and 400 ms, nor between 550 and 900 ms.

3.4. Phrase-level prosody: CPS experiment

For the CPS experiment, we found the factor sentence type to become significant from TW 1000–1500 ms onwards (refer to Table 5 for details on significant effects). The sentence type effect in the TW 2500–3000 ms, however, cannot be referred to boundary processing, but is driven by the intonation contour indicating the end of the sentence, with sentences without PBs being shorter than sentences with PBs. Statistical analyses did not reveal any interaction with literacy group, such that all children (i.e., children with and without later literacy difficulties) showed similar processing of the two sentence types, namely a broadly distributed positive shift for sentences with PBs, but not for sentences without PBs (Fig. 4).

4. Discussion

4.1. General discussion

In our ERP study, we investigated segmental and suprasegmental phonological processing phonology in preschool children with later developing literacy difficulties, such as DD. The present study specifically focused on testing word-level prosody, in addition to affirming previous findings on deficient segmental phonology and intact phrasal prosody in literacy-impaired school children (see Männel et al., 2017). Thus, the current findings address the question of whether literacy-impaired children generally show intact suprasegmental phonology, or whether their prosodic processing is differently affected at word or phrase levels.

Crucially, we tested all three different types of phonological processing, that is, processing at phoneme, word and phrase levels, within the same preschool children between the ages of 4.4 to 6 years using behaviour-independent ERP measures. Segmental phonology was investigated by the MMN (Näätänen et al., 1978) in vowel length discrimination, suprasegmental phonology at the word level was investigated by the MMN in pseudoword stress pattern discrimination implemented by a vowel length contrast, and suprasegmental phonology at the phrase level was investigated by the CPS (Steinhauer et al., 1999) in PB perception.

First, the findings of the present study could affirm our previous results on segmental and phrase-level suprasegmental phonology in literacy-impaired school children (Männel et al., 2017). Comparable to literacy-impaired school children, preschool children with later literacy difficulties show a reduced MMN to vowel length discrimination, but no alterations in CPS responses in PB perception. These results replicate our previous report of deficient segmental phonology, but intact phrasal prosody in literacy impairments. Second, our study revealed a new finding that children with later literacy difficulties show reduced MMN amplitudes to word stress contrasts compared to children without later literacy difficulties, indicating deficient word-level prosody. Thus, the current study delivers evidence that the prosodic unit under consideration is one of the driving factors differentiating intact and deficient suprasegmental phonological processing in children with impaired literacy. Our findings imply that literacy impairments are not only associated with deficient segmental phonology, but also with deficient suprasegmental phonology at the word level, whereas suprasegmental phonology at the phrase level seems to be intact.

In the following, we will first discuss our new finding on deficient word-level prosody in literacy impairment in light of existing evidence, before turning to the affirmation of our previous results and their implications.

Studies on word-level stress perception in children and adults with DD have revealed a mixed pattern of results. Most of the studies of individuals with DD point to word-level stress impairments (Anastasiou and Protopapas, 2015; Barry et al., 2012; Cuetos et al., 2018; Goswami et al., 2010; Goswami et al., 2013; Leong et al., 2011), but some studies also report intact abilities (Anderson et al., 2013; Mundy and Carroll, 2012; 2013). Here, task-related demands have been pinpointed as factors that might impede stress perception, such as task execution and increased working memory loads. In a direct comparison, for example, Mundy and Carroll (2012) observed adults with DD demonstrating impaired performance in an explicit production task, but intact performance in an implicit priming task. Furthermore, in some studies, stress perception difficulties in individuals with DD only emerged under increased working memory load (Soroli et al., 2010); as evident for more difficult stress pattern comparisons across words with different segmental patterns, but not for easier stress pattern comparisons across words with the same segmental patterns (Leong et al., 2011). In our study, we removed task requirements by obtaining behaviour-independent ERP responses under passive listening, but still observed problems in word-level stress perception implemented by a vowel length contrast in children with later literacy problems. However, task difficulty driven by stimulus characteristics still seems to play a role, because we only observed literacy group differences for the non-native stress pattern (i.e., second syllable stressed by vowel lengthening), but not for the native stress pattern as deviant (i.e., first syllable stressed by vowel lengthening). We suggest that the processing of second syllables stressed as deviant is more demanding, because stress assignment to the second syllables in words results in perceptually reduced salience and thus less easily discernible word onsets. Moreover, German is a trochaic language where bi-syllabic words are usually stressed on their first syllable, such that German listeners are less experienced with word stress on the second syllable. Both explanations receive support from developmental data showing that at age 2 months, German infants only discriminate perceptually more salient long syllables as deviants (corresponding to first syllables stressed) from short syllables as standards, but not yet vice versa (Friederici et al., 2002). Likewise, infants at age 5 months start to discriminate the native word stress pattern with stressed first syllables (i.e., deviants) in the context of stressed second syllables (i.e., standards), but not vice versa, indicating enhanced difficulty when discriminating the non-native word stress pattern (Weber et al., 2004). Thus, the acoustically less salient and non-native stress pattern that has been shown to lag behind in development was the stress pattern that still evoked literacy group differences in our study with preschool children.

When we tested the processing of phrase-level prosody in the same sample of preschool children, we could affirm our previous finding that PB processing as indicated by the CPS does not seem to be affected by literacy impairments (Männel et al., 2017). This result conforms to previous studies of intact phrasal prosody perception in children with DD (Geiser et al., 2014; Holliman et al., 2012), but there are also reports suggesting deficient phrasal prosody (Wood and Terrell, 1998). Crucially, with our approach of testing both phrase- and word-level prosodic abilities under passive listening in the same participant sample, we eliminated variations in task demands as potentially explanatory factors for different outcomes across studies. As we excluded task demands in the present study, another factor that might explain different outcomes across our experiments (i.e., vowel length discrimination, word stress discrimination, and PB processing) could be the particular characteristic of the prosodic unit under investigation. First, the more prominent acoustic realization of phrase- and sentence-level prosody (Nespor and Vogel, 1986; Peters et al., 2005), as opposed to word-level prosody (Dogil, 1995), can explain processing advantages for larger prosodic units. Moreover, larger units inherently provide more linguistic information and sentence contexts have been, for example, shown to promote word-level prosody perception (Barry et al., 2012), as well as reading performance in individuals with DD (Nation and Snowling, 1998). In addition to these considerations, there is increasing evidence showing that different aspects of prosody make different contributions to the reading process, with word-level prosody being more strongly associated with word reading and phrase-level prosody with reading comprehension (Holliman et al., 2014; Holliman et al., 2012; Whalley and Hansen, 2006). This dissociation implies that word- and phrase-level prosody might also be differently affected in individuals with DD, which we observed in the current study.

The current study also affirms our previous findings on deficient segmental phonology in literacy impairment (Männel et al., 2017), as indicated by reduced MMN to vowel length changes in pre-schoolers with later literacy difficulties. This result is consistent with several MMN studies reporting deficient phoneme processing in individuals with DD (see Bishop, 2007) and with longitudinal studies suggesting that these difficulties in phoneme processing develop already during infancy (Schaadt et al., 2015; van Zuijen et al., 2013) and predict later literacy development (Lohvansuu, et al., 2018). Here, we found reduced vowel length discrimination in pre-schoolers with compared to pre-schoolers without later literacy difficulties, similar to a Finnish study also reporting reduced MMNs in children at risk of DD (aged 6 years) in response to changes in vowel length (Lovio et al., 2010). Likewise, 6-month-olds already showed different Mismatch Responses to vowel length changes when they were at risk of DD compared to infants not at risk (Pihko et al., 1999; see also Leppänen et al., 2002). Thus, we suggest a causal relation between literacy acquisition at school and pre-school vowel length processing, at least for languages where some lexical distinctions rely on vowel length information (e.g., German and Finnish; see also Landerl, 2003).

Notably, we only observed differences in segmental phonology between pre-schoolers with and without later literacy difficulties, when analysing the short deviant vowel (among long vowels), but not when analysing the long deviant vowel (among short vowels; see also Männel et al., 2017). This result reflects our findings on word-level prosody, where only the more difficult contrast (i.e., second syllable stressed as deviant) revealed differences between pre-schoolers with and without later literacy difficulties. As for this contrast, it can be suggested that the distinction of the short deviant vowel among long vowel syllables is more difficult than the distinction of the long deviant vowel among short vowel syllables (Friedrich et al., 2004). Since the short deviant syllable mostly consists of the properties of the long syllable, whereas the long syllable contains additional information, makes the former perceptually less salient and more difficult to discriminate. Even school children continue to exhibit that they struggle more in the behavioural categorization of short vowels than long vowels (Landerl, 2003). Hence, task difficulty driven by stimulus characteristics seems to play a role in both segmental phonology and word-level prosody (both implemented by vowel lengthening). Whether phrase-level prosody is also affected in literacy impairments when stimulus discrimination difficulty under passive listening is enhanced is still an open question. For example, difficulty in PB processing can be manipulated by systematically varying the number and type of boundary cues. Männel et al. (2013) could show that younger children's processing of PBs is still more susceptible to the strength of boundary marking than older children's PB processing. While 6-year-olds showed a CPS in response to PBs, for which the dominant pause cue was missing, 3-year-olds only showed a CPS in the presence of either all cues or when the pitch cue was missing, but not when the pause cue was missing (Männel et al., 2013; Männel and Friederici, 2016). Therefore, if phrase-level prosody is affected in literacy impairment when task difficulty is enhanced, we would expect dyslexics to show reduced CPS in response to PBs when the dominant pause cue is missing.

4.2. Limitations of the current study

For a conclusive interpretation of our findings of phonological difficulties in DD regarding segmental phonology and word-level prosody, but not phrase-level prosody, additional conceptual and methodological factors need to be considered, which we will discuss in turn.

First, it is well known that different theories are formulated to discuss different causal factors leading to DD, such as visual, attention, and auditory deficits (e.g., see Goswami, 2015). Because we screened and selected our participants based on the frequently observed phonological deficits, we focused our discussion on this line of research. Although children were selected based on phonological deficits, we cannot exclude that our observed phonological difficulties in DD might be driven by more basic auditory processing deficits, instead of reflecting mere phonological problems (see Snowling, 2000; for the *phonological processing deficit theory*). Although the *rapid auditory processing deficit theory* also approves of phonological deficits in DD, this theory postulates a different core deficit, namely deficient processing of short and rapidly varying sounds (see Tallal, 1980; Tallal et al., 1993; for the *rapid auditory processing deficit*). However, these latter difficulties would also predict the current phonological processing pattern, because smaller linguistic units (i.e., phonemes and words) would be more affected than larger linguistic units (i.e., phrases). So far, some reports are in favour of deficient basic auditory processing in DD (e.g., Ben-Artzi et al., 2005; Cohen-Mimran and Sapir, 2007), while others affirm phonological deficits only (e.g., Breier et al., 2003). Interestingly, Boets et al. (2011) even demonstrated that both basic auditory processing deficits and phonological deficits uniquely contribute to written language impairments. Thus, our findings of phonological difficulties for smaller units (i.e., phonemes, words), but not for larger units (i.e., phrases), being associated with DD could be either due to a more general auditory deficit that leads to phonological deficits at the phoneme and word level or mere phonological deficits.

Second, we should reiterate that for the implementation of word stress, we used a vowel length contrast only, as opposed to a combination of different cues that can jointly mark word stress, such as pitch, intensity, and lengthening. Testing only the vowel length contrast might have been specifically challenging for children with later literacy difficulties, and group differences in word stress processing might abate when using a combination of different cues to word stress. Furthermore, we need to be careful in concluding that DD is characterized by difficulties in word-level prosody, given that the respective vowel length manipulation closely resembled the contrast used for segmental vowel length discrimination. Accordingly, difficulties in word stress discrimination could have been solely driven by difficulties in vowel length discrimination. However, the fact that children with later literacy difficulties experience problems in perceiving final long deviants (in the word-level manipulation), but not initial long deviants (in the phoneme-level manipulation) is at least partially supporting the conclusion of difficulties in word-level prosody. As both deviants consist of the same vowel length manipulation, only at different positions, we would expect deficient processing of both deviants if only the type of contrast itself was driving our findings of difficulties in word-level prosody in DD. Furthermore, our findings are consistent with other studies demonstrating deficient word-level prosody in DD (see also Anastasiou and Protopapas, 2015). Future studies, however, need to address the influence of pitch and intensity manipulation in order to confirm the present results and conclusions.

Third, it should be mentioned that the vowel contrast in our segmental manipulation might carry prosodic features. Specifically, the long-vowel syllable in the MMN study on segmental phonology was derived from the short-vowel syllable. Consequently, there was no quality contrast by means of spectral differences between our long- and short-vowel stimuli, but only a length difference, which is best described by reference to syllabic constituent structure. This implies that the segmental manipulation might be prosodic in nature and our findings on segmental phonological difficulties in DD are driven by prosodic difficulties in DD occurring for smaller units (i.e., at syllable and word level), but not for larger units. Although this alternative explanation needs to be considered, our results correspond to a vast number of studies on segmental phonological difficulties in DD, with deficient discrimination of phoneme length contrasts (e.g., Groth et al., 2011; Lovio et al., 2010; Pihko et al., 1999; Steinbrink et al., 2014) and, importantly, in phoneme identity (e.g., /te/ vs. /ti/, /te/ vs. /pe/: Lovio et al., 2010; /da/ vs. /ba/: Schulte-Körne et al., 1998). Thus, we are confident that our results are consistent with the conclusion of segmental phonological difficulties in DD.

Fourth, there is a fundamental difference between the experimental designs used for testing phonological processing at phoneme, word, and phrase levels. While both segmental phonology and word-level prosody were tested in oddball paradigms (i.e., testing stimulus discrimination in a 80:20 presentation rate), phrase-level prosody was tested by presenting sentence types in a 50:50 fashion. To rule out that these paradigm differences resulted in the lack of identifying phrasal prosody problems in children with later literacy difficulties, future studies should test prosodic processing in a similar fashion as employed for segmental phonology and word-level prosody. This could, for example, be realized by testing the processing of different prosodic sentence contours in an oddball manner (80:20 presentation rate).

Fifth, another explaining factor for the observed between-experiment differences could be the respective ages at which children were tested for the different levels of phonology. When testing vowel length and stress pattern discrimination, children were 4.4–4.6 years old, whereas PB processing was tested when children were 6 years old. This age difference between testing time points could have enabled children with later literacy difficulties to catch up with children without later literacy difficulties in their PB processing. However, we consider this explanation of the lack of CPS group differences unlikely, given that 3-year-olds already show typical CPS patterns to PB presented with all pause cues (Männel et al., 2013; Männel and Friederici, 2016). Most importantly, our result mirrors our previous findings of intact PB processing, but deficient vowel length discrimination in 12-year-old-school children tested on the same day (Männel et al., 2017). While future research should aim for testing all aspects of phonological processing at the same age, we argue that it is highly unlikely that age is the driving factor in explaining the current results.

4.3. Conclusion

Despite these potential limitations, our findings offer an important contribution to characterizing the phonological deficit in literacy impairments. Our study is the first to investigate the neural correlates of segmental (i.e., phonemes) and suprasegmental phonological processing, both at word and phrase levels in the same sample of pre-schoolers with and without later literacy difficulties. Importantly, with our longitudinal study, we could show across three ERP experiments that pre-schoolers at risk of DD and who developed literacy difficulties at school age, struggled with vowel length discrimination and with word-level prosodic processing, but had intact phrase-level prosodic processing. By this, we could affirm our previous results in literacy-impaired school children (Männel et al., 2017) in pre-schoolers at risk of literacy impairments, who were correspondingly classified into groups of children with (later) literacy difficulties based on their reading and spelling skills tested at school age. In addition, we contributed to the picture of prosodic processing in DD by showing that word-level prosody is, in contrast to phrase-level prosody, affected in literacy impaired children. Thus, we suggest that, exceeding the well-documented phonological processing abilities at the segmental level (Ramus et al., 2003; Snowling, 2000), suprasegmental phonological processing abilities at the word level are also an important precursor for successful literacy acquisition at school age. Accordingly, prosody-based interventions should, in addition to conventional phonological-awareness training programs, be considered for supporting pre-schoolers at risk of DD.

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Conflict of interest

The authors declare to have no conflict of interest.

References

Anastasiou D, Protopapas A. Difficulties in lexical stress versus difficulties in segmental phonology among adolescents with dyslexia. Sci Stud Read 2015;19:31–50.
Anderson A, Lin CY, Wang M. Native and novel language prosodic sensitivity in English-speaking children with and without dyslexia. Dyslexia 2013;19:92–112.
Barry JG, Harbodt S, Cantiani C, Sabisch B, Zobay O. Sensitivity to lexical stress in dyslexia: A case of cognitive not perceptual stress. Dyslexia 2012;18:139–65.
Ben-Artzi E, Fostick L, Babkoff H. Deficits in temporal-order judgments in dyslexia: Evidence from diotic stimuli differing spectrally from dichotic stimuli differing only by perceived location. Neuropsychologia 2005;43:714–23.
Bishop DVM. Using mismatch negativity to study central auditory processing in developmental language and literacy impairments: Where are we, and where should we be going? Psychol Bull 2007;133:651–72.
Boersma P. Praat, a system for doing phonetics by computer. Glot Int 2001;5:341–5.
Boets B, Vandermosten M, Poelmans H, Luts H, Wouters J, Ghesquiere P. Preschool impairments in auditory processing and speech perception uniquely predict future reading problems. Res Dev Disabil 2011;32:560–70.
Bögels S, Schriefers HJ, Vonk W, Chwilla D. Prosodic breaks in sentence processing investigated by event-related potentials. Lang Linguist Compass 2011;5:424–40.
Breier JI, Fletcher JM, Foorman BR, Klaas P, Gray LC. Auditory temporal processing in children with specific reading disability with and without attention deficit/hyperactivity disorder. J Speech Lang Hear 2003;46:31–41.
Calet N, Gutierrez-Palma N, Simpson IC, Gonzalez-Trujillo MC, Defior S. Suprasegmental phonology development and reading acquisition: A longitudinal study. Sci Stud Read 2015;19:51–71.
Cantiani C, Lorusso ML, Guasti MT, Sabisch B, Männel C. Characterizing the morphosyntactic processing deficit and its relationship to phonology in developmental dyslexia. Neuropsychologia 2013;51:1595–607.
Caravolas M, Lervag A, Defior S, Malkova GS, Hulme C. Different patterns, but equivalent predictors, of growth in reading in consistent and inconsistent orthographies. Psychol Sci 2013;24:1398–407.
Cohen-Mimran R, Sapir S. Deficits in working memory in young adults with reading disabilities. J Commun Disord 2007;40:168–83.
Coltheart M, Rastle K, Perry C, Langdon R, Ziegler J. DRC: A dual route cascaded model of visual word recognition and reading aloud. Psychol Rev 2001;108:204–56.
Corbera S, Escera C, Artigas J. Impaired duration mismatch negativity in developmental dyslexia. Neuroreport 2006;17:1051–5.
Cuetos F, Martínez-García C, Suárez-Coalla P. Prosodic perception problems in Spanish dyslexia. Sci Stud Read 2018;22:1–14.
Cutler A, Norris D. The role of strong syllables in segmentation for lexical access. J Exp Psychol-Hum Perc Perf 1988;14:13–121.
David D, Wade-Woolley L, Kirby JR, Smithrim K. Rhythm and reading development in school-age children: a longitudinal study. J Res Read 2007;30:169–83.
Dogil G. Phonetic correlates of word stress. Arbeitspapiere des Instituts für Maschinelle Sprachverarbeitung der Universität Stuttgart 1995;2:1–60.
Friederici AD, Friedrich M, Christophe A. Brain responses in 4-month-old infants are already language specific. Curr Biol 2007;17:1208–11.
Friederici AD, Friedrich M, Weber C. Neural manifestation of cognitive and precognitive mismatch detection in early infancy. Neuroreport 2002;13:1251–4.
Friedrich M, Weber C, Friederici AD. Electrophysiological evidence for delayed mismatch response in infants at-risk for specific language impairment. Psychophysiol 2004;41:772–82.
Geiser E, Kjelgaard M, Christodoulou JA, Cyr A, Gabrieli JDE. Auditory temporal structure processing in dyslexia: processing of prosodic phrase boundaries is not impaired in children with dyslexia. Ann Dyslexia 2014;64:77–90.
Goswami U. Sensory theories of developmental dyslexia: three challenges for research. Nat Rev Neurosci 2015;16:43–54.
Goswami U, Gerson D, Astruc L. Amplitude envelope perception, phonology and prosodic sensitivity in children with developmental dyslexia. Read Writ 2010;23:995–1019.
Goswami U, Mead N, Fosker T, Huss M, Barnes L, Leong V. Impaired perception of syllable stress in children with dyslexia: A longitudinal study. J Mem Lang 2013;69:1–17.
Goswami U, Thomson J, Richardson U, Stainthorp R, Hughes D, Rosen S, et al. Amplitude envelope onsets and developmental dyslexia: A new hypothesis. Proc Natl Acad Sci USA 2002;99:10911–6.
Groth K, Lachmann T, Riecker A, Muthmann I, Steinbrink C. Developmental dyslexics show deficits in the processing of temporal auditory information in German vowel length discrimination. Read Writ 2011;24:285–303.
Gutierrez-Palma N, Raya-Garcia M, Palma-Reyes A. Detecting stress patterns is related to children's performance on reading tasks. Appl Psycholinguist 2009;30:1–21.
Hämäläinen JA, Leppänen PHT, Eklund K, Thomson J, Richardson U, Guttorm TK, et al. Common variance in amplitude envelope perception tasks and their impact on phoneme duration perception and reading and spelling in Finnish children with reading disabilities. Appl Psycholinguist 2009;30:511–30.
Holliman AJ, Williams GJ, Mundy IR, Wood C, Hart L, Waldron S. Beginning to disentangle the prosody-literacy relationship: a multi-component measure of prosodic sensitivity. Read Writ 2014;27:255–66.
Holliman AJ, Wood C, Sheehy K. Sensitivity to speech rhythm explains individual differences in reading ability independently of phonological awareness. Br J Dev Psychol 2008;26:357–67.
Holliman AJ, Wood C, Sheehy K. The contribution of sensitivity to speech rhythm and non-speech rhythm to early reading development. Educ Psychol 2010a;30:247–67.
Holliman AJ, Wood C, Sheehy K. Does speech rhythm sensitivity predict children's reading ability 1 year later? J Educ Psychol 2010b;102:356–66.
Holliman AJ, Wood C, Sheehy K. A cross-sectional study of prosodic sensitivity and reading difficulties. J Res Read 2012;35:32–48.
Jansen H, Mannhaupt G, Marx H, Skowronek H. Das Bielefelder Screening (BISC). Göttingen: Hogrefe; 2002.
Kaufman AS, Kaufman NL, Melchers P, Preuß U. Kaufman Assessment Battery for Children (K- ABC). Göttingen: Hogrefe; 2009.
Klicpera C, Schabmann A, Gasteiger-Klicpera B. Lesen-und Schreibenlernen während der Pflichtschulzeit: Eine Längsschnittuntersuchung über die Häufigkeit und Stabilität von Lese-und Rechtschreibschwierigkeiten in einem Wiener Schulbezirk? Zeitschrift für Kinder-und Jugendpsychiatrie 1993;21:214–25.
Klicpera C, Gasteiger-Klicpera B. Sind Rechtschreibschwierigkeiten Ausdruck einer phonologischen Störung? Zeitschrift für Entwicklungspsychologie und Pädagogische Psychologie 2000;32:134–42.

Lachmann T, Berti S, Kujala T, Schröger E. Diagnostic subgroups of developmental dyslexia have different deficits in neural processing of tones and phonemes. Int J Psychophysiol 2005;56:105–20.

Landerl K. Categorization of vowel length in German poor spellers: An orthographically relevant phonological distinction. Appl Psycholinguist 2003;24:523–38.

Landerl K, Wimmer H. Development of word reading fluency and spelling in a consistent orthography: An 8-year follow-up. J Educ Psychol 2008;100:150–61.

Landerl K, Wimmer H, Frith U. The impact of orthographic consistency on dyslexia: a German-English comparison. Cognition 1997;63:315–34.

Leong V, Hämäläinen J, Soltesz F, Goswami U. Rise time perception and detection of syllable stress in adults with developmental dyslexia. J Mem Lang 2011;64:59–73.

Leppänen PHT, Richardson U, Pihko E, Eklund KM, Guttorm TK, Aro M, et al. Brain responses to changes in speech sound durations differ between infants with and without familial risk for dyslexia. Dev Neuropsychol 2002;22:407–22.

Lochrin M, Arciuli J, Sharma M. Assessing the relationship between prosody and reading outcomes in children using the PEPS-C. Sci Stud Read 2015;19:72–85.

Lohvansuu K, Hämäläinen JA, Ervast L, Lyytinen H, Leppänen PHT. Longitudinal interactions between brain and cognitive measures on reading development from 6 months to 14 years. Neuropsychologia 2018;108:6–12.

Lovio R, Näätänen R, Kujala T. Abnormal pattern of cortical speech feature discrimination in 6-year-old children at risk for dyslexia. Brain Res 2010;1335:53–62.

Männel C, Friederici AD. Pauses and intonational phrasing: ERP studies in 5-month-old German infants and adults. J Cog Neurosci 2009;21:1988–2006.

Männel C, Friederici AD. Intonational phrase structure processing at different stages of syntax acquisition: ERP studies in 2-, 3-, and 6-year-old children. Dev Sci 2011;14:786–98.

Männel C, Friederici AD. Accentuate or repeat? Brain signatures of developmental periods in infant word recognition. Cortex 2013;49:2788–98.

Männel C, Meyer L, Wilcke A, Boltze J, Kirsten H, Friederici AD. Working-memory endophenotype and dyslexia-associated genetic variant predict dyslexia phenotype. Cortex 2015;71:291–305.

Männel C, Schipke CS, Friederici AD. The role of pause as a prosodic boundary marker: Language ERP studies in German 3- and 6-year-olds. Dev Cog Neurosci 2013;5:86–94.

Männel C, Schaadt G, Illner FK, van der Meer E, Friederici AD. Phonological abilities in literacy-impaired children: Brain potentials reveal deficient phoneme discrimination, but intact prosodic processing. Dev Cog Neurosci 2017;23:14–25.

Männel C, Friederici AD. Neural correlates of prosodic boundary perception in German preschoolers: If pause is present, pitch can go. Brain Res 2016;1632:27–33.

Marshall CR, Harcourt-Brown S, Ramus F, van der Lely HKJ. The link between prosody and language skills in children with specific language impairment (SLI) and/or dyslexia. Int J Lang Commun Disord 2009;44:466–88.

Moll Kristina, Ramus Franck, Bartling Jürgen, Bruder Jennifer, Kunze Sarah, Neuhoff Nina, Streiftau Silke, Lyytinen Heikki, Leppänen Paavo HT, Lohvansuu Kaisa, Tóth Dénes, Honbolygó Ferenc, Csépe Valéria, Bogliotti Caroline, Iannuzzi Stéphanie, Démonet Jean-François, Longeras Emilie, Valdois Sylviane, George Florence, Soares-Boucaud Isabelle, Le Heuzey Marie-France, Billard Catherine, O'Donovan Michael, Hill Gary, Williams Julie, Brandeis Daniel, Maurer Urs, Schulz Enrico, van der Mark Sanne, Müller-Myhsok Bertram, Schulte-Körne Gerd, Landerl Karin. Cognitive mechanisms underlying reading and spelling development in five European orthographies. Learn Instruct 2014;29:65–77. https://doi.org/10.1016/j.learninstruc.2013.09.003.

Mundy IR, Carroll JM. Speech prosody and developmental dyslexia: Reduced phonological awareness in the context of intact phonological representations. J Cog Psychol 2012;24:560–81.

Mundy IR, Carroll JM. Spelling stress regularity effects are intact in developmental dyslexia. Q J Exp Psychol 2013;66:816–28.

Näätänen R, Gaillard AWK, Mantysalo S. Early selective-attention effect on evoked-potential reinterpreted. Acta Psychol 1978;42:313–29.

Nation K, Snowling MJ. Semantic processing and the development of word-recognition skills: Evidence from children with reading comprehension difficulties. J Mem Lang 1998;39:85–101.

Nespor M, Vogel I. Prosodic phonology. Dordrecht: Foris; 1986.

Neuhoff N, Bruder J, Bartling J, Warnke A, Remschmidt H, Müller-Myhsok B, Schulte-Körne G. Evidence for the late MMN as a neurophysiological endophenotype for dyslexia. PLoS ONE 2012;7 e34909.

Paul I, Bott C, Heim S, Wienbruch C, Elbert TR. Phonological but not auditory discrimination is impaired in dyslexia. Eur J Neurosci 2006;24:2945–53.

Peters B, Kohler KJ, Wesener T. Phonetische Merkmale prosodischer Phrasierung in deutscher Spontansprache. In: Kohler KJ, Kleber F, Peters B, editors. Prosodic Structures in German Spontaneous Speech (AIPUK 35a). Kiel: IPDS. p. 143–84.

Pihko E, Leppanen PHT, Eklund KM, Cheour M, Guttorm TK, Lyytinen H. Cortical responses of infants with and without a genetic risk for dyslexia: I. Age effects. Neuroreport 1999;10:901–5.

Price PJ, Ostendorf M, Shattuckhufnagel S, Fong C. The use of prosody in syntactic disambiguation. J Acoust Soc Am 1991;90:2956–70.

Ramus F, Rosen S, Dakin SC, Day BL, Castellote JM, White S, et al. Theories of developmental dyslexia: insights from a multiple case study of dyslexic adults. Brain 2003;126:841–65.

Schaadt G, Männel C, van der Meer E, Pannekamp A, Friederici AD. Facial speech gestures: the relation between visual speech processing, phonological awareness, and developmental dyslexia in 10-year-olds. Dev Sci 2016;19:1020–34.

Schaadt G, Männel C, van der Meer E, Pannekamp A, Oberecker R, Friederici AD. Present and past: Can writing abilities in school children be associated with their auditory discrimination capacities in infancy? Res Dev Disabil 2015;47:318–33.

Schneider W, Schlagmüller M, Ennemoser M. LGVT 6–12: Lesegeschwindigkeits-und-verständnistest für die Klassen 6–12. Göttingen: Hogrefe; 2007.

Schulte-Körne G, Deimel W, Bartling J, Remschmidt H. Auditory processing and dyslexia: Evidence for a specific speech processing deficit. Neuroreport 1998;9:337–40.

Selkirk E. Phonology and syntax: The relation between sound and structure. Cambridge, MA: MIT Press; 1984.

Seymour PHK, Aro M, Erskine JM, Wimmer H, Leybaert J, Elbro C, et al. Foundation literacy acquisition in European orthographies. Br J Psychol 2003;94:143–74.

Snowling M. Dyslexia. 2nd ed. Oxford: Blackwell; 2000.

Soroli E, Szenkovits G, Ramus F. Exploring dyslexics' phonological deficit III: foreign speech perception and production. Dyslexia 2010;16:318–40.

Speer SR, Warren P, Schafer AJ. Situationally independent prosodic phrasing. Lab Phonol 2011;2:35–98.

Steinbrink C, Klatte M, Lachmann T. Phonological, temporal and spectral processing in vowel length discrimination is impaired in German primary school children with developmental dyslexia. Res Dev Disabil 2014;35:3034–45.

Steinhauer K, Alter K, Friederici AD. Brain potentials indicate immediate use of prosodic cues in natural speech processing. Nat Neurosci 1999;2:191–6.

Stock C, Schneider W. Deutscher Rechtschreibtest (DERET) (German writing test). Göttingen: Hogrefe; 2008.

Stock C, Marx P, Schneider W. Basiskompetenzen für Lese-Rechtschreibleistung (test for basic competences for reading and writing). Göttingen: Beltz Test GmbH; 2003.

Tallal P. Auditory temporal perception phonics, and reading disabilities in children. Brain Lang 1980;9:182–98.

Tallal P, Miller S, Fitch RH. Neurobiological basis of speech: A case for the pre-eminence of temporal processing. Ann NY Acad Sci 1993;682:27–47.

van Zuijen TL, Plakas A, Maassen BAM, Maurits NM, van der Leij A. Infant ERPs separate children at risk of dyslexia who become good readers from those who become poor readers. Dev Sci 2013;16:554–63.

Weber C, Hahne A, Friedrich M, Friederici AD. Discrimination of word stress in early infant perception: Electrophysiological evidence. Cog Brain Res 2004;18:149–61.

Whalley K, Hansen J. The role of prosodic sensitivity in children's reading development. J Res Read 2006;29:288–303.

Wimmer H. The nonword reading deficit in developmental dyslexia: Evidence from children learning to read German. J Exp Child Psychol 1996;61:80–90.

Wood C. Metrical stress sensitivity in young children and its relationship to phonological awareness and reading. J Res Read 2006;29:270–87.

Wood C, Terrell C. Poor readers' ability to detect speech rhythm and perceive rapid speech. Br. J Dev Psychol 1998;16:397–413.

World Health Organization. International Statistical Classification of Diseases and Related Health Problems. In: World Health Organization, editor. Geneva: World Health Organization; 2009.

World Medical Association. World medical association declaration of Helsinki: Ethical principles for medical research involving human subjects. JAMA. 2013; 310: 2191–4.

Ziegler JC, Goswami U. Becoming literate in different languages: similar problems, different solutions. Dev Sci 2006;9:429–36.

Ziegler JC, Bertrand D, Toth D, Csepe V, Reis A, Faisca L, et al. Orthographic depth and its impact on universal predictors of reading: A cross-language investigation. Psychol Sci 2010;21:551–9.

Ziegler JC, Perry C, Coltheart M. The DRC model of visual word recognition and reading aloud: An extension to German. Eur J Cogn Psychol 2000;12:413–30.