

Diminished brain responses to second-language words are linked with native-language literacy skills in dyslexia

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ABSTRACT

Dyslexia is characterized by poor reading skills, yet often also difficulties in second-language learning. The differences between native- and second-language speech processing and the establishment of new brain representations for spoken second language in dyslexia are not, however, well understood. We used recordings of the mismatch negativity component of event-related potential to determine possible differences between the activation of long-term memory representations for spoken native- and second-language word forms in Finnish-speaking 9–11-year-old children with or without dyslexia, studying English as their second language in school. In addition, we sought to investigate whether the bottleneck of dyslexic readers' second-language learning lies at the level of word representations or smaller units and whether the amplitude of mismatch negativity is correlated with native-language literacy and related skills. We found that the activation of brain representations for familiar second-language words, but not for second-language speech sounds or native-language words, was weaker in children with dyslexia than in typical readers. Source localization revealed that dyslexia was associated with weak activation of the right temporal cortex, which has been previously linked with word-form learning. Importantly, the amplitude of the mismatch negativity for familiar second-language words correlated with native-language literacy and rapid naming scores, suggesting a close link between second-language processing and these skills.

1. Introduction

Developmental dyslexia refers to reading impairment despite sufficient tuition and normal intelligence, hearing, and vision. It is the most common learning difficulty with prevalence of 3–10% (Snowling, 2000). Despite of a complex etiology, dyslexia is typically characterized by a phonological deficit, including deficient phonological awareness, phonological working memory, and rapid automatized naming (RAN) (Snowling, 2000; Ramus et al., 2003; for a recent review, see Ramus and Ahissar, 2012). The phonological deficit may be linked with inefficient auditory processing since newborn infants at risk for dyslexia show atypical pattern of auditory event-related potentials (ERP) (Leppänen et al., 2010). Ramus and Szenkovits (2008) have, however, suggested that phonological representations may be intact in dyslexia, whereas access to phonological units is compromised. Recent neuroimaging results have been interpreted to support this view. For example,

Boets et al. (2013) found that speech sounds induced similar activation of auditory cortices in dyslexic and typical readers but the structural and functional connectivity of the left arcuate fasciculus, connecting left superior temporal and frontal brain regions, was hampered in dyslexic as compared with typical readers. Also other studies have linked arcuate fasciculus with reading skills (Hoefl et al., 2011; Yeatman et al., 2012; Myers et al., 2014; Gullick and Booth, 2015), supporting previous notions that cerebral disconnection might contribute to reading difficulties in developmental dyslexia (Paulesu et al., 1996).

In dyslexia, impaired reading in the native language is not the only outcome of underlying phonological processing difficulties. In practice, dyslexic readers often struggle with learning a foreign or a second language, resulting in poor proficiency in this academically and socially important skill. Second-language learning in dyslexia has been addressed by Di Betta and Romani (2006), who compared the learning of

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native-language pseudowords and non-native words associated with pictures between adults with or without dyslexia. Those with dyslexia were found to have a specific deficit in the learning of word forms across languages, although the processing of word meanings was intact. Paired associate learning tasks with pseudowords have resulted in similar conclusions (Litt and Nation, 2014). Soroli et al. (2010), in turn, explored non-native speech perception and production in adults with or without dyslexia. They used discrimination and repetition tasks including native and foreign phonetic segments and word-stress cues embedded in pseudowords. Only the discrimination of foreign word stress was impaired in dyslexic readers, when short-term memory was challenged.

Recent findings showing deficient functional connectivity through the arcuate fasciculus in dyslexia (Hoeft et al., 2011; Boets et al., 2013; Gullick and Booth, 2015) may be critical for explaining dyslexic readers' difficulties in second-language learning. The left frontal areas have been suggested to participate in the categorization of speech sounds and the establishment of non-native phonetic categories (Myers, 2014). However, the participation of these areas in the categorization of speech sounds depends on their connections with auditory cortex in the temporal lobe, a candidate tract being the arcuate fasciculus (Saur et al., 2008). In addition to the processing of speech sounds, the left arcuate fasciculus has been suggested to mediate word learning (López-Barroso et al., 2013). Thus, the functional connectivity between the left temporal and frontal brain areas may be particularly important for establishing both phonetic and word representations in the brain, and both kinds of representations are required for second-language learning. As a result, weak connectivity between these brain areas in dyslexia may be expected to result in poor second-language learning.

However, several questions about second-language learning and its link with literacy in dyslexia remain unanswered. Neuroimaging studies have suggested that the arcuate fasciculus is deficient in dyslexia (Hoeft et al., 2011; Boets et al., 2013; Gullick and Booth, 2015), yet its effect on different levels of speech processing and their temporal dynamics, which is out of the scope of functional magnetic resonance imaging (fMRI) and diffusion tensor imaging (DTI) studies, remains unclear. The connectivity between the left frontal and temporal brain areas might affect the learning of both non-native phonetic categories (Myers, 2014) and words or word forms (López-Barroso et al., 2013), raising a question whether the 'bottleneck' of spoken second-language learning in dyslexia is the establishment of sublexical (phonetic or phonemic) representations or lexical representations that consist of word forms linked with meaning. On the basis of findings suggesting intact processing of native and foreign phonetic segments (Soroli et al., 2010) but impaired learning of native or non-native word forms in dyslexia (Di Betta and Romani, 2006; Litt and Nation, 2014), we hypothesize that the bottleneck is the establishment of new word representations, specifically that of word forms required for full lexical representations, which may be linked with more general serial processing deficits in dyslexia (Hari and Renvall, 2001; Ben-Yehudah et al., 2004; Laasonen et al., 2012; Ramus and Ahissar, 2012; Romani et al., 2015; Majerus and Cowan, 2016). In this case, however, the question rises whether dyslexia exerts a different influence on the processing of spoken native-language and second-language words in the brain, since the establishment of representations for word forms in either language requires serial processing. On the one hand, the learning of new word forms has been suggested to be similarly impaired for native and second language in adults with dyslexia (Di Betta and Romani, 2006), and delays in children's native-language development are sometimes associated with reading difficulties (Lyytinen et al., 2005). On the other hand, however, dyslexia cannot be detected on the basis of native-language spoken language skills only and dyslexic readers typically struggle more with second-language learning than with native-language learning, speaking against a general word learning difficulty in dyslexia. Thus, it is not clear whether children with or without dyslexia show a different pattern of activation of neural representations for familiar native-language

and second-language words.

To this end, we examined the activation of long-term memory representations for spoken native-language and second-language word forms in Finnish-speaking 9–11-year-old children with or without dyslexia, studying English as a second language in school. To tap these brain representations, we used recordings of auditory ERP and its mismatch negativity (MMN) component (Näätänen et al., 1978; for a review, see Näätänen et al., 2007). The MMN is typically elicited in an oddball paradigm, which refers to a sequence of sounds with a high probability of repeating *standard* sounds and a low probability of *deviant* sounds that differ acoustically from the standard. In the brain, the standards automatically generate a predictive model about following sounds (Winkler, 2007), and deviants violating these predictions elicit the MMN. Its amplitude varies as a function of acoustic deviance, but it is also enhanced by the activation of long-term memory representations for speech sounds and words (e.g., Näätänen et al., 1997; Pulvermüller et al., 2001; for reviews, see Näätänen, 2001; Pulvermüller and Shtyrov, 2006). Importantly, the MMN is elicited even when attention is directed away from stimulation (Näätänen et al., 2007), which may be particularly important when studying developmental disorders (Ramus and Ahissar, 2012).

By comparing MMN responses between children with or without dyslexia, we aimed, firstly, to determine whether the processing of second-language words is more compromised than that of native-language words in dyslexia, and whether this is due to sublexical or lexical (word-form) representations. Secondly, to account for potential processing differences between the groups of children with or without dyslexia, we used source modeling to investigate the activation of temporal auditory areas and the left frontal cortex during the early word processing stages (< 200 ms from the recognition point) that are most relevant for word recognition (Pulvermüller and Shtyrov, 2006). Thirdly, we sought to investigate whether the activation of brain representations for native and second language is linked with literacy and aspects of phonological processing, such as rapid naming, which are typically impaired in dyslexia. Since dyslexia is often accompanied by difficulties in second-language learning, we hypothesized that children with dyslexia would show particularly pronounced difficulties in second language processing. Further, we expected that if the processing of unfamiliar second-language items (lacking lexical representations) was inefficient but native-language processing was intact in dyslexia, then second-language phonetic representations would be of poor quality or poorly activated. If this was the case, there would be a deficit at least at the sublexical level. However, inefficient processing of familiar second-language words that are represented in long-term memory but intact processing of unfamiliar second-language items in children with dyslexia would suggest that the learning of word forms is more impaired than their auditory processing. In addition, we hypothesized that second-language processing as reflected by the MMN responses might correlate with literacy and phonological skills due to the role of the same brain structures in literacy (Hoeft et al., 2011; Boets et al., 2013; Gullick and Booth, 2015) and word learning (Hickok and Poeppel, 2007; López-Barroso et al., 2013). Because of potentially deficient functional connectivity between temporal and frontal areas, children with dyslexia were also hypothesized to show weaker activation of the left frontal cortex for second-language words.

2. Materials and methods

2.1. Ethics statement

The study was approved by the Ethical Committee of Helsinki University's Faculty of Behavioural Sciences. Participation was voluntary. Participants and their caregivers gave informed oral or written consent, respectively.

2.2. Participants

Participants were 9–11-year-old native speakers of Finnish, who studied English as a second language in school. Based on pre-tests and background screening, participants were assigned into two groups, namely, children with or without dyslexia. The latter served as controls.¹ The dyslexia group included 19 children (7 girls, 12 boys; mean age 10 years 9 months, SD 8 months). On average, they had studied English for 16 months (SD 7 months). The control group consisted of 21 children (9 girls, 12 boys; mean age 10 years 6 months, SD 10 months) who had studied English for 15 months on average (SD 7 months).

Participants were screened with pre-tests that measured literacy, intelligence, and phonological skills. All of them were conducted in Finnish. Literacy was assessed with standardized Finnish tests ALLU (Lindeman, 1998) and LukiLasse (Häyrynen et al., 1999). ALLU requires the segmentation of letter strings lacking spaces into words within the time limit of 3.5 min. This test enables to divide readers into weak (23%), average (54%) and above average (23%) groups, which are further divided into three skill levels each (i.e., altogether nine skill levels). LukiLasse tests the accuracy and speed of reading single words aloud within the time limit of 2 min and writing dictated words or sentences without time limit. Intelligence was examined with Wechsler Intelligence Scale for Children IV (WISC; Wechsler, 2010), including block design, digit span, vocabulary, and coding. Naming was determined with Rapid Alternating Naming test (RAN; Ahonen et al., 2003), including color and letter tasks. Finally, phonological awareness was assessed with Common unit test, where the task is to name a common phoneme in two auditorily presented words. Specifically, the child is presented with 15 spoken pseudoword pairs (e.g., *lauhkua – terike*, *aamestus – hilpialli*) via headphones. The pseudowords consist of Finnish phonemes and their length varies between five and 12 phonemes. The common phoneme can be at any position in the pseudoword. Before the assessment trials, the child is presented with three practice trials (e.g., *mirki – lukke*). In the practice trials, if the child's answer is correct, the researcher praises the child and repeats the correct answer. If the child does not give the correct answer, the researcher repeats the pseudowords and tells the child the correct answer. After practice trials, each of the 15 assessment trial pairs is presented only once and the child is asked to name aloud which sound they heard to be similar in both pseudowords. No feedback is given during the assessment trials. The test score is the sum of correct answers in the assessment trials. In the pre-tests, children sat in a quiet room with an experimenter who presented the tests. Testing took less than one hour.

To be included in the study, all children had to reach the criterion of not having scores below one standard deviation in any WISC subtest included in the study (i.e., minimum standard score was 7 in block design, digit span, vocabulary, and coding). In addition, the criteria for inclusion in the group of dyslexic readers were a dyslexia diagnosis or performance in the literacy-skill pre-test as follows: 1) the standard score in the single word reading task was at least one standard deviation below the average and either 2a) the standard score in the dictation task was at least one standard deviation below the average or 2b) scores in the technical reading task belonged to the weakest 23%. Out of 19 children with dyslexia, 8 were included on the basis of their performance and 11 had a dyslexia diagnosis, yet all of them fulfilled the pre-test criteria. The criteria for inclusion in the control group were as follows: no dyslexia suspicions, standard scores in the single word reading and dictation tasks being no more than one standard deviation below the average, and scores of the technical reading task not belonging to the weakest 23%. All participants had lived their life in a

¹ Also a group of younger typically developing children matched with the dyslexia group according to reading level would have been useful as a control. However, it would have been very difficult to find younger children with comparable exposure to English.

Finnish-speaking environment except one child with dyslexia who had been exposed to English between 2 and 4 years of age while living abroad. According to parental reports, the children had no other neurological problems, had normal hearing, and were right-handed, with the exception of two control children being left-handed. Parents reported that outside school, children with or without dyslexia were exposed to English TV programs for 3.5 and 3 h and English games for 2 and 1.9 h per week, respectively.

As shown by Table 1, no differences were found between the groups in WISC block design, vocabulary, and coding tasks, whereas in digit span tapping phonological short-term memory controls outperformed the children with dyslexia. RAN was significantly faster in controls than in dyslexic readers for both colors and letters. Controls had also better phonological awareness than the children with dyslexia.

Since 8 out of 19 children were included in the dyslexia group on the basis of their pre-test performance, we also compared z-scores of children with or without a dyslexia diagnosis to see whether these subgroups' literacy and phonological skills differed from each other. No differences were found in word reading, technical reading, phonological awareness or RAN colors (see Table 2). Regardless of diagnosis, all children in the dyslexia group had scores falling to the lowest 10th percentile in word reading. However, the children without a diagnosis outperformed those with a diagnosis in dictation, whereas children with a diagnosis named letters faster than those without a diagnosis (see Table 2). Since reading skills were very similar between the subgroups (if anything, scores were slightly lower in those without a diagnosis), it seems likely that the observed differences were mainly due to some other factors than the severity of dyslexia. A possible factor affecting the results is time: the children without a diagnosis were particularly slow as indicated by RAN letters task, but they could compensate their deficit in the dictation task lacking time constraints. It is also noteworthy that in line with previous observations that males are more likely to be referred for evaluation than females with equivalent reading problems (Quinn and Wagner, 2015), among diagnosed children there were ten boys and one girl, whereas among children without a diagnosis there were six girls and two boys. Such ascertainment bias (Quinn and Wagner, 2015) may explain why most of our female participants did not have diagnoses despite equivalent deficits in reading.

2.3. Experimental design

2.3.1. Stimuli

Stimuli consisted of spoken English and Finnish words and pseudowords (marked with an asterisk from hereon) [*ʃu:*] *shoe*, [*ʃi:*] *she*, [*ʃaɪ*] *shy*, and [*ʃɔɪ*]* *shoy**, and [*su:*] *suu* 'mouth', [*si:*]* *sii**, [*sai*] *sai* 'got' and [*soi*] *soi* 'plays/rings/played/ringed/allowed' (for simplicity, the stimuli will be hereafter referred to with their orthographic form). Because Finnish phonology does not include /*ʃ*/, the English items could be recognized as foreign from their very beginning. The English items were expected to differ as a function of the frequency of use: *she* was familiar and frequently used on English lessons, *shy* less frequently used, and pseudoword *shoy** not used at all. According to a frequency ranking, *she* is among the most frequent English words, occurring 3801 times per million tokens, whereas *shy* and *shoe* are less frequent, each occurring 11 times per million tokens (Leech et al., 2016). The frequencies of the Finnish words were 355 per million tokens for *sai*, 32 for *soi* and 32 for *suu* (Huovilainen, 2018). The Finnish word forms were chosen to match the English word forms phonetically rather than by their frequency of occurrence.² The frequent English word *she* has a

² Unfortunately, all aspects could not be matched at the same time between the Finnish and English stimuli due to the limited selection of monosyllabic words in Finnish. Since it is well-established that the MMN is very sensitive to acoustic changes, the comparison between MMNs to Finnish and English items would have been difficult or impossible, if the stimuli had been matched

Table 1
Participants' literacy and cognitive skill scores. The two columns on the left show the mean (± SD) and range [min max] of standardized tests (WISC and LukiLasse), skill level (1–9) for ALLU, raw response times (in seconds) for RAN, and raw score for Common unit. The next two columns show the mean and range [min max] of z-scores for all tests. LukiLasse and ALLU were used as the criteria of inclusion to the groups of children with dyslexia and their controls and WISC subtests as participation criteria.

	Children with dyslexia: standard score/ skill level/raw score	Controls: standard score/skill level/raw score	Children with dyslexia: z-score	Controls: z-score	t-test comparing the groups
LukiLasse, word reading	4.11 (± 1.73) [1 6]	11.71 (± 1.31) [9 14]	-1.96 [-3 -1.33]	0.57 [-0.33 1.33]	t = -15.79, p < 0.001
LukiLasse, dictation	5.63 (± 3.09) [1 11]	10.90 (± 1.55) [8 13]	-1.46 [-3 0.33]	0.30 [-0.67 1]	t = -6.92, p < 0.001
ALLU, technical reading	2.42 (± 0.96) [1 5]	5.10 (± 1.37) [4 9]	-1.26; [-2.6 -0.1]	0 [-0.7 1.9]	t = -7.06, p < 0.001
WISC block design	11.00 (± 2.83) [7 16]	11.19 (± 3.19) [7 17]	0.33 [-1 2]	0.40 [-1 2.33]	t = -0.20, n.s.
WISC digit span	8.74 (± 1.73) [7 12]	10.48 (± 2.20) [7 14]	-0.42 [-1 0.67]	0.16 [-1 1.33]	t = -2.76, p = 0.009
WISC vocabulary	11.05 (± 2.15) [7 14]	11.81 (± 2.34) [8 15]	0.35 [-1 1.33]	0.68 [-0.67 1.67]	t = -1.06, n.s.
WISC coding	10.53 (± 2.84) [7 18]	12.05 (± 3.04) [7 19]	0.18 [-1 2.67]	0.60 [-1 3]	t = -1.63, n.s.
RAN colors, speed	49 (± 11) [33 78]	44 (± 7) [33 58]	-0.96 [-4.12 0.78]	-0.16 [-2.69 1.06]	t = -2.33, p = 0.025
RAN letters, speed	31 (± 7) [18 45]	26 (± 4) [18 37]	-1.27 [-3.96 1.26]	-0.08 [-2.33 1.98]	t = -3.17, p = 0.003
Common unit (phonological awareness)	5.42 (± 3.72) [0 12]	9.38 (± 2.94) [4 15]	-1.07 [-2.61 0.8]	0.05 [-1.47 1.65]	t = -3.76, p = 0.001

higher frequency value than any of the Finnish words, yet it is noteworthy that due to their limited exposure to English, the Finnish participants must have been exposed to any of the native-language words used here more than any of the English words.

The stimuli were modified from natural recordings. During the recording in a sound-shielded room, an early bilingual male native speaker of Finnish and English pronounced the words and pseudowords several times. The recordings were screened by native speakers of Finnish and English, and then processed so that they were equalized in terms of segmental durations, pitch contours, and amplitude envelopes within Praat (Boersma and Weenink, 2010). Specifically, each recording was segmented into fricatives and vowels; an overlap-add method was used to adjust the duration of each fricative and vowel to their respective average duration; an envelope-add method was used to impose the pitch contour for an example syllable (*shoy**) onto each recording; then the root mean square intensity envelope for an example syllable (*shy*) was imposed on each of the recordings (see Fig. 1).

2.3.2. EEG recordings and analysis

During electroencephalography (EEG) recording, the children sat comfortably in a chair and watched a soundless video without subtitles, while auditory stimuli were delivered through headphones on a 50 dB hearing level. Before the measurement, they were instructed to ignore the auditory stimuli and to concentrate on the video. EEG was recorded with Biosemi ActiView 6.05 system and a 64-channel cap and additional electrodes on the nose, two mastoids, and an extra electro-oculogram (EOG) below the left eye. Reference electrode was the default reference of the Biosemi system (approximately at PO1). Testing took less than two hours including preparation and breaks.

Finnish and English items were presented in separate sequences in an oddball paradigm. The order of stimuli in the sequences was pseudorandom (there were always at least two standards between deviant stimuli). In the English sequence, *shoe* served as the standard stimulus (p = 0.80) and *she*, *shy* and *shoy** as the deviant stimuli (p = 0.066 each). In the Finnish sequence, *suu* served as the standard (p = 0.80) and *sii**, *sai* and *soi* as the deviants (p = 0.066 each). Stimulus onset asynchrony was 800 ms. Both sequences were divided into six blocks, which were presented to the participants in sequences of three blocks for each language, after which the language changed. The order of languages was counterbalanced. Altogether, each deviant stimulus was presented 156 times and each standard stimulus 1902 times.

After the recording, EEG data were re-referenced to nose to check whether responses had typical MMN topography, bad EEG channels, if any, were interpolated using the other EEG channels, the data were filtered with a pass-band of 1–30 Hz (roll-off 24 dB/octave), epoched -100–800 ms, epochs with artifacts exceeding ± 100 µV at any channel were rejected, and the ERP responses were separately averaged for each stimulus type with BESA Research 6.0. Using in-house Matlab scripts, the baseline of the waveforms was corrected to zero at a 100 ms pre-stimulus window and standard ERPs were subtracted from the deviant ERPs to determine their difference and to identify the MMN responses. Before quantification, the data were re-referenced to the average of the mastoids to improve signal-to-noise ratio. To quantify MMN amplitudes, peak latencies were first determined from grand-average waveforms for each stimulus type and group at FCz showing maximal amplitudes, and then the peak latencies were averaged across the groups for each stimulus type. If responses to word forms with diphthongs had two peaks, the latency of the later peak was selected.

(footnote continued)

according to the word frequency rather than the phonetic structure. We cannot exclude the possibility that word frequency caused some MMN amplitude differences between stimulus types (see Shtyrov et al., 2011), yet the frequency does not solely explain any group differences which were of exclusive interest here (see Discussion for details).

Table 2
Literacy and phonological skill z-scores and range [min max] in children with or without a dyslexia diagnosis within the dyslexia group.

	Children with a diagnosis	Children without a diagnosis	t-test comparing the subgroups
LukiLasse, word reading	-1.91 [-3 -1.33]	-2.04 [-3 -1.33]	t = 0.49, n.s.
LukiLasse, dictation	-1.88 [-3 0]	-0.88 [-1.67 0.33]	t = -2.34, p = 0.032
ALLU, technical reading	-1.13 [-2.6 -0.1]	-1.3 [-1.9 -0.9]	t = 0.65, n.s.
RAN colors, speed	-0.85 [-4.12 0.78]	-1.11 [-2.83 0.5]	t = 0.43, n.s.
RAN letters, speed	-0.69 [-2.93 1.26]	-2.07 [-3.96 -0.61]	t = 2.49, p = 0.024
Common unit (phonological awareness)	-1.27 [-2.61 0.8]	-0.8 [-2.32 0.51]	t = -0.95, n.s.

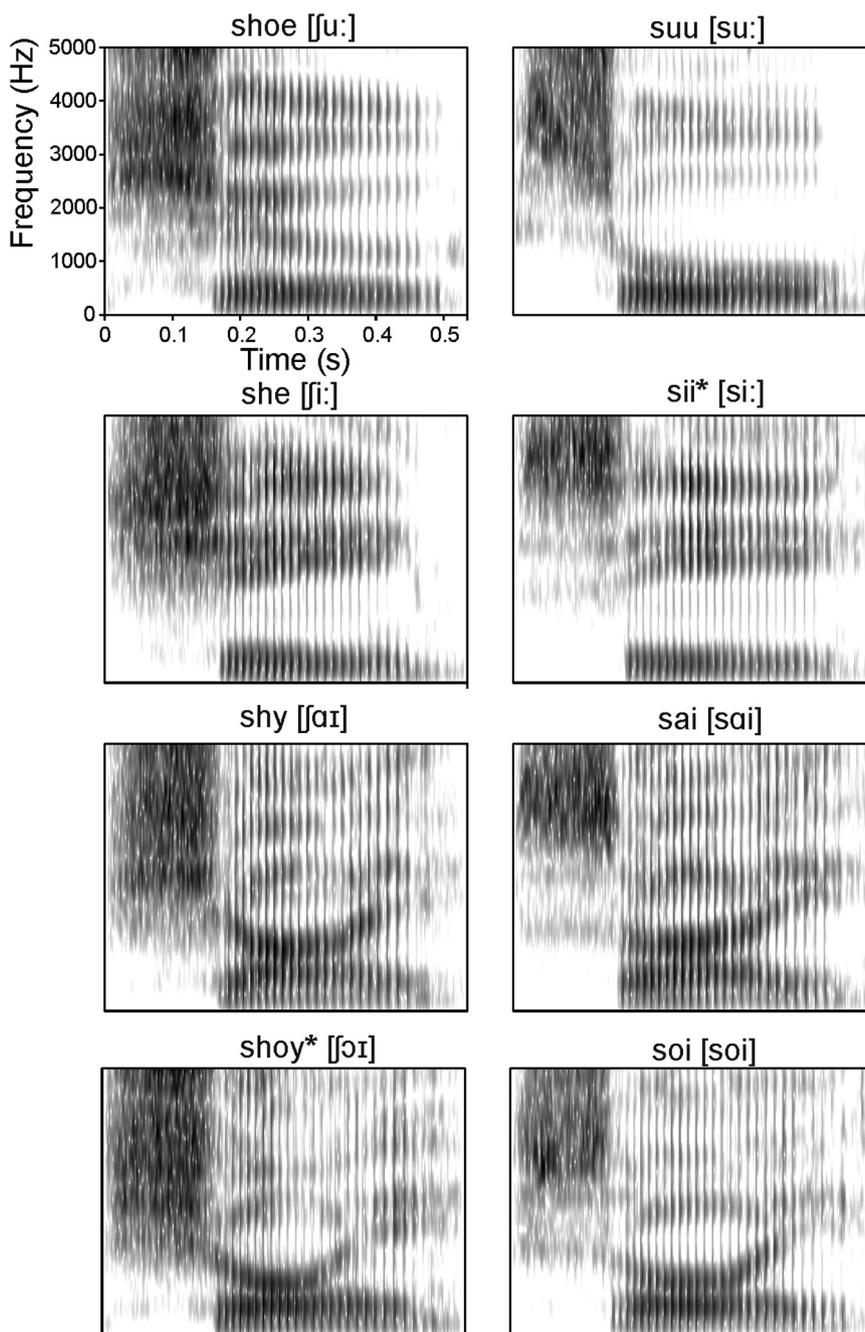


Fig. 1. Spectrograms of the stimuli. An asterisk denotes a pseudoword.

This is because especially in the native language with larger lexicon and, consequently, many lexical competitors, the words could not be recognized with certainty before the last vowel. Therefore, it is likely that the first peak was elicited by the first vowel change, whereas the second peak reflected word recognition (Pulvermüller et al., 2001), in

addition to the second vowel change. A 40 ms time window, centered at the average latency, was then used to measure mean amplitudes from individual difference waveforms at fronto-central scalp sites F3, Fz, F4, FC3, FCz, FC4, C3, Cz, and C4. For both groups, the time windows were 218–258 ms for *she*, 210–250 ms for *shy*, 224–264 for *shoy**,

199–239 ms for *sii**, 258–298 ms for *sai*, and 295–335 for *soi*.

To localize the sources of MMN responses differing between the groups, equivalent current dipole (ECD) methods were applied to deviant-minus-standard difference waveforms in BESA Research 6.0. Source localization was conducted only for the difference waveforms of those participants who showed an MMN, that is, who showed a fronto-central negative peak between 200 and 300 ms (as determined by the grand-average difference waveform). Since individual MRIs were not available, the head model of BESA Research 6.0 for 10–12 year-old children was used. Principal component analysis (PCA) was used to estimate the contribution of sources in BESA Research 6.0. We hypothesized that the MMN would have bilateral temporal sources and possibly a left frontal source, if speech production areas contributed to the processing. To capture the activation of bilateral auditory areas in the temporal lobes, two dipoles were fitted in 40 ms time windows centered at individual MMN peak latencies between 200 and 300 ms. Activation was expected to spread to frontal areas slightly later (Opitz et al., 2002), and therefore a third dipole was fitted either in the same time window or in a time window that started 10 ms later, depending on the timing of residual activity that was not explained by the first and second dipoles. In few cases, fitting of a fourth dipole was attempted to see whether there was bilateral frontal activity, if the third dipole was located in the frontal area between the hemispheres. Since we aimed to study source strengths of specific, pre-determined sources (left and right temporal and left frontal) and averaging source waveforms across different brain areas was not feasible, the source waveforms of ECDs falling outside the regions of interest were not further analyzed. For example, the strength of ECDs at parietal, parieto-occipital, right frontal or subcortical areas was not analyzed. In addition, if there were two temporal sources in the same hemisphere, only the waveform of the source closest to auditory cortex was chosen for source strength analysis.

Individual participants were included in the statistical analysis of sources if they had a minimum of 75% goodness of fit of the model and at least one source in the cortex or its vicinity. As a result, 17 children with dyslexia and 17 controls were included in the statistical analysis of sources, yet not all participants showed all sources that were sought. On average, the model with three (or four) dipoles reached a goodness of fit of 87%. To quantify the activation of the left and right temporal and left frontal sources, we measured peak latencies of grand-average source waveforms for each source and each group and averaged the latencies across the groups. Then individual dipole strengths were measured for each dipolar source in 40 ms time windows centered at the averaged latencies, which were 228–268 ms for the left temporal source, 217–257 ms for the right temporal source, and 220–260 ms for the left frontal source.

2.4. Statistical analysis

Statistical comparisons of cognitive test scores between the groups were conducted with independent samples *t*-tests and the statistical analysis of the MMN responses with repeated-measures ANOVA including factors Group (children with dyslexia vs. controls), Language (native vs. second language), Word form (*she/sii** vs. *shy/sai* vs. *shoy**/*soi*), Coronal scalp site (frontal, fronto-central, central), and Sagittal scalp site (left, midline, right). Significant effects were followed up by Bonferroni-corrected pairwise comparisons if needed. Only main effects or interactions involving the factor Group are reported, because any conclusions about dyslexia are based on differences between the groups, whereas the other factors are not per se relevant for the research questions.

The statistical analysis of the dipole strengths of temporal sources was conducted with independent samples *t*-test comparing the groups. Bilateral temporal sources, or at least one temporal source, were found in most participants (in the left hemisphere in 12 children with dyslexia and 10 controls; in the right hemisphere in 13 children with dyslexia

and 12 controls). We were also interested in differences between the groups in the activation of the left frontal source because it was hypothesized to be deficient in dyslexia. However, we could not compare statistically the groups' dipole strengths because the left frontal source was found in too few children.

To study whether the activation of brain representations is linked with cognitive skills, we conducted correlation analysis (Pearson's *r*) between MMN mean amplitude for the frequent familiar second-language word *she*, averaged across fronto-central electrode sites, and scores in literacy and RAN. Literacy and RAN scores used in comparisons consisted of the average z-score across the three literacy tasks (LukiLasse reading, LukiLasse dictation, ALLU) and the average z-score across RAN speed in color and letter tasks, respectively, where positive values denote above-average performance and negative values denote below-average performance. In addition, since previous work by Kimppa et al. (2018) found different effects between children with dyslexia and typical readers when correlating ERP and LukiLasse dictation, we run correlation analysis of MMN and LukiLasse dictation z-scores separately for the two groups. Finally, correlation analysis was run for the MMN amplitude for *she* and the strength of its right temporal source to see whether the activity of this source is linked with the MMN differences. All statistical comparisons were conducted with SPSS and alpha level 0.05 was applied.

3. Results

ANOVA for the MMN revealed a significant interaction of Group, Language, and Word form [$F(2,76) = 3.63, p = 0.031$]. According to pairwise comparisons, the groups did not differ significantly from each other in any of the native-language word forms. For the second-language word forms, the dyslexic readers' MMN was significantly weaker for the second-language word *she* compared with controls ($p = 0.004$), whereas no significant difference between the groups was found for the other second-language word forms (see Figs. 2 and 3 and Table 3).

Source modeling typically (but not always) resulted in bilateral temporal dipoles and a third dipole in frontal, temporal or parietal areas, yet only the strength of the bilateral temporal and left frontal sources were further analyzed. No significant differences were found between the strength of ECDs in the left temporal source [25.15 vs. 20.98 nAm for controls and children with dyslexia; $t(20) = -0.57, n.s.$]. However, the right temporal source was more strongly activated in controls than in children with dyslexia [23.23 nAm vs. 13.06 nAm, respectively; $t(23) = -2.14, p = 0.043$; see Fig. 4]. The strength of the right temporal source correlated with the MMN amplitude for *she*, $r = -0.41, p = 0.043$. The left frontal source was found only in nine controls (7.09 nAm) and four children with dyslexia (12.13 nAm). Overall, the contribution of the frontal source to the MMN was small: according to PCA, the contribution of the left temporal source was up to 9% in individuals with bilateral temporal and left frontal sources.

Correlation analysis conducted across groups indicated a significant negative correlation between literacy scores and the MMN amplitude for the familiar second-language word *she*, $r = -0.49, p = 0.001$, suggesting that larger (more negative) MMN was associated with higher literacy scores (see Fig. 5). When correlations were tested within each group, they did not reach significance (children with dyslexia: $r = -0.30, n.s.$; controls $r = -0.15, n.s.$). However, it is noteworthy that the use of literacy scores as an inclusion criterion decreased variation of these scores within the groups, as participants not reaching the criterion were excluded. This affects especially the scores of LukiLasse word reading where -1 SD cut-off was applied to all children. Previous work by Kimppa et al. (2018) has suggested that LukiLasse dictation task correlates differently with ERP between children with dyslexia and typical readers. Therefore, correlations with MMN and LukiLasse dictation z-scores were run for the two groups separately. A significant negative correlation was found in children with dyslexia only, $r = -0.46, p = 0.046$ (controls: $r = 0.22, n.s.$). Across groups, a

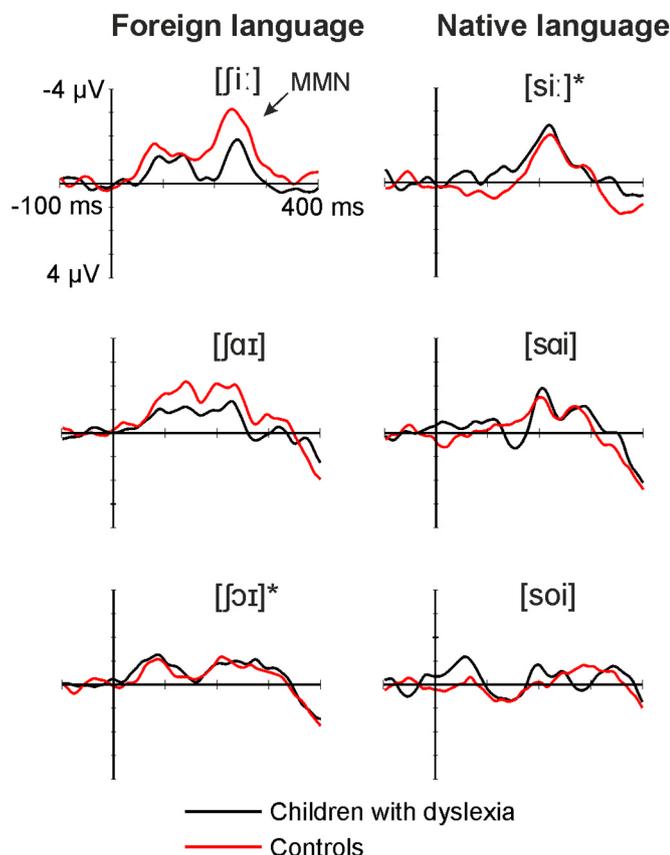


Fig. 2. MMN responses to foreign and native items in children with or without dyslexia at FCz. An asterisk denotes a pseudoword.

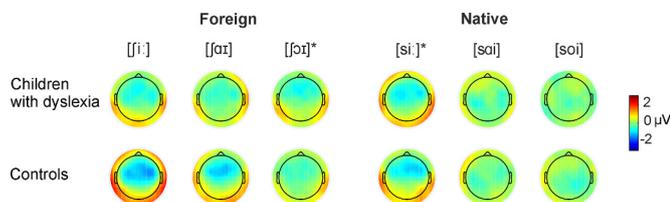


Fig. 3. Scalp distributions of MMN responses to foreign and native items in children with or without dyslexia (average reference). An asterisk denotes a pseudoword.

significant negative correlation was also found between the MMN amplitude for the second-language word *she* and RAN speed, $r = -0.57$, $p < 0.001$. When tested within each group, this correlation persisted being significant in children with dyslexia ($r = -0.48$, $p = 0.04$) and marginally significant in controls ($r = -0.43$, $p = 0.054$).

4. Discussion

The present study aimed to determine whether long-term memory representations for spoken second-language word forms are compromised in dyslexia, whether this is due to sublexical (phonetic) or lexical (word-form) processing, and which cortical sources underlie their deficient activation. In addition, we investigated how the activation of brain representations is linked with cognitive skills that are impaired in dyslexia, such as literacy and rapid naming. Compared with typical readers, in children with dyslexia the speech processing as indexed by the MMN was found deficient for the most familiar second-language word only, whereas no significant group differences were found in the processing of the other native-language and second-language word forms. Source localization suggested that for the most familiar second-language word, the right auditory cortex was weakly activated in children with dyslexia. Children's MMN amplitude for the most familiar second-language word correlated significantly with literacy scores and RAN speed, particularly in children with dyslexia.

Diminished MMN for the most frequent second-language word *she* in children with dyslexia with the absence of MMN group differences for the other second-language or native-language word forms suggests that the dyslexic readers' auditory or speech processing was not generally impaired - at least when processing speech stimuli lacking rapid cues of recognition (cf. Schwartz and Tallal, 1980). This is in line with Froyen's et al. (2011) previous findings, suggesting similar MMNs to vowels in children with or without dyslexia in an auditory condition (yet not in an audiovisual condition). Poor sublexical representations do not account for the pattern of results in the current dyslexic sample either, since poor phonetic representations should have affected the processing of the other word forms as well. This is because the initial consonant /ʃ/ was included not only in *she* but also in the other second-language stimuli which did not elicit diminished responses. Similarly, the vowel /i/, which is quite similar in English and Finnish (Wiik, 1965; see also Fig. 1 for spectrograms), was not only included in *she* but also in the native-language word form *sii**, and the response to the latter was not diminished in children with dyslexia. If only the sublexical level determined the processing, the categorization of /i/ should have been possible via the intact native-language /i/ representation. In addition, sublexical deficits in second language should have been observed in the MMN for *shoy** which is an unfamiliar second-language item and does not have a lexical representation in the long-term memory, yet no difference was observed between the groups for *shoy**. Thus, in line with Soroli et al. (2010), we found no evidence of deficits in the processing of second-language speech sounds in dyslexia.

Group differences were observed for the second-language word *she* that has a high frequency. Since the MMN amplitude may be modulated by word frequency (Shtyrov et al., 2011), we cannot exclude the possibility that word frequency may have affected the amplitudes in the present data as well. However, the high word frequency of *she* in English cannot solely account for the group difference, since no such difference was observed for the most frequent native word *sai* and the children must have been exposed to native *sai* considerably more than to second-language *she*. In addition, it has been shown that reading promotes vocabulary growth (Duff et al., 2015), which raises a

Table 3

MMN amplitudes (± SD) in children with dyslexia and controls, averaged across fronto-central channels that were included in statistical analysis. An asterisk denotes a pseudoword.

	MMN amplitude (µV) in children with dyslexia	MMN amplitude (µV) in controls
Second-language, <i>she</i>	-1.27 (± 1.65)	-2.91 (± 1.74)
Second-language, <i>shy</i>	-1.08 (± 1.61)	-1.63 (± 1.64)
Second-language, <i>shoy</i> *	-0.62 (± 1.49)	-0.76 (± 1.64)
Native-language, <i>sii</i> *	-1.99 (± 2.05)	-1.56 (± 1.73)
Native-language, <i>sai</i>	-1.09 (± 1.97)	-1.00 (± 1.69)
Native-language, <i>soi</i>	-0.27 (± 1.42)	-0.70 (± 1.91)

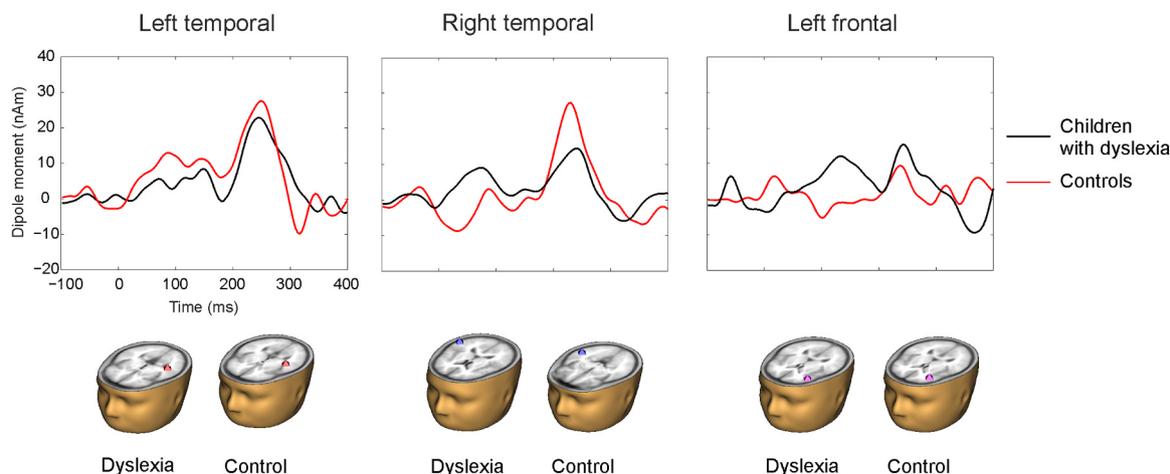


Fig. 4. Top: Source waveforms obtained from ECD analysis for left temporal, right temporal and left frontal sources in children with or without dyslexia. Bottom: ECDs in left temporal, right temporal and left frontal areas in a child with dyslexia and a control child (placed on MRI template, not individual MRIs).

possibility that deficits with auditory word form representations could be mediated by the reduced exposure to print in dyslexic individuals. However, according to WISC vocabulary results, the current groups did not differ from each other significantly in this respect in their native language. In addition, the amount of exposure to the second language in spoken or written form could affect the activation of auditory second-language word forms. Nevertheless, the present groups did not differ from each other in the length of their English studies in school, and according to parental reports, children with dyslexia had not been exposed to English less than controls outside the school (average exposure to English TV programs 3.5 h vs. 3 h per week and to English games 2 h vs. 1.9 h per week in children with dyslexia and controls, respectively). Thus, exposure being similar between the groups, differences between them suggest that children with dyslexia may not benefit from the exposure as much as controls.

Since acoustic or sublexical processing deficits, word frequency effects, vocabulary differences, or the length of exposure do not account for the findings, the observed data pattern seems to be best explained by dyslexic readers' compromised long-term memory representations for second-language word forms. The difference between the groups that reached significance was found for the most familiar second-language word *she*. According to our interpretation, repeated exposure to this

word has enabled the control children to establish a robust representation for it, whereas in children with dyslexia the representation is weaker, as indicated by a smaller MMN. The reason for not seeing a significant group difference in the other second-language word *shy* may be that, on average, the representation for this less frequent non-native word is still quite weak in both groups due to limited exposure. In line with this, no difference was observed between the groups for the unfamiliar pseudoword *shoy** that cannot have a word-form representation in the long-term memory at all. Taken together, this data pattern suggests that dyslexia is associated with an impairment in forming robust brain representations for new second-language word forms, which manifests when the representations should have emerged to the long-term memory. This impairment may form a bottleneck for second-language learning in dyslexia. Related to long-term memory, recent research has shown associations between reading skills and overnight vocabulary consolidation effects at the cortex (Landi et al., 2018). Furthermore, poor learning of novel words has been linked with the consolidation of vocabulary during sleep in children with dyslexia (Smith et al., 2018). Therefore, the consolidation of word forms may contribute to the impairment in forming novel word representations.

The finding of compromised neural representations for second-language words is compatible with previous behavioral findings by

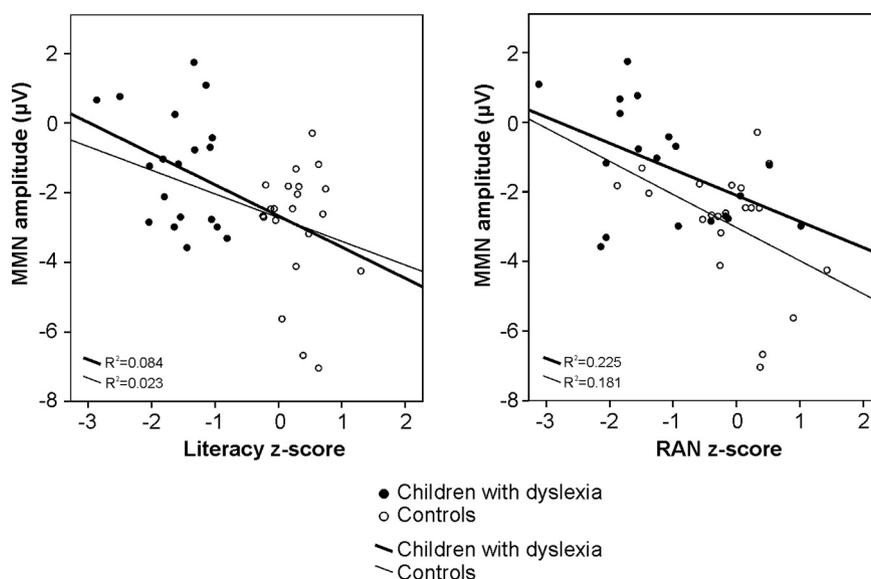


Fig. 5. Correlations between MMN amplitudes for the familiar second-language word *she* and literacy scores (left) and rapid naming (RAN, right).

Di Betta and Romani (2006) and Litt and Nation (2014), who suggested a specific deficit in the learning of word forms in dyslexia. In general, difficulties in word-form learning could be linked with the deficit in serial processing in dyslexia (Hari and Renvall, 2001; Ben-Yehudah et al., 2004; Laasonen et al., 2012; Ramus and Ahissar, 2012; Romani et al., 2015; Majerus and Cowan, 2016), although with short words used here the serial processing requirements should be minimal. It is noteworthy, however, that according to the present data, children with dyslexia did not show any word-form processing deficit in their native language, suggesting that their long-term memory representations for native words were likely as robust as those of the controls (see Pulvermüller et al., 2001). This implies that difficulty to represent word forms that is observed in learning experiments (Di Betta and Romani, 2006; Litt and Nation, 2014) might be overcome by sufficient exposure or practice, which results in automatization. That is, dyslexic individuals might need more exposure to establish robust word representations than typical readers, but for native language this need may not become evident outside laboratory since native-language exposure is readily available.

According to ECD analysis for the MMN response to the most familiar second-language word *she*, the only source differing significantly between the groups was the right temporal one at auditory cortex or its vicinity. The strength of the right temporal source was also significantly correlated with the MMN amplitude for *she*. Thus, although differences in additional sources of activation cannot be excluded, the observed group differences in MMN may have at least partly been due to the weak activation of the right auditory cortex in children with dyslexia (for right-hemispheric sources of activity for words, see MacGregor et al., 2012). Although we found no differences in MMNs between the groups to native monosyllabic words, the weak activation of the right auditory cortex for second-language words in dyslexia is compatible with previous findings showing abnormal processing of speech in the right auditory cortex in dyslexia (Abrams et al., 2009; Molinaro et al., 2016). In line with Goswami's (2011) "temporal sampling" framework, suggesting atypical entrainment at delta and theta rates, poor readers have been demonstrated to have abnormal asymmetry pattern for syllable-rate processing (i.e., no right-hemispheric dominance; Abrams et al., 2009) and impaired speech entrainment in the delta band (0.5–1 Hz) which is accompanied by reduced delta synchronization between the right auditory cortex and the left inferior frontal cortex (Molinaro et al., 2016). The right hemisphere may be specifically involved in the processing of foreign words: Nora et al. (2017) have recently reported that children's learning effects were right-lateralized for foreign word forms. It is also noteworthy that according to the current ECD analysis, the right temporal source had the shortest peak latency, that is, it was typically activated first for the familiar second-language word, implying that in children the right hemisphere plays an important role in the recognition of second-language words.

In our data, frontal sources were found in very few children with dyslexia. Together with weak right temporal activation in these children, this may point to the same direction as Molinaro's et al. (2016) previous finding which suggested that synchronized activity between the right auditory cortex and the left inferior frontal cortex is reduced in poor readers. However, in the current data the ECD strengths of observed frontal sources neither seemed to differ between the groups (see Fig. 4), nor could be statistically tested because frontal ECDs were found in too few children. Therefore, the hypothesis of deficient activation of the left frontal cortex in second-language processing in dyslexia requires further research.

Besides significant differences in literacy scores that were used to assign the participants into groups, cognitive tests indicated that as compared with controls, the children with dyslexia had a shorter digit span (i.e., poorer phonological short-term memory) and they were slower in rapid naming. Taken together, as a group, the dyslexic readers appeared to show typical symptoms of dyslexia that have been associated with a phonological deficit, including poor reading, phonological

short-term memory, and naming (Ramus and Ahissar, 2012; Vellutino et al., 2004; Wagner and Torgesen, 1987). Interestingly, literacy and naming skills were found to correlate with the MMN amplitude for the second-language familiar word (Fig. 5), suggesting that better performance in these cognitive tasks is linked with stronger activation of second-language representations (as indicated by larger MMN responses). Previous studies have suggested that reading and naming share the same neural networks in the brain (McCrary et al., 2005), albeit with a different degree of activation (Price et al., 2006). Correspondingly, a plausible account for the link between literacy skills, naming and brain representations for spoken second-language words is the involvement of the same brain structures in all of them, most likely including the dorsal stream of speech processing (see Scott and Johnsrude, 2003; Hickok and Poeppel, 2007). In their dual-stream model, Hickok and Poeppel (2007) suggest that the dorsal stream serves auditory-motor integration by connecting the auditory analysis areas of the temporal cortex and the articulatory network in the frontal cortex via a sensory-motor interface. Furthermore, auditory-motor interaction is proposed to occur at two levels, where a segmental level is involved in articulatory-phonetic processing and learning, whereas a sequence level is involved in learning new words by coding the sequences of sounds and syllables (Hickok and Poeppel, 2007). The processing of serial order of sound sequences required for word learning (Majerus and Boukeba, 2013) has been proposed to be impaired in dyslexia (Szmalec et al., 2011; see, however, Staels and Van den Broeck, 2015). In the light of these and present results, we suggest that second-language learning is hampered in dyslexic readers because the sequence-level processing of the dorsal stream is inefficient in dyslexia, affecting specifically word-form learning. This could be caused by deficient functional connectivity through the arcuate fasciculus and especially its direct pathway (Hoeft et al., 2011; Boets et al., 2013; Gullick and Booth, 2015), which has been found to mediate word learning (López-Barroso et al., 2013).

The fact that we found differences between the groups in the activation of brain representations for second language, but not for native language (cf. Froyen et al., 2011), highlights a difference in native-language and second-language speech processing. At sublexical level, native-language speech sounds activate mostly brain areas involved in auditory-phonetic processing, whereas second-language speech sounds have been found to activate also brain areas involved in articulatory-motor processing in frontal cortex (Callan et al., 2004). Beyond sublexical level, there is cumulative evidence that native-language processing that aims at comprehension takes place in the ventral stream of speech processing in typical listening conditions (Scott and Johnsrude, 2003; Hickok and Poeppel, 2007; DeWitt and Rauschecker, 2012). In contrast, reading, naming, discrimination, working memory, and second-language learning have been suggested to activate the dorsal stream of speech processing (Hickok and Poeppel, 2007). Interestingly, these involve more complex tasks with explicit processing, mental manipulations, and phonological working-memory load that often result in impaired performance in dyslexia (for a review, see Ramus and Ahissar, 2012). Taken together, these findings linking simple native-language speech listening predominantly with the ventral stream but second-language processing and complex native-language processing with the dorsal stream may explain the more pronounced deficits in phonological skills and second-language learning than in native-language speech processing in dyslexia.

In school environment, second language is learned not only by listening and speaking, but also from textbooks. Children are exposed to both auditory and orthographic forms of words and it is difficult to disentangle their contribution to learning. Since our word of interest *she* is very frequent, the participants must have had a plenty of chances to learn the word from speech, and therefore it is unlikely that dyslexic readers' difficulties to encode the orthographic form of the word *she* could solely account for the current pattern of findings. Nevertheless, the orthographic form is likely to affect more the learning of less

frequent words that are not heard and produced so often. In this case, the difficulty to learn second-language word forms in dyslexia might be modulated by the orthographic properties of the target language. For example, children with dyslexia might have more difficulties with the orthographic forms and their integration with the auditory word forms in opaque languages (such as English) than in transparent languages (such as Finnish). These difficulties may be especially pronounced if native language is transparent and second language is opaque.

To the best of our knowledge, this is the first ERP study focusing on the early stages of second-language word processing in dyslexia. We show that during the early processing stages (< 200 ms from the deviance or recognition point), the activation of brain representations for familiar spoken second-language words is weaker in children with dyslexia than in typical readers. Since source localization suggested significant differences between the groups in the right but not in the left hemisphere and the strength of the right temporal source correlated with the MMN amplitude, weak activation of the right temporal cortex in children with dyslexia may at least partly drive this effect. The current data suggest that dyslexia is associated with a deficit in representing second-language word forms, which may hamper language learning. This interpretation is supported by correlations observed between second-language word processing and literacy and naming scores. Although further research is needed, the present results clarify the links between reading and speech as well as the bottlenecks of language learning in dyslexia. Since word learning tasks can be conducted at younger age than reading tasks, the results showing that reading skills are more closely linked with second-language word learning than native-language processing may also have applicability to early diagnostics of dyslexia.

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