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# Brain event-related potentials to phoneme contrasts and their correlation to reading skills in school-age children

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**Abstract**

Development of reading skills has been shown to be tightly linked to phonological processing skills and to some extent to speech perception abilities. Although speech perception is also known to play a role in reading development, it is not clear which processes underlie this connection. Using event-related potentials (ERPs) we investigated the speech processing mechanisms for common and uncommon sound contrasts (/ba/-/da/-/ga/ and /ata/-/at: a/) with respect to the native language of school-age children in Finland and the US. In addition, a comprehensive behavioral test battery of reading and phonological processing was administered. ERPs revealed that the children could discriminate between the speech sound contrasts (place of articulation and phoneme length) regardless of their native language. No differences emerged between the Finnish and US children in their change detection responses. The brain responses to the phoneme length contrast, however, correlated robustly with reading scores in the US children, with larger responses being linked to poorer reading skills. Finnish children also showed correlations between the reading and phonological measures and ERP responses, but the pattern of results was not as clear as for the US children. The results indicate that speech perception is linked to reading skills and this link is more robust for uncommon speech sound contrasts.

**Keywords**

children, cross-linguistic, dyslexia, EEG, event-related potentials, phonology, reading, speech

## Introduction

Development of reading skills has been shown to be tightly linked to facility with phonological processing skills (e.g., Anthony & Francis, 2005; Bradley & Bryant, 1978; Goswami & Bryant, 1990; Melby-Lervåg, Lyster, & Hulme, 2012; Wagner & Torgesen, 1987). Reading skills have also been previously linked to speech perception abilities (e.g., McBride-Chang, 1995; Mody, Studdert-Kennedy, & Brady, 1997). Here we set out to investigate the relationship between speech sound processing, using brain event-related potentials (ERPs), and reading skills in two different languages, English and Finnish.

Speech perception is known to play a role in reading development, but it is not clear which processes underlie this connection. Deficient speech processing measured with ERPs as well as discrimination and categorization tasks are related to reading failure in individuals with dyslexia (e.g., Hämäläinen et al., 2009; Leppänen et al., 2002; McBride-Chang, 1995; Richardson, Leppänen, Leiwo, & Lyytinen, 2003; Schulte-Körne, Deimel, Bartling, & Remschmidt, 1998), and atypical specialization to phoneme contrasts of one's own native language is related to deficient reading skills (Serniclaes, Van Heghe, Mousty, Carré, & Sprenger-Charolles, 2004). It is also known that speech perception abilities change during the course of life as a result of spoken language exposure (Kuhl et al., 2008).

For studying speech representations in the brain, the electroencephalogram (EEG) technique offers an objective measure at any age (for reviews, see Bishop, 2007; Conboy, Rivera-Gaxiola, Silva-Pereyra, & Kuhl, 2008; Friederici, 2005; Kuhl, 2004; Schulte-Körne & Bruder, 2010). Two ERPs derived from EEG have been shown to index auditory and speech sound discrimination accuracy: mismatch negativity (MMN) and late discriminative negativity (LDN) (Cheour, Korpilahti, Martynova, & Lang, 2001; Näätänen, Astikainen, Ruusuvirta, & Huotilainen, 2010). The amplitude of MMN to speech stimuli is also modulated by longer-term experience with speech sound representations, leading to larger responses for native contrasts as compared to non-native contrasts (Kirmse et al., 2008; Näätänen et al., 1997; Winkler et al., 1999). The attenuated MMN to non-native contrasts is likely to be due to top-down processes such as tuning of native speech sound categories and the consequent drop of discrimination accuracy for within-category speech contrasts (Kuhl et al., 2008; Näätänen et al., 1997).

There is a less clear picture on how native and non-native speech sounds affect the LDN. Several alternatives for the functional significance of this ERP component has been put forward, for example that it would reflect pre-attentive cognitive evaluation of the stimuli (Ceponiene et al., 2004; Jakoby, Goldstein, & Faust, 2011) or the formation of memory representations of the stimuli (Barry,

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Hardiman, & Bishop, 2009). The LDN seems to be related to success in learning a foreign language (Jakoby et al., 2011; Shestakova, Huotilainen, Ceponiene, & Cheour, 2003) and the capacity to learn new words as reflected by a non-word repetition task (Barry et al., 2009). These studies indicate that LDN reflects an important processing stage in speech perception.

The strength of these ERP responses also differs between children with dyslexia and typically developing individuals (e.g., Hämäläinen et al., 2013; Lohvansuu et al., 2014; Maurer, Bucher, Brem, & Brandeis, 2003; Schulte-Körne et al., 1998). Other ERP responses that are also generated as a consequence of afferent activation, and the related processing, have been found to differentiate between individuals with reading problems and with typical reading skills (e.g., Hämäläinen et al., 2013; Helenius, Salmelin, Richardson, et al., 2002; Lohvansuu et al., 2014). For example, in children, the obligatory ERPs form a series of responses termed P1, N2 (or N250), and N4 named after their latency and order (e.g., Ceponiene et al., 2005). Moreover, infants at high familial risk for dyslexia already show abnormal brain responses to the contrasts of their native language (Leppänen, Pihko, Eklund, & Lyytinen, 1999; Leppänen et al., 2002; van Zuijen, Plakas, Maassen, Maurits, & van der Leij, 2013) as well as to speech sounds occurring rarely in the mother tongue (Guttorm, Leppänen, Hämäläinen, Eklund, & Lyytinen, 2010; Guttorm, Leppänen, Richardson, & Lyytinen, 2001; Guttorm et al., 2005). Furthermore, among typically developing children, correlations between neural responses to speech, reading and phonological skills have been observed (Bonte, Poelmans, & Blomert, 2007; Espy, Molfese, Molfese, & Modglin, 2004; Kuuluvainen, Alku, Makkonen, Lipsanen, & Kujala, 2016; Parviainen, Helenius, Poskiparta, Niemi, & Salmelin, 2011).

The first aim of this study was therefore to examine how longer-term exposure to native language affects the brain responses generated by detection of deviant speech sounds embedded in a stream of repeated speech sounds in both English-speaking and Finnish-speaking school-aged children. We hypothesized that language-group differences would emerge, particularly for the phoneme length contrast. The phoneme length contrast is not semantically distinctive in English whereas it is in Finnish. Supporting our hypothesis, earlier studies have observed amplitude differences in MMN responses to phoneme length changes in Finnish- and German-speaking adults (e.g., Kirmse et al., 2008). For the other speech sound contrasts we used, i.e., consonant–vowel syllables with place-of-articulation changes (see the Methods section below), the change-detection ERP responses were expected to be larger for sounds that are common than sounds that are uncommon in the Finnish language, although to a lesser degree due to the English language exposure of almost all Finnish children.

The second aim of the study was to examine whether the ERP responses to speech sounds that are common or uncommon in one's native language were associated with reading skills or skills that are highly predictive of reading accuracy and speed (i.e., phonological awareness, rapid naming, verbal short-term memory) as previous studies have shown such associations for native speech sound processing (e.g., Bonte et al., 2007; Kuuluvainen et al., 2016).

# Methods

## Participants

The Finnish children were recruited from the Central Finland area via the local day-care centers, schools and a learning disability clinic. Altogether 41 children (20 girls, 21 boys) participated in the EEG study at the age of 10.3–12.5 years (at the fourth grade in school). They had been screened for exclusion criteria (learning disabilities other than dyslexia, neurological disorders, medication, head injuries, hearing problems). There were four children with a diagnosis of dyslexia and additional nine children had reading scores below −1.25 SDs at the second grade (at the fourth grade, however, only five of them had reading scores below −1.25 SDs). These children were included in the final sample of 38 children with successful EEG data acquisition.

The children from the USA were recruited from the greater New Haven CT region via local advertisements. Altogether 76 children participated in the EEG study at the age of 4.9–12.2 years (kindergarten to fifth grade in school) who had been screened for exclusion criteria (neurological disorders, medication, head injuries, hearing problems). Some children were excluded based on the diagnosis of attention deficit disorder (nine), minor brain dysfunction (six), and specific language impairment (three). There were six children with a diagnosis of dyslexia who were included in the final sample. Good EEG data were obtained from the experiment with English speech sounds for 54 children and from the experiment with Finnish speech sounds for 44 children.

## Behavioral measures: Finland

All behavioral assessments were conducted in June–November, at the end of fourth grade and the start of fifth grade in two testing sessions, to characterize the reading level, phonological skills, and verbal working memory of the children.

*Working memory.* Series of numbers both forward and backward from the Wechsler Intelligence Scale for Children—Third edition (WISC-III) were used (Wechsler, 1991).

*Reading in Finnish.* Six reading tests were used. Standardized test of word list reading (Lukilasse; Häyrinen, Serenius-Sirve, & Korkman, 1999), number of correctly read words in 45 s was used as the score; non-word list reading based on Tests of Word Reading Efficiency (TOWRE; Torgesen et al., 1999), number of correctly read non-words in 45 s was used as the score; standardized test of sentence reading where the children had to read a sentence and match it with the related correct picture (Lindeman, 1998), number of read sentences in 120 s was used as the score; text reading (Puolakanaho et al., 2008), number of correctly read words in 1 minute was used as the score; pseudoword text reading (Eklund, Torppa, Aro, Leppänen, & Lyytinen, 2015), number of correctly read words and total reading time were used as the scores; lexical decision task where the children silently read words and had to decide whether the word had a meaning or not, number of correct decisions was used as the score.

*Writing in Finnish.* Writing four-syllabic words from dictation, number of correct items out of 10 was used as the score; writing four-syllabic pseudowords from dictation, number of correct items out of 12 was used as the score.

*Phonological processing.* Phoneme deletion task requiring children to delete a specified phoneme from 1–3 syllabic non-words, number of correct items out of 18 was used as the score; phoneme length perception where the child heard through headphones two non-words and had to decide whether they were the same or different

**Table 1.** Details of the speech stimuli used in the experiments.

| | English | | | Finnish | | |
|---|---|---|---|---|---|---|
| | /ba/ | /da/ | /ga/ | /ata/ | Intermediate /atta/ | Long /atta/ |
| Stimulus type | Standard | Deviant | Deviant | Standard | Deviant | Deviant |
| Contrast | Place of articulation | Place of articulation | Place of articulation | Gap duration (95 ms) | Gap duration (155 ms) | Gap duration (255 ms) |
| Total duration (ms) | 251 | 251 | 251 | 298 | 359 | 440 |

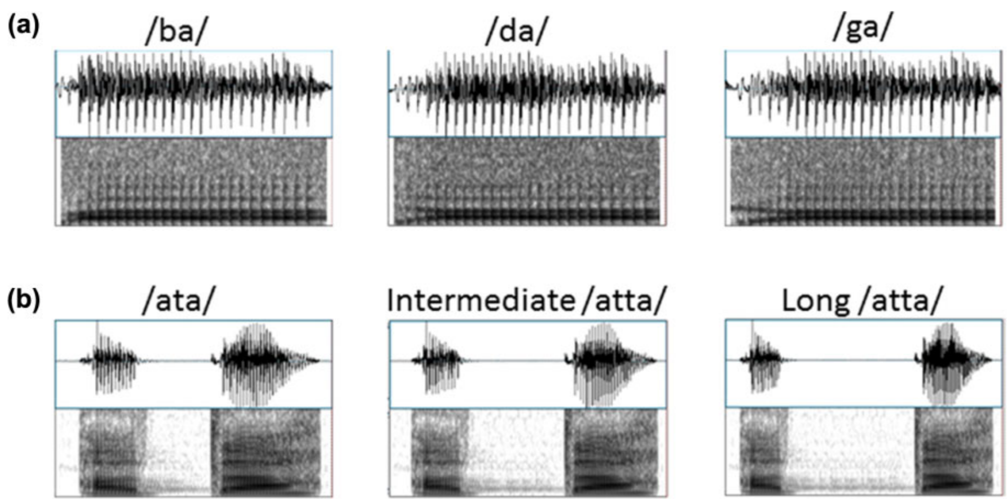


**Figure 1.** Waveforms and spectrograms of (a) English; and (b) Finnish stimuli used in the experiments.

(Hämäläinen et al., 2009), number of correct items out of 22 was used as the score; non-word repetition task from the Neuropsychological test battery (NEPSY; Korkman, Kirk, & Kemp, 1998), number of correct items out of 16 was used as the score.

*Rapid naming.* Rapid automatized naming task (RAN: Objects Letters; Denckla & Rudel, 1976). Total matrix completion time (in seconds) was used as a measure.

## *Behavioral measures: US*

All behavioral assessments were conducted year round, and children participated in two testing sessions to characterize reading level, phonological skills, and verbal working memory. Standard scores from all tests were used in the analyses.

The Comprehensive Test of Phonological Achievement (CTOPP*)* (Wagner, Torgesen, & Rashotte, 1999), subtests of Phonological Awareness (Elision, Blending Words, and Blending Non-words) were administered to determine awareness and access to the speech sound structure. Subtests of Phonological Memory (Memory for Digits and Non-word Repetition) and Rapid Naming were also administered to assess phonological encoding in working memory and speed of lexical retrieval.

TOWRE (Torgesen et al., 1999) comprises two subtests requiring the speed reading of real English words (Sight Word Efficiency) and of pseudowords (Phonemic Decoding Efficiency). For both subtests, the items are ordered from easiest to most difficult, and the examinee is asked to read as many items as possible in 45 s. Total score across the subtests was also calculated.

The Gray Oral Reading Test-3 (GORT-3) (Widerholdt & Bryant, 1992) was used as an assessment of reading proficiency. Participants read aloud stories of increasing difficulty, followed by answering questions about the stories. This test measures oral reading ability in the domains of accuracy in terms of word pronunciation, fluency, and comprehension.

The Peabody Picture Vocabulary Test-III (PPVT-III) was used to measure lexical/vocabulary skills (Dunn & Dunn, 1997). In the PPVT, stimulus words are provided for which an individual must select the corresponding picture from a field of four. The PPVT-IV is arranged to provide words of increasing difficulty.

The Wechsler Abbreviated Scales of Intelligence (WASI) (Psychological Corporation, 1999) is administered as a measure of IQ. The four subtests of the WASI—Vocabulary, Block Design, Similarities, and Matrix Reasoning are used to measure various facets of intelligence, including verbal knowledge, spatial reasoning, and visual information processing. Vocabulary and Similarities subtests compose Verbal IQ. Block Design and Matrix Reasoning subtests make up the Performance IQ.

## *Stimuli and procedure*

Three passive oddball experiments were run for all children with English (/ba/, /da/, /ga/), Finnish (/ata/, intermediate /atta/ and long /atta/), and Taiwan Mandarin (/fau/ with three different lexical tones) speech stimuli (see Table 1 and Figure 1 for details of the English and Finnish stimuli). Place-of-articulation contrast was used in the English experiment with the consonant–vowel syllable /ba/ as the standard sound and /da/ and /ga/ syllables as the deviant

**Table 2.** Average epoch numbers (SDs) included in event-related potential averaging after artifact rejection for the Finnish ($n = 38$) and US ($n = 54$ for /ba/-/da/-/ga/, $n = 44$ for /ata/-/atta/) samples.

| | Pre-/da/ standard | Pre-/ga/ standard | /da/ deviant | /ga/ deviant | Pre-intermediate /atta/ standard | Pre-long /atta/ standard | Intermediate /atta/ deviant | Long /atta/ deviant |
|---|---|---|---|---|---|---|---|---|
| Finnish | 100.3 (18.8) | 101.0 (19.6) | 102.5 (18.3) | 100.0 (19.5) | 94.2 (12.8) | 93.0 (14.3) | 94.5 (13.9) | 92.1 (14.3) |
| US | 73.2 (22.5) | 72.4 (21.9) | 73.0 (21.9) | 72.3 (22.9) | 80.0 (20.5) | 80.6 (21.3) | 80.5 (20.7) | 80.9 (19.8) |

sounds, and stop consonant (silent gap) length contrast was used in the Finnish experiment with the pseudoword /ata/ as the standard sound (short consonant length) and an intermediate /atta/ and long /atta/ sounds as the deviant sounds (8.3% probability for each deviant in each experiment). The long /atta/ sound was clearly categorized as having a long consonant length, whereas the intermediate /atta/ was in the long category but close to the category border (Richardson et al., 2003). The experiments were run in the same order (English, Finnish, Chinese) for all children. The experiment with the Taiwan Mandarin stimuli was not carried out for all children due to fatigue and is therefore not reported here. In each experiment the standard sound was repeated 1000 times and two deviants were each repeated 125 times. The stimuli were presented in a pseudorandom order such that there were always at least two standard stimulus presentations between each deviant stimulus.

Stimuli were presented at a comfortable hearing level through a loudspeaker situated approximately 80 cm above the participant with 75–82 dB(C). The onset-to-onset stimulus onset asynchrony (SOA) was 1220 ms in each experiment, which caused the offset-to-onset interstimulus interval (ISI) to vary according to the length of the stimuli.

During the experiment the participants sat in an armchair watching a muted movie and were asked not to pay attention to the presented speech stimuli. The ERP measurement lasted altogether ca. 1.5 hours. Breaks were provided when necessary.

## EEG acquisition

In both sites, the EEG data were collected with an Electric Geodesics Inc. (EGI) EEG-system and NetStation 4.2 software (http://www.egi.com/). Ag-AgCl electrodes with a EGI 128-channel Hydrocel sensor net were used with Cz as the reference channel during recording. The sampling rate was 500 Hz. The EEG was filtered online with a highpass filter of 0.1 Hz and a lowpass filter of 200 Hz. Electrode impedances were set below 50 kΩ at the beginning of the experiment. During the experiment, the quality of the data was monitored and the electrode impedances were adjusted when necessary.

## Data analysis

The EEG data was analyzed using BESA Research 6.0 (BESA GmbH, Gräfelfing, Germany). Channels showing continuously bad data were interpolated using the spherical spline method (3.0 channels on average for the Finnish sample, 5.3 for the US sample). The EEG data was offline filtered using zero-phase 0.5 Hz (12 dB/Oct) highpass and 30 Hz (24 dB/Oct) lowpass. Independent component analysis (ICA) (Infomax algorithm on a 20–120 s time window containing at least two blinks) was used for correcting eye blink artifacts in the data. For averaging the epoch length was −200–1020 ms with 200 ms pre-stimulus baseline. Artifact rejection criteria were 175 μV (maximum minus minimum amplitude) within the whole epoch and 75 μV for fast transient amplitude changes. See Table 2 for accepted number of epochs after artifact rejection. The groups differed in the number of epochs (US children having less epochs after artifact rejection than Finnish children; all $p < 0.006$) when tested with independent sample *t*-tests.

Due to the large number of behavioral reading measures in Finnish, principal axis factoring (based on correlation matrix, varimax rotation, and Bartlett factor scores) was used for the six reading variables yielding two factors: reading accuracy and reading speed, explaining 49% and 29% of the total variance, respectively. In addition, the scores of the two writing tasks were summed, and the time (in seconds) for the two RAN tasks was averaged.

ERPs to the deviant stimuli and the pre-deviant standard stimuli were examined. When examining the responses to the pre-deviant standard stimuli only those results similar to both pre-deviant standards are reported for each experiment. The responses to the pre-deviant standard stimuli were examined separately to have a comparable signal-to-noise ratio (same number of trials) to the deviant stimulus responses. To test the effect of native language exposure, the ERP responses were compared between the Finnish and US samples in BESA Statistics 2.0 (BESA GmbH, Gräfelfing, Germany) using non-parametric permutation statistics and clustering (time points and electrodes) that are based on initial independent sample *t*-tests. All analyses used a channel neighbor distance of 3 cm and time window 0–998 ms. Clustering (time points and electrodes) is used to control for Type I error (see Maris & Oostenveld, 2007). The number of permutations was 1000. To control for the effects of age, it was entered as a covariate into BESA Statistics 2.0 using permutation statistics based on one-way ANOVA (between groups comparison). For completeness, we report whether the group effects were affected by the age covariate. To examine the effects of speech sound discrimination on reading skills the ERP data (each channel and each time point for each type of stimulus) was correlated with the behavioral measures of reading and reading related skills in BESA Statistics 2.0. The correlations were also corrected for multiple comparisons of channels and time points using permutation statistics and data clustering as implemented in BESA Statistics 2.0. Therefore, the time windows and channel clusters were data-driven and not defined a priori.

# Results

## Cognitive skills

Descriptive statistics of the cognitive skill measures are presented in Tables 3 and 4.

## ERP results

***Differences between responses to the deviant and standard stimuli.*** To ascertain whether the children were able to detect the

**Table 3.** Descriptive statistics of the cognitive skill measures for the Finnish children ($n = 38$).

| | Mean | SD | Range |
|---|---|---|---|
| Age (years) | 11.08 | 0.51 | 10.3–12.5 |
| Digit span, raw score | 11.6 | 2.8 | 8–21 |
| Word list reading (Lukilasse), correct items | 45.9 | 12.0 | 19–71 |
| Text reading, correct items | 119.1 | 4.8 | 104–124 |
| Non-word text reading, correct items | 43.6 | 11.4 | 19–66 |
| Sentence reading, correct items | 37.8 | 10.8 | 14–57 |
| Lexical decision, correct items | 143.8 | 4.5 | 131–150 |
| Writing, words, correct items | 5.7 | 2.5 | 0–10 |
| Writing, non-words, correct items | 8.3 | 2.1 | 3–12 |
| Phoneme deletion, correct items | 14.8 | 3.2 | 4–18 |
| Non-word repetition, correct items | 9.7 | 2.0 | 4–14 |
| Rapid automatic naming, objects, time (s) | 49.6 | 8.8 | 33–72 |
| Rapid automatic naming, letters, time (s) | 28.9 | 7.4 | 16–52 |
| Phoneme length perception, correct items | 16.9 | 2.6 | 11–21 |

**Table 4.** Descriptive statistics of the cognitive skill measures for the US children.

| | Mean | SD | Range |
|---|---|---|---|
| Age (years), $n = 54$ | 7.97 | 1.67 | 4.9–11.2 |
| Phonological awareness, $n = 46$ | 107.4 | 15.6 | 85–151 |
| Phonological memory, $n = 48$ | 96.3 | 9.9 | 79–127 |
| Rapid automatic naming, $n = 21$ | 102.6 | 12.6 | 85–124 |
| Gray oral reading test, accuracy, $n = 42$ | 9.1 | 4.3 | 1–17 |
| Gray oral reading test, comprehension, $n = 42$ | 11.8 | 3.4 | 5–19 |
| Gray oral reading test, fluency, $n = 42$ | 10.1 | 4.3 | 1–18 |
| Tests of word reading efficiency, total, $n = 43$ | 107.6 | 20.3 | 66–146 |
| Tests of word reading efficiency, phonemic, $n = 43$ | 106.8 | 16.9 | 79–140 |
| Tests of word reading efficiency, sight, $n = 43$ | 105.9 | 18.1 | 59–138 |
| Peabody picture vocabulary test, $n = 52$ | 113.4 | 11.1 | 95–139 |
| Performance IQ, $n = 43$ | 109.6 | 14.2 | 79–138 |
| Verbal IQ, $n = 44$ | 110.7 | 13.7 | 61–151 |

differences between the stimuli, the responses to the deviant and standard stimuli were compared. Differences were found for all conditions and in both samples, except between those for the deviant /da/ and standard /ba/ in the US sample. See below details of the stimulus differences in Tables 5 and 6, and Figures 2 and 3 for the ERP waveforms, and Figures 4 and 5 for the topographies.

*Differences between Finnish and US samples.* To test whether there are language-specific differences in the neural responses, we compared ERP amplitudes between the groups. First, the group differences were examined for the responses to the standard and deviant sounds separately in order to see processing differences at the level of exogenous responses. There were general group differences that resulted from larger responses starting with the N250 for all stimuli in the Finnish children compared to the US children, see Table 7 for a summary of these differences. When age was used as a covariate the significant amplitude differences between the groups remained.

Second, the group differences were examined for the difference waves (response to the deviant minus response to the standard) in order to examine processing related to change detection mechanisms that have been linked to discrimination abilities in previous literature (e.g., Näätänen et al., 2010). When examining the difference waves, the cluster-based test showed one cluster where the Finnish and the US children differed for the response to the deviant /ga/ sound. This difference was most prominent at parieto-occipital electrodes at 576–886 ms ($p < 0.043$). The US children had larger negative going responses at the parietal electrodes than the Finnish children while Finnish children had larger positive going responses at the occipital electrodes. When age was entered as a covariate to the analysis this group difference became non-significant. Therefore, it is not discussed further.

*Correlations.* The second goal of the study was to examine whether the brain responses to common and uncommon speech sound contrasts would be linked to reading ability. The associations between the amplitudes of exogenous and change detection responses are correlated with the reading measures below.

*Correlations to common speech sound stimuli.* In the Finnish sample the ERP amplitudes for intermediate and long /atta/s showed significant correlations with phonological measures (digit span, phoneme deletion, non-word repetition) and reading accuracy, as shown in Table 8. Larger negative amplitudes were associated with better performance in the tasks. The scalp areas and time windows with largest correlations, however, varied depending on the variables. There were no significant correlations between the ERP amplitudes and cognitive skill measures in the US sample for the common speech sound stimuli (/ba/, /da/, /ga/).

*Correlations to uncommon speech sound stimuli.* In the Finnish sample the response to the deviant /ga/ sound correlated with reading speed, accuracy, and phoneme deletion scores. For reading speed the correlation indicated faster reading speed with larger response, for reading accuracy better accuracy with smaller (more negative) amplitudes, and for phoneme deletion better phoneme deletion skill with larger positive amplitudes. There was also a correlation between the response to the deviant /da/ sound and reading speed, indicating faster reading speed with a larger response. When difference waves were examined the response to the deviant /ga/ showed correlation with RAN, indicating slow rapid naming with large positive voltages. Table 8 again shows that the scalp areas and time windows with maximal correlations vary depending on the behavioral measure.

In contrast, in the US sample, systematic and robust correlations were found between the responses to the uncommon speech sounds (/ata/, intermediate and long /atta/s) and reading skills (Table 9). Poor performance in GORT reading accuracy, fluency, and comprehension as well as TOWRE reading tasks were linked to larger ERP amplitudes for all variables. The time windows where the correlations were observed encompassed all ERP components, starting from P1 generated by the first syllable of the stimulus at the fronto-central channels and at the parieto-occipital channels starting from P1 generated by the second syllable of the stimulus.

The difference waves showed a similar correlation pattern for GORT reading accuracy, fluency, and comprehension: the larger the amplitude, the poorer the reading starting from the MMN time window, or even earlier. Correlations were also found between the difference wave amplitudes and TOWRE sight word and phonemic reading skills. The difference wave for the intermediate /atta/ correlated significantly with TOWRE sight word reading and had three correlation clusters: parieto-occipital channels at 280–554 ms, the more negative the voltage the better the reading score; parieto-occipital channels at 658–998 ms, the more negative the voltage

**Table 5.** Summary of the statistical differences between the responses to the deviant and standard stimuli in the Finnish sample ($n = 34$).

| | Cluster number | p-value | Cohen's d | 95% confidence interval | Topography | Time window (ms) | Event-related potential components |
|---|---|---|---|---|---|---|---|
| /da/ vs. /ba/ | 1 | <0.0001 | 0.99 | 0.46–1.23 | Parietal | 238–400 | N250/MMN |
| | 2 | <0.005 | 0.61 | 0.12–0.78 | Temporal—fronto-central | 416–738 | LDN |
| | 3 | <0.009 | −0.76 | −1.02–(−0.26) | Left parieto-occipital | 502–750 | LDN |
| | 4 | <0.042 | −0.60 | −1.17–(−0.17) | Left fronto-central | 260–386 | N250 |
| /ga/ vs. /ba/ | 1 | <0.0001 | 0.66 | 0.17–0.91 | Fronto-central | 274–950 | MMN+LDN |
| | 2 | <0.0001 | −0.74 | −0.75–(−0.18) | Parietal | 400–876 | LDN |
| | 3 | <0.042 | −0.73 | −1.79–(−0.43) | Right temporal | 252–440 | N250 |
| Intermediate /atta/ vs. /ata/ | 1 | <0.0001 | 0.73 | 0.27–1.14 | Fronto-central | 556–826 | N250/LDN to second syllable |
| | 2 | <0.0001 | −0.77 | −1.18–(−0.31) | Fronto-central | 254–514 | Atta4 larger N250, P1 to second syllable |
| | 3 | <0.003 | −0.60 | −1.14–(−0.16) | Parieto-occipital | 500–798 | LDN more positive for atta4 |
| | 4 | <0.004 | 0.93 | 0.55–1.59 | Fronto-central | 174–286 | larger N250 for atta4 |
| | 5 | <0.004 | 0.68 | 0.31–1.52 | Parieto-occipital/left temporal | 318–474 | Earlier N250 for ata1 |
| | 6 | <0.014 | −0.79 | −1.77–(−0.49) | Parieto-occipital/right temporal | 198–280 | Larger N250 for atta4 |
| Long /atta/ vs. /ata/ | 1 | <0.0001 | −1.83 | −2.58–(−1.56) | Fronto-central until 592 ms then parieto-occipital | 362–998 | P1_2 and N250_2 for atta8 |
| | 2 | <0.0001 | 1.14 | 0.61–1.41 | Fronto-central | 560–998 | N250_2 for atta8 |
| | 3 | <0.002 | 0.87 | 0.66–2.09 | Parieto-occipital | 366–542 | P1_2 for atta8 |
| | 4 | <0.009 | 1.03 | 0.66–1.67 | Fronto-central | 212–364 | Larger N250 for atta8 |
| | 5 | <0.014 | −0.74 | −1.83–(−0.45) | Parieto-occipital | 174–370 | Larger N250 for atta8 |

Note: Cohen's *d* and 95% confidence intervals were calculated for the channel and time window showing maximal differences in the cluster-based permutation statistic. atta4 = intermediate; /atta/, atta8 = long; /atta/, ata1 = /ata/.

**Table 6.** Summary of the statistical differences between the response significances to the deviant and standard stimuli in the US sample ($n = 54$ for /ba/-/da/-/ga/, $n = 44$ for /ata/-/atta/).

| | Cluster number | p-value | Cohen's d | 95% confidence intervals | Topography | Time window (ms) | Event-related potential components |
|---|---|---|---|---|---|---|---|
| /ga/ vs. /ba/ | 1 | <0.0001 | 0.69 | 0.30–1.04 | Parieto-occipital—frontro-central | 80–492; 494–998 | P1, N250, LDN |
| | 2 | <0.027 | −0.67 | −1.23–(−0.34) | Frontal | 102–476 | P1 |
| | 3 | <0.036 | −0.57 | −1.35–(−0.27) | Left temporal | 270–736 | LDN |
| Intermediate /atta/ vs. /ata/ | 1 | <0.001 | 0.85 | 0.39–1.14 | Frontro-central | 488–876 | N250 to 2nd syllable in /atta/ |
| | 2 | <0.003 | −0.79 | −1.12–(−0.34) | Left temporo-occipital | 488–994 | N250 to 2nd syllable in /atta/ |
| | 3 | <0.006 | −1.17 | −1.80–(−0.85) | Frontro-central | 340–476 | N250 to 2nd syllable in /ata/ |
| | 4 | <0.020 | 0.80 | 0.64–2.06 | Parieto-occipital | 364–470 | N250 to 2nd syllable in /ata/ |
| | 5 | <0.012 | −1.02 | −1.81–(−0.75) | Frontro-central | 182–364 | Larger N250 for /atta/ |
| Long /atta/ vs. /ata/ | 1 | <0.0001 | 1.11 | 1.01–2.23 | Frontro-central until 372 ms then parieto-occipital | 212–546 | Larger N250 for /atta/ and P1 to 2nd syllable in /atta/ |
| | 2 | <0.0001 | −1.86 | −2.61–(−1.65) | Frontro-central | 330–534 | N250 to 2nd syllable in /ata/ |
| | 3 | <0.002 | 0.99 | 0.46–1.13 | Frontro-central | 540–956 | N250 to 2nd syllable in /atta/ |
| | 4 | <0.004 | −0.55 | −1.11–(−0.15) | Parieto-occipital | 528–868 | N250 to 2nd syllable in /atta/ |
| | 5 | <0.038 | −0.37 | −0.95–0.06 | Parieto-occipital | 224–374 | Larger N250 for /atta/ |

Note: Cohen's *d* and 95% confidence intervals were calculated for the channel and time window showing maximal differences in the cluster-based permutation statistic.

the better the reading score; and left fronto-central channels at 324–748 ms, the more positive the voltage the better the reading score. The difference wave for the long deviant /atta/ correlated significantly with the TOWRE sight word reading score, showing a variable topography for the maximal correlations depending on the latency: starting at the fronto-central channels at 464 ms changing to parieto-occipital channels at 800 ms and continuing until 998 ms, the more positive the voltage the better the reading score.

See Figures 6 and 7 for examples of the correlation coefficient topographies between the ERP measures and cognitive skill test scores.

## Discussion

We set out to examine whether exposure to one's native language would result in differential brain responses in school-age children, and whether these responses would be associated with reading skills as predicted by research on dyslexia and phonological processing. Finnish and US children differed in ERP amplitude for all stimulus types, with the Finnish sample having larger responses. After including age as a covariate in our model, however, no group differences were observed for the difference waves for the Finnish or English stimuli, indicating

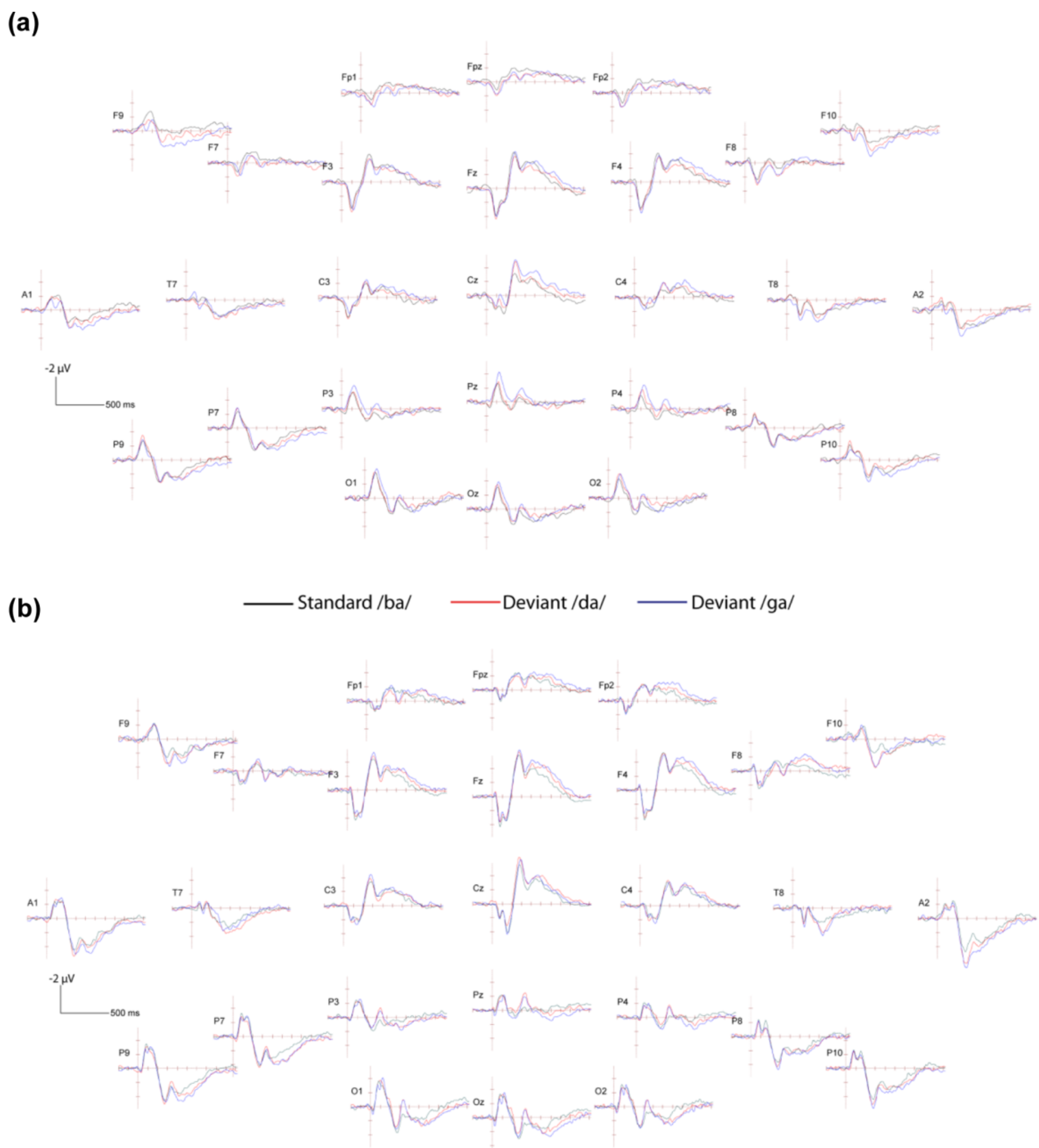


**Figure 2.** ERP waveforms in response to (a) the English stimuli in the US sample of children ($n = 54$); and (b) the Finnish sample of children ($n = 38$). Black line is the response to the standard /ba/ stimulus, blue line the deviant /da/ stimulus, and red line the deviant /ga/ stimulus. ERP montage has been transformed to the standard 10-10 electrode positions and re-referenced to the average reference. Horizontal line marks 100 ms and vertical line marks 1 µV, negative voltages are plotted upwards.

that long-term language exposure did not cause robust differences in ERP responses related to detection of speech sound changes. Critically, associations between the ERPs and reading measures in both the Finnish and the US children were found, mainly to the ERPs elicited by the speech sounds that were uncommon in the native language.

Exposure to native language was hypothesized to enhance the processing of the speech sounds common in each language. This was not found in the current study. There might be two possible explanations for the lack of clear group differences for change detection responses. First, the Finnish children had already studied English at school for two years and had most likely been exposed to

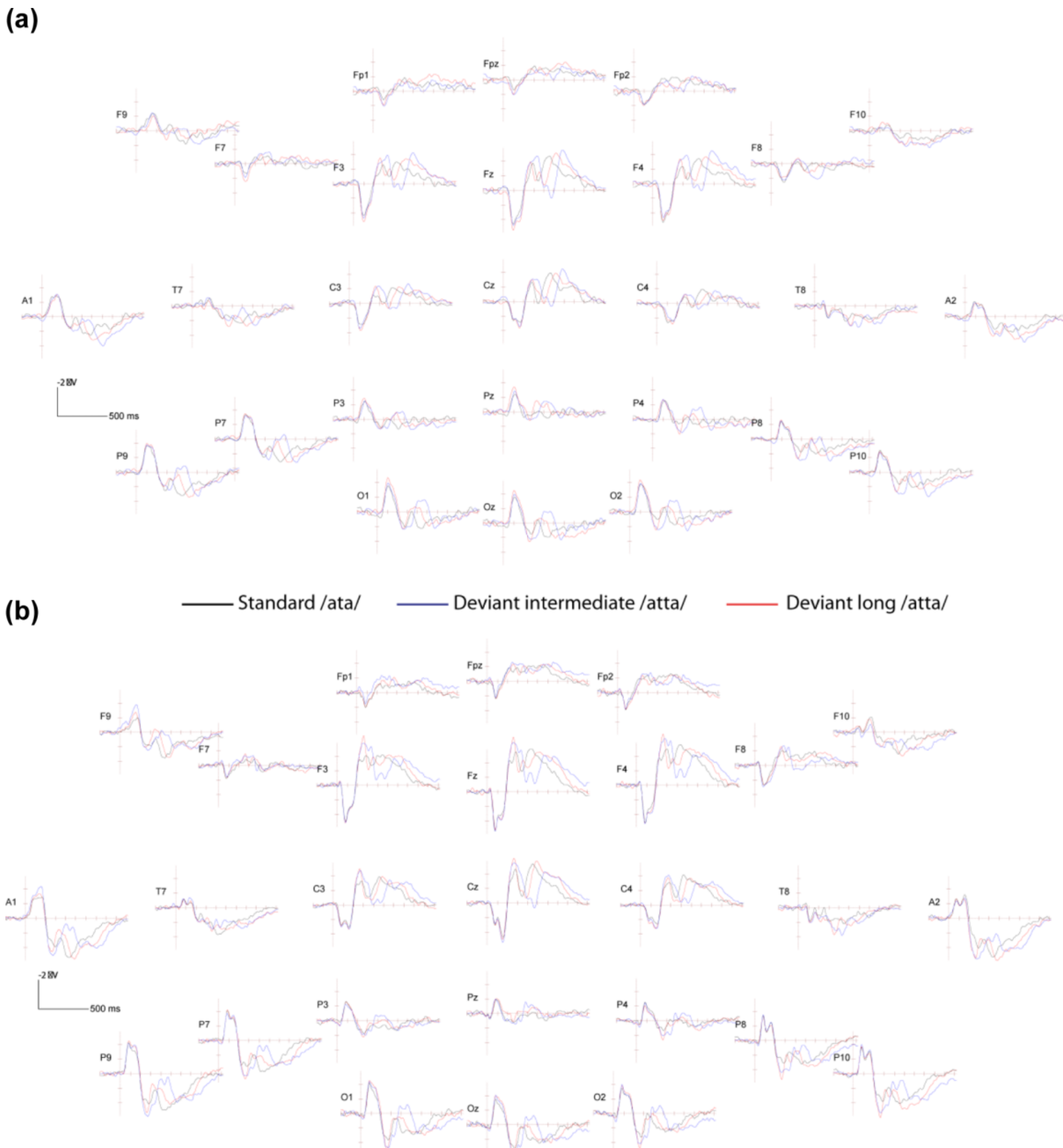


**Figure 3.** ERP waveforms in response to (a) the Finnish stimuli in the US sample of children ($n = 44$); and (b) the Finnish sample of children ($n = 38$). Black line is the response to the standard /ata/ stimulus, blue line to the deviant intermediate /atta/ stimulus, and red line the deviant long /atta/ stimulus. ERP montage has been transformed to the standard 10-10 electrode positions and re-referenced to the average reference. Horizontal line marks 100 ms and vertical line marks 1 μV, negative voltages are plotted upwards.

English in the environment. In addition, although the /ba/-/da/-/ga/ contrasts do not form semantically distinctive minimal word pairs in Finnish, all of these stop consonants are part of the Finnish phonology. Second, the Finnish speech sound contrast with a stop consonant length change (as in /ata/-/atta/) involves a shift in the major energy peak in the stimulus. This leads to large differences in afferent activation and obligatory responses between the stimuli, and therefore makes the examination of the difference wave between the short /ata/ and the long /atta/ sounds difficult to interpret. The heavy overlap with the obligatory responses could diminish the native language effect on the discriminatory ERP responses.

We also hypothesized that the ERP responses elicited by speech processing would be associated with phonological skills and reading skills based on theories on impaired reading skills (e.g., Elbro,

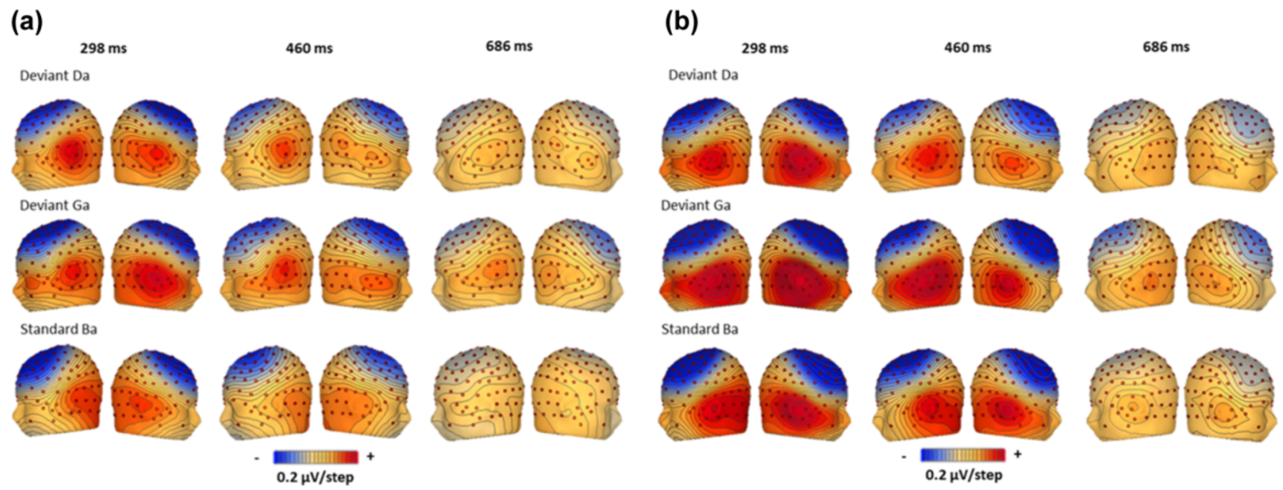


**Figure 4.** Topographic maps of the voltages in the English speech sound experiment. (a) US children, $n = 54$; (b) Finnish children, $n = 38$. Time points correspond to: 298 ms = MMN, 460 ms = N4, 686 ms = LDN. The contour lines represent 0.2 µV per line, red is positive voltages, blue is negative voltages.

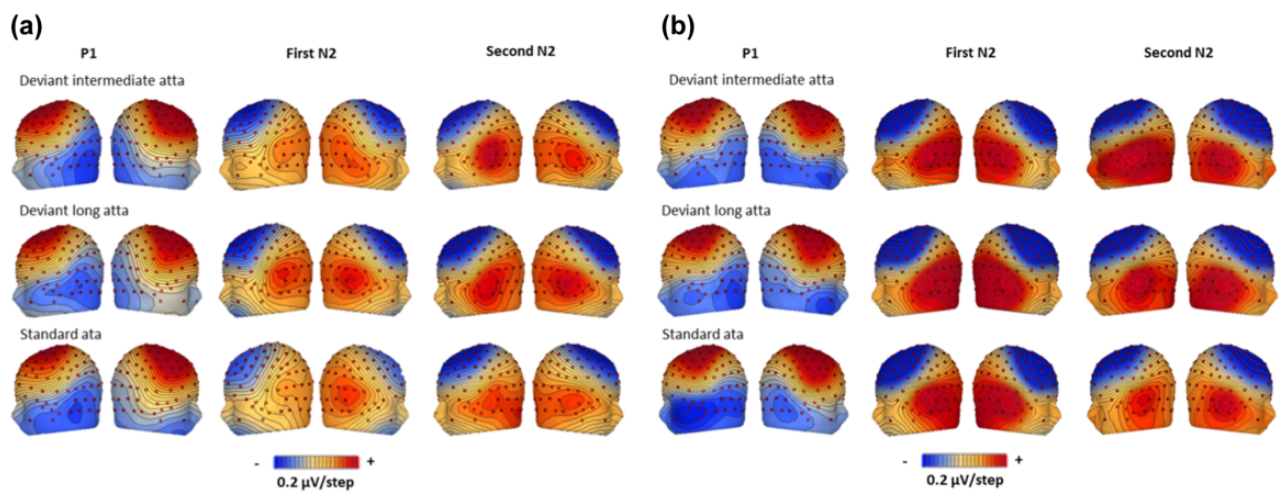


**Figure 5.** Topographic maps of the voltages in the Finnish speech sound experiment. (a) US children, $n = 44$; (b) Finnish children, $n = 38$. The components correspond to time points: P1 = 160 ms, first N2 = 288/274/328 ms, second N2 = 452/520/588 ms for standard /ata/, deviant intermediate /atta/, and deviant long /atta/, respectively. The contour lines represent 0.5 µV per line, red is positive voltages, blue is negative voltages.

1998; Elbro & Jensen, 2005; Espy et al., 2004; Mody et al., 1997). In the current study, the correlations between the ERP responses and cognitive test scores, mainly reading scores, were most robust in the US sample and for the ERP responses to the stimulus contrasts that are uncommon to English (phoneme length). The larger the responses to the uncommon speech stimulus the poorer were the reading skills. This would be in line with theories on longer-term phonological representations being important for reading acquisition and development (e.g., Vellutino, Fletcher, Snowling, & Scanlon, 2004) and with the effects of perceptual narrowing to native speech sounds during the first year of life (Kuhl et al., 2008; Tsao, Liu, & Kuhl, 2004). Less efficient perceptual narrowing to native speech sounds has been shown to be correlated with poorer later language skills (Kuhl et al., 2008; Tsao et al., 2004) and increased discrimination accuracy of non-native speech sound contrasts to be linked with reading problems (Serniclaes et al., 2004). Therefore, in the current study, it is likely that the larger ERP responses to the speech sound contrasts uncommon to English would reflect poorly developed longer-term phonological representations in children.

The Finnish sample also showed an association between the ERP measures and phonological measures for both types of speech stimuli (common and uncommon to Finnish). Interestingly the correlation between the cognitive measures and the ERP amplitudes to the phonemic length contrasts was opposite in the Finnish sample compared to the US sample. This suggests that better change detection of native language features (i.e., larger ERP amplitude) would be linked to better reading and reading-related cognitive skills, whereas better change detection of non-native language features would be linked to poorer reading skills. On the other hand, in the Finnish children the direction of the association for the voiced stop consonant contrasts that are uncommon in the Finnish language was opposite to that found for the US children: the Finnish children showed better cognitive performance with larger change detection responses for /ba/-/ga/ contrast. The time window of the correlation seemed to correspond to that of MMN (phoneme deletion) and LDN (reading speed), but the topography pattern of the correlations were not typical for the MMN response. For the Finnish children, at the

**Table 7.** Summary of the statistical differences between the ERP responses of the Finnish ($n = 38$) and the US children ($n = 54$ for /ba/-/da/-/ga/, $n = 44$ for /ata/-/atta/).

| | Cluster number | *p*-value | Cohen's *d* | 95% confidence interval | Topography | Time window (ms) | Event-related potential components |
|---|---|---|---|---|---|---|---|
| /ba/-/da/-/ga/ | | | | | | | |
| /da/ | 1 | <0.0001 | 1.19 | 0.77–1.64 | Temporo-occipital | 190–712 | N250 and N4 |
| | 2 | <0.002 | −0.87 | −1.17–(−0.40) | Fronto-central | 340–714 | N4/LDN |
| | 3 | <0.024 | −1.20 | −1.76–(−0.86) | Fronto-central | 194–330 | N250 |
| /ga/ | 1 | <0.002 | 1.26 | 1.02–2.06 | Parieto-occipital | 90–520 | P1 and N4 |
| | 2 | <0.017 | −1.03 | −2.00–(−0.82) | Fronto-central | 118–334 | N250 |
| | 3 | <0.019 | −0.92 | −1.32–(−0.49) | Fronto-central | 344–660 | N4/LDN |
| Pre-/da/ standard | 1 | <0.006 | −0.97 | −1.26–(−0.51) | Fronto-central | 178–694 | N250 and N4 |
| | 2 | <0.042 | 0.77 | 0.47–1.63 | Left temporal | 196–676 | N250 and N4 |
| Pre-/ga/ standard | 1 | <0.022 | −0.85 | −1.55–(−0.53) | Fronto-central | 180–406 | N250 |
| | 2 | <0.015 | 0.87 | 0.56–1.66 | Right temporal | 180–724 | N250 and N4 |
| Difference wave: /da/ | 1 | Not significant | – | – | | | |
| Difference wave: /ga/ | 1 | <0.043 | 0.60 | 0.18–1.00 | Parieto-occipital | 576–886 | LDN |
| /ata/-/atta/ | | | | | | | |
| Intermediate /atta/ | 1 | <0.0001 | −0.93 | −1.41–(−0.51) | Fronto-central | 154–998 | N250 for 1st syllable, P1, 250 for 2nd syllable |
| | 2 | <0.003 | 1.17 | 0.79–1.73 | Temporo-occipital | 184–998 | N250 for 1st syllable, P1, 250 for 2nd syllable |
| Long /atta/ | 1 | <0.005 | −1.02 | −1.14–(−0.46) | Fronto-central | 386–998 | P1, N250 for 2nd syllable |
| | 2 | <0.012 | −1.18 | −1.92–(−0.89) | Fronto-central | 84–366 | P1, N250 for 1st syllable |
| | 3 | <0.019 | 1.14 | 1.06–2.34 | Temporo-occipital | 180–364 | P1, N250 for 1st syllable |
| | 4 | <0.036 | 1.01 | 0.81–2.03 | Temporo-occipital | 638–998 | N250/LDN for 2nd syllable |
| Pre intermediate /atta/ standard | 1 | <0.0001 | −1.26 | −1.45–(−0.71) | Fronto-central | 182–892 | N250 for 1st syllable, P1, N250 for 2nd syllable |
| | 2 | <0.0001 | 1.06 | 0.61–1.47 | Temporo-occipital | 168–988 | N250 for 1st syllable, P1, N250 for 2nd syllable |
| Pre long /atta/ standard | 1 | <0.0001 | −1.32 | −1.70–(−0.86) | Fronto-central | 138–704 | N250 for 1st syllable, P1, N250 for 2nd syllable |

Note: Cohen's *d* and 95% confidence intervals were calculated for the channel and time window showing maximal differences in the cluster-based permutation statistic.

**Table 8.** Summary of the correlations between the ERP and cognitive skill measures in the Finnish sample ($n = 38$).

| ERP stimuli | Cognitive measure | Topography | Time window (ms) | Pearson correlation coefficient | 95% confidence interval | *p*-value |
|---|---|---|---|---|---|---|
| /Ga/ | Reading speed | Right fronto-central | 664–998 | −0.478 | −0.692–(−0.187) | $p < 0.004$ |
| /ga/ | Reading accuracy | Fronto-central | 2–250 | −0.617 | −0.782–(−0.370) | $p < 0.026$ |
| /ga/ | Phoneme deletion | Parieto-occipital | 200–370 | 0.625 | 0.381–0.787 | $p < 0.046$ |
| /da/ | Reading speed | Parieto-occipital | 480–722 | −0.487 | −0.698–(−0.199) | $p < 0.036$ |
| Intermediate /atta/ | Digit span | Fronto-central | 372–816 | −0.442 | −0.667–(−0.142) | $p < 0.049$ |
| Difference wave: /ga/ | Rapid automatic naming, time | Temporo-occipital | 434–662 | 0.598 | 0.345–0.771 | $p < 0.030$ |
| Difference wave: intermediate /atta/ | Phoneme deletion | Right parieto-occipital | 200–466 | −0.662 | −0.810–(−0.434) | $p < 0.019$ |
| Difference wave: intermediate atta | Non-word repetition | Central | 308–746 | −0.525 | −0.723–(−0.247) | $p < 0.010$ |
| Difference wave: long /atta/ | Reading accuracy | Fronto-central | 514–788 | −0.557 | −0.744–(−0.289) | $p < 0.020$ |

Note: correlation coefficient and 95% confidence intervals are calculated from the maximal channel at the time window indicated by the cluster-based permutation statistic.

age of 12 years there could already be many intervening variables, for example exposure to English language via TV, music, the internet, gaming, and school, affecting the ERP amplitudes that could obscure the effects of the English stimuli as uncommon sounds and therefore also affect the associations with cognitive skill measures. Also, the English stimulus contrasts used are a part of the Finnish phonology, though they occur relatively rarely, and therefore might not be processed as non-native. These could have had an effect on the different correlation pattern between the US and Finnish samples.

The orthographic differences between Finnish and English could also affect the strength of the associations between the ERP measures and reading skills. The reading processes in the transparent Finnish language could rely less on phonological processes than in the opaque English language (Ziegler et al., 2010). This is reflected, for example, in previous results showing a stronger

**Table 9.** Summary of the correlations between the ERP and cognitive skill measures in the US sample.

| Stimulus | Cognitive measure | Topography | Time window (ms) | Pearson correlation coefficient | 95% confidence interval | Cluster p-value |
|---|---|---|---|---|---|---|
| Intermediate /atta/ | GORT accuracy ($n = 34$) | Fronto-central | 156–998 | 0.683 | 0.449–0.830 | <0.008 |
| Intermediate /atta/ | GORT accuracy ($n = 34$) | Parieto-occipital | 412–816 | −0.557 | −0.753–(−0.270) | <0.019 |
| Intermediate /atta/ | GORT fluency ($n = 34$) | Fronto-central | 136–998 | 0.618 | 0.353–0.791 | <0.014 |
| Intermediate /atta/ | GORT fluency ($n = 34$) | Parieto-occipital | 412–744 | −0.538 | −0.741–(−0.245) | <0.045 |
| Intermediate /atta/ | GORT comprehension ($n = 34$) | Fronto-central | 136–998 | 0.613 | 0.347–0.788 | <0.017 |
| Intermediate /atta/ | GORT comprehension ($n = 34$) | Parieto-occipital | 412–744 | −0.532 | −0.737–(−0.236) | <0.047 |
| Long /atta/ | GORT accuracy ($n = 34$) | Fronto-central | 120–998 | 0.701 | 0.476–0.840 | <0.001 |
| Long /atta/ | GORT fluency ($n = 34$) | Fronto-central | 124–998 | 0.689 | 0.457–0.833 | <0.001 |
| Long /atta/ | GORT comprehension ($n = 34$) | Fronto-central | 158–998 | 0.728 | 0.517–0.855 | <0.001 |
| Long /atta/ | GORT comprehension ($n = 34$) | Right temporal | 408–910 | −0.604 | −0.782–(−0.334) | <0.048 |
| Intermediate /atta/ | TOWRE phonemic ($n = 35$) | Fronto-central | 186–826 | 0.628 | 0.373–0.795 | <0.013 |
| Long /atta/ | TOWRE phonemic ($n = 35$) | Fronto-central | 166–872 | 0.624 | 0.368–0.793 | <0.001 |
| Long /atta/ | TOWRE phonemic ($n = 35$) | Right parieto-occipital | 158–468 | −0.609 | −0.784–(−0.347) | <0.046 |
| Intermediate /atta/ | TOWRE sight word ($n = 35$) | Right parieto-occipital | 228–998 | −0.468 | −0.693–(−0.159) | <0.001 |
| Intermediate /atta/ | TOWRE sight word ($n = 35$) | Fronto-central | 182–990 | 0.569 | 0.291–0.759 | <0.002 |
| Long /atta/ | TOWRE sight word ($n = 35$) | Fronto-central | 70–430 | 0.636 | 0.385–0.800 | <0.005 |
| Long /atta/ | TOWRE sight word ($n = 35$) | Fronto-central | 448–902 | 0.464 | 0.155–0.690 | <0.010 |
| Long /atta | TOWRE sight word ($n = 35$) | Right parieto-occipital | 116–604 | −0.657 | −0.813–(−0.415) | <0.018 |
| Long /atta/ | TOWRE sight word ($n = 35$) | Right temporal | 564–996 | −0.546 | −0.744–(−0.260) | <0.036 |
| Difference wave: Intermediate /atta/ | GORT accuracy ($n = 34$) | Fronto-central | 242–998 | 0.726 | 0.515–0.855 | <0.003 |
| Difference wave: intermediate /atta/ | GORT accuracy ($n = 34$) | Parieto-occipital | 240–662 | −0.738 | −0.861–(−0.533) | <0.003 |
| Difference wave: intermediate /atta/ | GORT fluency ($n = 34$) | Fronto-central | 2–998 | 0.494 | 0.187–0.713 | <0.002 |
| Difference wave: intermediate /atta/ | GORT fluency ($n = 34$) | Parieto-occipital | 240–662 | −0.692 | −0.835–(−0.462) | <0.024 |
| Difference wave: intermediate /atta/ | GORT comprehension ($n = 34$) | Fronto-central | 2–998 | 0.697 | 0.470–0.838 | <0.002 |
| Difference wave: intermediate /atta/ | GORT comprehension ($n = 34$) | Parieto-occipital | 40–672 | −0.627 | −0.796–(−0.366) | <0.003 |
| Difference wave: long /atta/ | GORT accuracy ($n = 34$) | Fronto-central—parieto-occipital | 320–998 | 0.497 | 0.191–0.715 | <0.005 |
| Difference wave: long /atta/ | GORT accuracy ($n = 34$) | Frontal–fronto-central–occipital | 34–354 | 0.601 | 0.330–0.781 | <0.036 |
| Difference wave: long /atta/ | GORT fluency ($n = 34$) | Fronto-central | 314–998 | 0.533 | 0.237–0.738 | <0.005 |
| Difference wave: long /atta/ | GORT fluency ($n = 34$) | Parieto-occipital | 36–354 | 0.679 | 0.442–0.827 | <0.036 |
| Difference wave: long /atta/ | GORT comprehension ($n = 34$) | Fronto-central | 298–998 | 0.731 | 0.522–0.857 | <0.005 |
| Difference wave: long /atta/ | GORT comprehension ($n = 34$) | Parieto-occipital | 408–998 | −0.580 | −0.768–(−0.301) | <0.003 |
| Difference wave: intermediate /atta/ | TOWRE sight word ($n = 35$) | Parieto-occipital | 280–554 | −0.586 | −0.769–(−0.314) | <0.013 |
| Difference wave: intermediate /atta/ | TOWRE sight word ($n = 35$) | Parieto-occipital | 658–998 | −0.561 | −0.754–(−0.281) | <0.015 |
| Difference wave: intermediate /atta/ | TOWRE sight word ($n = 35$) | Left fronto-central | 324–748 | 0.484 | 0.180–0.704 | <0.030 |
| Difference wave: long /atta/ | TOWRE sight word ($n = 35$) | Fronto-central–parieto-occipital | 464–998 | 0.258 | −0.082–0.545 | <0.002 |

Note: correlation coefficient and 95% confidence intervals are calculated from the maximal channel at the time window indicated by the cluster-based permutation statistic.

association between phonological skills and reading in opaque orthographies than in transparent orthographies, particularly at later school age (e.g., Georgiou, Parrila, & Papadopoulos, 2008; Ziegler et al., 2010). It is possible that the ERP measures are more closely linked to phonological abilities, and therefore stronger associations between ERP measures and reading were found in the English speaking children.

Most previous studies that have found associations between ERP measures and reading or reading-related skills have examined individuals with dyslexia and/or using sounds from only one language (e.g., Hämäläinen et al., 2013; Lohvansuu et al., 2014; Schulte-Körne et al., 1998). Other studies examining typically developing children have also found associations between ERP responses to non-linguistic sounds measured in young children and reading skills at school age (Espy et al., 2004), and ERP responses to native speech sounds, phonological skills, and prereading skills in kindergarten children (Kuuluvainen et al., 2016). Also, associations between infant ERPs to non-speech sounds and later language

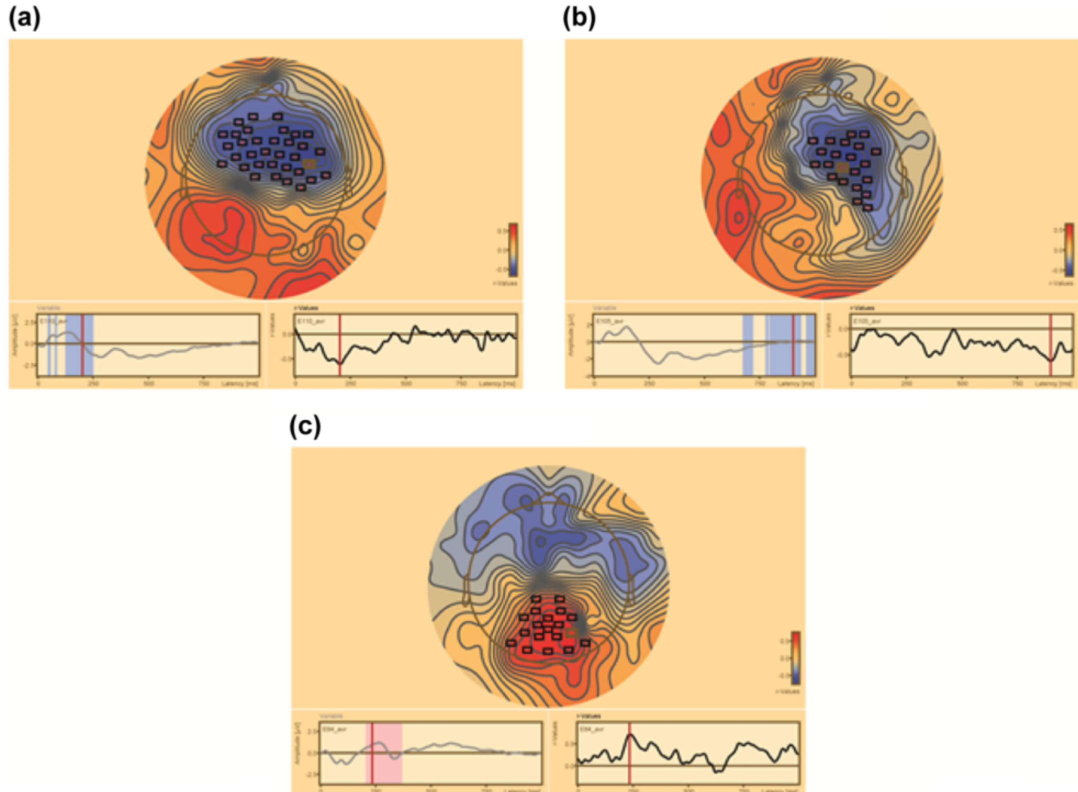

**Figure 6.** Topographic distribution of the correlation coefficient values between the deviant /ga/ stimulus and cognitive measures in the Finnish sample ($n = 38$). (a) Reading accuracy, 204 ms; (b) reading speed 898 ms; (c) phoneme deletion, 236 ms. Channel clusters with statistically significant values are indicated in the boxes in the lower part of each figure. In the topography plot, red color denotes positive coefficients and blue negative coefficients. Topography is plotted at the highest coefficient values (time point is indicated in parenthesis after the cognitive measure). Lower left: Time windows associated with the channel cluster are marked with red and blue on the ERP waveform from the channel with maximal correlation. Lower right: correlation coefficients for each time point at the maximal channel.

skills have been observed in both typically developing children and children at risk of language problems (Choudhury & Benasich, 2011). These studies suggest that the associations between ERP responses and reading-related skills are more readily observable for native speech sound contrasts earlier in development than at school age. This could be due to the ongoing changes of the phonological representations that can be larger at younger ages than in the older school-age children.

The majority of the significant correlations were found for the deviant sounds in wide time windows encompassing both the obligatory P1 and N250 responses as well as the change detection responses MMN and LDN. No associations were found, however, between the ERP responses to the standard sounds and cognitive skill measures. This suggests that general level encoding, not just change detection and sound discrimination related processes, of the rarely presented speech sounds is associated with reading skills. This was somewhat unexpected because previous studies suggest that, in particular, the MMN and LDN responses would be sensitive to exposure to different languages (e.g., Jakoby et al., 2011; Näätänen et al., 1997; Shestakova et al., 2003; Winkler et al., 1999). Most previous studies have not examined the associations between MMN, LDN, and reading ability, however, as continuous variables, or have examined only the effect of language exposure, and not reading skills, on these ERPs. Previous studies on ERP responses in individuals with dyslexia, on the other hand, have also shown associations between obligatory N250 responses and reading or pre-reading skills in children (Hämäläinen et al., 2013; Hämäläinen, Lohvansuu, Ervast, & Leppänen, 2015) and N1 response and reading in adults (Helenius et al., 2002).

In order to specifically examine the contribution of MMN and LDN in the correlations, the obligatory responses should be controlled for using reversed standard and deviant probabilities or a mixture of stimuli occurring with equal probabilities to the deviant stimuli in the oddball experiment (e.g., Jacobsen & Schröger, 2001; Lohvansuu et al., 2013; Schröger & Wolff, 1996). Due to time limitations and the endurance of the child participants such control experiments were not carried out in the current study.

An additional interesting finding was the larger responses of the Finnish children compared to the US children for all of the stimuli. This enhancement was particularly prominent at the N250 time window while it was not present at the P1 time window. This indicates that the cause of the larger responses is not related to technical issues in the EEG measurements but to differences in the two samples. The cause of the larger responses cannot, however, be solved based on the variables available from the current datasets.

There were two differences between the samples that could have affected the results. First, the Finnish children were older than the US children. Age covariate did not eliminate the group differences, however, and therefore it is unlikely to be the primary cause for the larger ERPs in the US children. Second, despite the same analysis pipeline for both of the datasets there were more trials left in the Finnish data than in the US data. Poorer signal-to-noise ratio

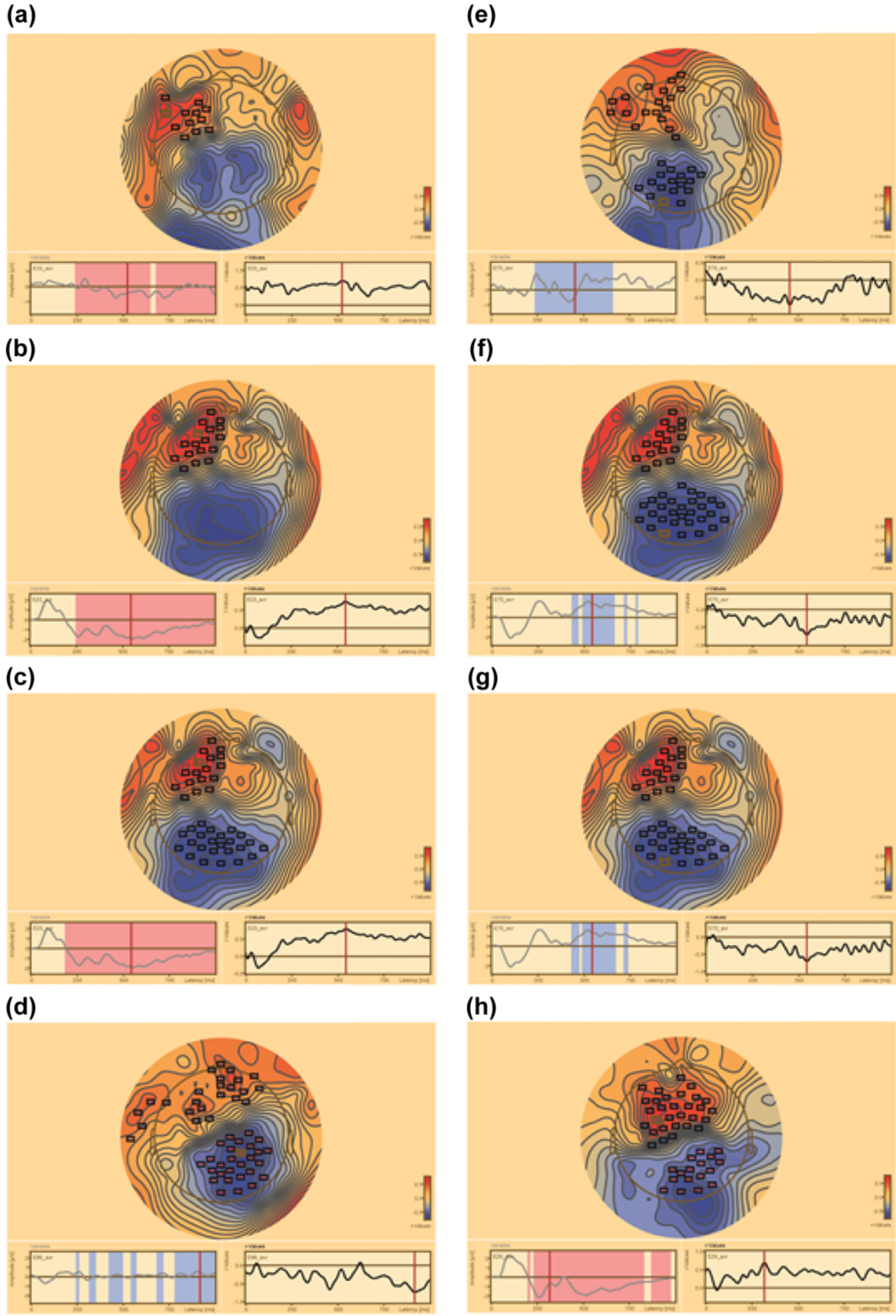


**Figure 7.** Topographic distribution of the correlation coefficient values between the intermediate deviant /atta/ stimulus and reading test scores, for TOWRE ($n = 35$), and for GORT ($n = 34$) in the US sample. (a) GORT accuracy, cluster 1; 454 ms; (b) GORT fluency, cluster 1; 544 ms; (c) GORT comprehension, cluster 1; 542 ms; (d) TOWRE sight word, cluster 1; 912 ms; (e) GORT accuracy, cluster 2; 454 ms; (f) GORT fluency, cluster 2; 542 ms; (g) GORT comprehension, cluster 2; 542 ms; (h) TOWRE sight word, cluster 2; 318 ms. Channel clusters with statistically significant values (first cluster, left hand column; second cluster, right hand column) are indicated in the boxes in the lower part of each figure. In the topography plot, red denotes positive coefficients and blue denotes negative coefficients. Topography is plotted at the highest coefficient values (time point indicated in parenthesis after the reading test name). Lower left: time windows associated with the channel cluster are marked with red and blue on the ERP waveform from the channel with maximal correlation. Lower right: correlation coefficients for each time point at the maximal channel.

usually leads to larger ERP responses, but here the Finnish children had larger responses and a slightly better signal-to-noise ratio based on the trial numbers, and therefore this is an unlikely explanation for the results.

Overall, our results show that processing of uncommon speech sound contrasts with respect to native language is associated with reading skills. This is in line with earlier studies on young children, showing that less efficient specialization to the native language can be associated with poorer language skills (Kuhl et al., 2008; Tsao et al., 2004) and with reading problems (Serniclaes et al., 2004). Our results also support the link between speech perception, phonological skills, and reading skills, particularly in opaque orthographies.

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