JYU DISSERTATIONS 672

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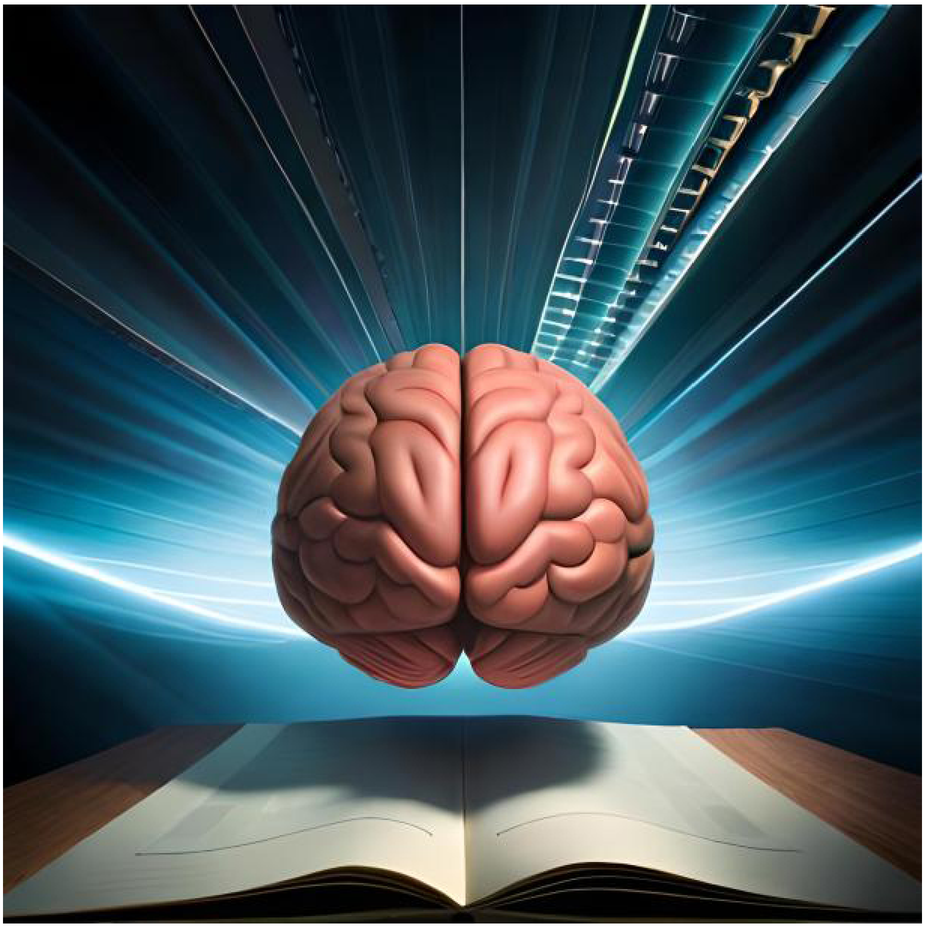
Neural Correlates of Speech and Print Processing in Children with or without Reading or Attention Deficits in Native and Foreign Languages



UNIVERSITY OF JYVÄSKYLÄ
FACULTY OF EDUCATION AND PSYCHOLOGY

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ABSTRACT

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Neural correlates of speech and print processing in children with or without reading or attention deficits in native and foreign languages
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Reading difficulties (RD) and attentional problems (AP) are the most frequently reported learning disorders in school-aged children. Although extensive research has been conducted on the subject, several questions about the neural processes in these learning difficulties remain to be answered. This dissertation investigates neural correlates of speech processing, visual reading processing, and auditory attentional processing in typical children and in children with reading or attentional difficulties. High-density event-related potentials (ERPs), fixation-related potentials (FRPs), and source reconstruction methods were used. In addition, behavioral measures were used to complement the brain data. In Study I, discriminatory brain processes, the mismatch response (MMR), and the late discriminative negativity (LDN), were investigated in native (Finnish) and foreign (English) language contexts in typical children (CTR, N=86) and in children with RD (N=26). Atypical discriminatory responses with enhanced brain activity to native and foreign speech items were found in the RD group. Furthermore, in both groups, brain responses were different for the native language stimuli than for foreign speech stimuli. Study II investigated speech-perception-related obligatory responses (P1-N250), and early visual response in reading (N170). The results showed associations between brain activity in both modalities and brain activity with reading scores. The brain responses to speech reflected in the source activity of the temporal sources were found to be associated with the brain activity to print in the temporo-occipital areas. Furthermore, the brain activity for speech and print showed correlations with the reading scores. Study III investigated the involuntary attention brain response (P3a) in speech processing investigated, both in typical children and in children with AP (N=17), using native and foreign language stimuli. The results showed a group difference in the P3a response, and significant correlations between the attention score and the brain activity in the native context in both groups. No significant correlations were found in the foreign language context. The neural network of attention was also investigated, using source analysis. Enhanced brain responses were found in the AP group, both at the scalp and source levels. Overall, this dissertation investigated the temporal brain dynamics of different processes and their relationships and showed how they varied between different populations of children with and without learning disorders.

Keywords: Reading difficulties, Attentional problems, Speech processing, Event-related potentials, Fixation-related potentials, Source analysis.

TIIVISTELMÄ (ABSTRACT IN FINNISH)

Azaiez Zammit Chatti, Najla
Aivoaktivaatio äidinkielisen ja vieraankielisen puheen ja painetun tekstin prosessointiin sellaisilla lapsilla, joilla on lukemisen tai tarkkaavaisuuden vaikeuksia
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Lukivaikeudet ja tarkkaavaisuushäiriöt ovat yleisimmin raportoituja oppimishäiriöitä kouluikäisillä lapsilla. Mittavasta tutkimuksesta huolimatta useisiin näiden oppimisvaikeuksien aivoperustaan liittyviin kysymyksiin ei olla vielä saatu vastausta. Tässä väitöskirjassa tutkitaan puheen prosessoinnin, visuaalisen lukemisen prosessoinnin ja auditiivisen tarkkaavaisuuden prosessoinnin neuraalisia korrelaatioita tyypillisesti kehittyneillä lapsilla ja lapsilla, joilla on lukemisen tai tarkkaavaisuusden vaikeuksia. Tutkimuksessa käytettiin aivovasteita (ERP), fiksaatiopotentiaaleja (FRP, silmänliikkeisiin aikasidottuja aivovasteita) ja aivoaktivaation lähdemallinnusmenetelmiä. Lisäksi tutkimuksessa käytettiin käyttäytymistason mittareita täydentämään aivojen tuottamaa tietoa. Tutkimuksessa I tutkittiin aivojen esitietoista erottelua mittaaviaprosesseja, poikkeavuusnegatiivisutta (MMR) ja myöhäistä erottelunegatiivisuutta (LDN) äidinkielen (suomi) ja vieraan kielen (englanti) puheärsykkeisiintyypillisesti kehittyneillä lapsilla (kontorlliryhmä, CTR, N=86) ja lapsilla, joilla oli lukemisen vaikeuksia (RD, N=26). Lukivaikeusryhmässä havaittiin epätyypilline erottelua heijastava aivovaste ollen suurentunut sekä äidinkielisiin että vieraskielisiin puheääniin. Lisäksi aivovasteet poikkesivat toisistaan äidinkielen ärsykkeisiin verrattuna vieraan puheen ärsykkeisiin kummassakin ryhmässä. Tutkimuksessa II tutkittiin puheen havaitsemiseen liittyviä aivojen perusvasteita ääniin (ns. P1-N250 komponenttia) ja niiden yhteyksiä lukemisen perusprosesseja heijastaviin visuaalisiin aivovasteisiin (ns. N170 komponenttiin) lähteen paikannusmallinnuksen avulla. Kuulotiedon ja puhetiedon käsittelyä heijastavien aivoaktivaatiolähteiden välillä havaittiin yhteyksiä. Aivojen ohimolohkon kuulo-ja puhealueiden aktivaatiolla oli selkeä yhteys sanantunnistusta heijastavaan aktivaatioon ohimo-ja takaraivolohkojen liittymäkohdan läheisyydessä olevalla ns. visuaalisella sanan tunnistamisalueella (VWFA). Lisäksi puheen prosessointia heijastava aktivaatio oli yhteydessälukutehtävässä suoriutumiseen. Tutkimuksessa III tutkittiin tahattoman huomion suuntaamista heijastavaa aivovastetta (ns. P3a) sekä äidin että vieraan kielen puheärsykkeisiintyypillisesti kehittyvillä lapsilla ja lapsilla, joilla oli tarkkaavaisuuden pulmai (N=17). Tulokset osoittivat, että P3a-vaste äidinkielisiin puheääniin erotteli ryhmiä ja oli yhteydessä tarkkaavaisuutta mittaaviin opettajan arviointeihin. Vieraan kielen prosessointia heijastavilla aivovasteilla ei havaittu olevan yhteyksiä tarkkaavaisuuteen. Tarkkaavaisuuden hermoverkkoa tutkittiin myös lähteenpaikannus analyysin avulla. Tarkkavaaisuuspulmaisten ryhmässä havaittiin suurentuneita aivovasteita sekä lähdeaktivaation että sensorien (päänpinnalta) mitattavien aivovasteiden tasolla. Kaiken kaikkiaan tämän väitöskirjan tulokset osoittivat eroja tyypillisesti kehittyvien lasten ja oppimisen vaikeuksista kärsivien lasten sekä eri kielisiä ärsykkeitä heijastavien aivovasteiden välillä.

Avainsanat: Aivojen ja aivojen aivotutkimus: Lukivaikeudet, tarkkaavaisuusongelmat, puheen prosessointi, tapahtumiin liittyvät potentiaalit, fiksaatioon liittyvät potentiaalit, lähdeanalyysi.

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LIST OF ORIGINAL PUBLICATIONS

I. Azaiez, N., Loberg, O., Lohvansuu, K., Ylinen, S., Hämäläinen, J. A., & Leppänen, P. H. (2022). Discriminatory brain processes of native and foreign language in children with and without reading difficulties. *Brain Sciences*, *13*(1), 76.

II. Azaiez, N., Loberg, O., Hamalainen, J., & Leppänen, P. H. (2022). Brain source correlates of speech perception and reading processes in children with and without reading difficulties. *Frontiers in Neuroscience*, 1100.

III. Azaiez, N., Loberg, O., Hämäläinen, J. A., & Leppänen, P. T. (2023). Auditory P3a response to native and foreign speech in children with or without attentional deficit. *Neuropsychologia*, 108506.

In this dissertation, all instructions and comments given by the supervisors and co-authors were considered. The author of the thesis contributed to the original publications as follows: the author collected the EEG and eye-tracking data with the help of research assistants, conducted the analyses, and wrote and published the three manuscripts.

FIGURES

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ORIGINAL PAPERS

1 INTRODUCTION

Learning difficulties are neurodevelopmental disorders that affect children at an early age and are commonly observed as learning problems in school-aged children. Neurodevelopmental disorders is a broad term that may be defined in two ways. The first definition refers to conditions that affect children's neurological development with a specific genetic or etiological factor that generates a specific impairment. In the second definition, this term refers to conditions that have multifactorial etiology and represents a large spectrum of impairments, defining a neurodevelopmental disorder. When these disorders affect learning processes, they are identified as learning difficulties or learning disorders; examples include developmental dyslexia as a reading disorder, or attention deficit hyperactivity disorder (AD/HD) as an attentional disorder (Bishop 2010).

Considerable attention has been devoted to better understanding these disorders because they affect children from birth or at a very early age and also because they have a long-term impact on an individual's life and need to be detected during the early phases (Catts et al., 2016; Fletcher et al., 2018; Jenkins et al., 2002) in order to obtain better results after adequate treatment/training. These impairments usually represent a burden, as individuals are incapable of achieving the normal levels of learning skills that society requires. Children who have learning disorders usually face issues in terms of managing their academic, social, emotional, and psychological situations (Fortes et al., 2016; Germanó et al., 2010). These neurodevelopmental learning disorders could be noticed by the child's parents during the first years of life or by teachers at pre-school or school when the child reaches school age. Reading difficulties (RD) and attentional problems (AP) are the most frequently reported learning disorders in school-aged children (Fortes et al., 2016). They are also frequently reported to co-occur within the same individuals (Boada et al., 2012; Germanó et al., 2010; Lonergan et al., 2019; Shaywitz et al., 2017).

The present dissertation investigated the temporal brain dynamics of the brain responses, reflecting speech processing in children with and without reading or attentional difficulties. Discriminatory brain processes, obligatory brain processes (that is, brain responses to auditory stimuli), attentional brain processes, and reading processes were investigated using native (Finnish) and/or foreign (English) speech stimuli.

1.1 Reading and attentional difficulties

During childhood, children learn a set of skills that demand complex cognitive functions, such as reading or maintaining attention to specific tasks. First, children are required to master the language that is spoken in their environment. This language is usually acquired in a natural and automatic way, where the child innately starts to learn the language spoken in his or her environment, started by passive exposure to his/her parents' speech since birth. Reading is not an innate skill and it depends heavily on good language processing skills. This is because both speech and print processing (in reading) rely primarily on the same neural representations established during language learning (Hornickel & Kraus, 2013; Wang et al., 2020). Therefore, reading disorders are often associated with language disorders (Adolf & Hogan, 2018; Pammer, 2013; Snowling et al., 2020). Despite the complexity of the reading process, most children successfully master the reading skill. However, a subgroup between an average of 5–10 percent, which can reach up to 20 percent, may show an impairment or a deficit in establishing a connection between spoken and written language and suffer from reading impairment or reading difficulty; this is also commonly labeled as dyslexia (Gialluisi et al., 2021; Noordenbos et al., 2012; Rice et al., 2023; Yang et al., 2022; Ylinen et al., 2019).

Dyslexia is a neurodevelopmental impairment that has been identified as the difficulty acquiring proper reading and spelling skills, despite the absence of any sensory impairment or other neurological disorders. It is frequently reported during childhood (Démonet et al., 2004; Noordenbos et al., 2012; Ramus, 2003; Vellutino et al., 2004; Ylinen et al., 2019), appearing despite an average or above-average level of general cognitive skills and normal spoken and vocabulary language skills (Peterson & Pennington, 2015).

The ability to maintain attention during a task is another important part of the learning process. It is a cognitive function that plays a key role in language processing and reading acquisition (Kurland, 2011; Myachikov & Posner, 2005; Valdois et al., 2019; Wei & Ma, 2017). The most studied attention disorder is known as AD/HD (attention deficit hyperactivity disorder), although milder forms of attentional impairment may also occur. AD/HD is defined in the presence of a set of symptoms that includes inattention and/or hyperactivity/impulsivity (Black & Grant, 2014). As mentioned above, reading and attentional disorders (different forms) are the most frequent learning disorders reported in school-age children with frequent comorbidity (Gnanavel et al., 2019; Langer et al., 2019), occurring in 25–48 percent of cases based on a recent clinical study (He et al., 2022). According to the current evidence in the literature, this common co-occurrence of the two disorders could be explained by common genetic origins between reading and attentional problems (Boada et al., 2012; Sánchez-Móran et al., 2018).

Another important learning skill is the acquisition of a second or foreign language. In the context of neurodevelopmental disorders, this additional requirement adds an extra layer of complexity to the learning process. It can become very challenging for some children to learn a foreign language when they have difficulty with their native language in the first place. Little evidence is currently available in the literature on the neural bases of foreign language learning in the context of learning disorders, where only suggestions were proposed based on classroom observations and behavioral evaluations (Sparks et al., 2005; Leons et al., 2009; Kałdonek-Crnjaković, 2018; Doyle, 2020). In the current study, foreign speech processing was approached to investigate the neural representations of a foreign language in contrast to native language in children with learning difficulties. Moreover, studying foreign processes makes it possible to investigate the brain representation of different speech items after different exposure periods (long-term exposure for (Finnish) native items versus short-term exposure for (English) foreign items).

1.2 Cortical language and speech perception network

The neurobiological bases of language have been widely investigated in brain research; they were a particular focus of investigations in reading research, as these cognitive skills were shown to be interconnected (Goswami 2016). Several brain regions in both hemispheres are included in language processing (Egorova et al., 2016) with complex networks and connections shown to be responsible for transmitting information from one brain region to the other (for details, see Fridriksson et al., 2016; Hodgson et al., 2021). For example, previous research has shown the presence of ventral and dorsal pathways (e.g., Hickok & Poeppel, 2007, the dual stream model of speech perception).

On the cortical level, the current language network includes activations in the frontal, temporal, parietal, and occipital lobes (Fedorenko et al., 2014; Friederici & Gierhan, 2013; Fridriksson et al., 2016). These areas include important gyri, such as the inferior temporal gyrus, the superior temporal gyrus, and the middle temporal gyrus. The network includes in the dominant left hemisphere for language, Broca's area (which comprises the pars opercularis (BA44) and the pars triangularis (BA45)). The network also includes the pars orbitalis (BA47), located anterior to Broca's area, and more ventrally and medially the frontal operculum, the premotor cortex (BA6), the supplementary motor area, Wernicke's area (BA42 and BA22), and in the temporal lobe the auditory cortices (including the primary auditory cortex, and Heschl's gyrus) (Ardila et al., 2015; Friederici 2017, pp. 6–7). See Figure 1 for a schematic illustration of this network. Other cortical structures were found to play an accessory role in language processes (Campbell & Tiler, 2018). These additional neuronal structures serve as relational systems between the language network and other cognitive and sensory functions; for example, for the integration of language via the sensory systems (auditory cortex and visual cortex) (Fedorenko & Thompson-Schill, 2014). Other systems, such as attention and memory processing systems, were also shown to be essential for successful language processing (Gilliam et al., 2009; Robinson, 2003). The language network can also be divided according to the functional processes. As Hodgson and colleagues (2021) showed, specific language networks are activated during semantic and phonological processes.

The present dissertation investigated the main cortical areas of language processing (frontal, temporal, and parietal areas) in the context of speech processing and in relation to reading (Study II) and attentional skills (Study III).

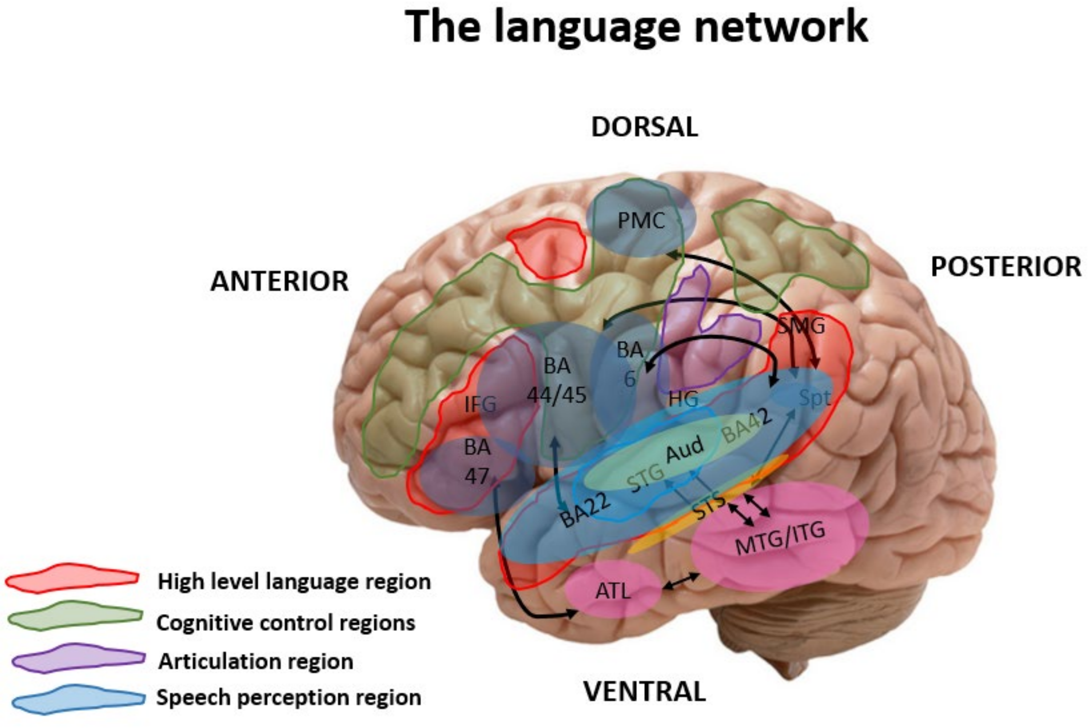

FIGURE 1 Schematic representation of the language network and its main brain areas (based on Hickok (2009) and Fedorenko & Thompson-Schill (2014)). Note: IFG: inferior frontal gyrus; PMC: Premotor cortex (dorsal); STG: superior temporal gyrus; Aud: auditory cortex; MTG/ITG: middle temporal gyrus/inferior temporal gyrus; SMG: supramarginal gyrus; STS: superior temporal sulcus; ATL: anterior temporal lobe; Spt: Sylvian parietal temporal region; HG: Hechler's gyrus. BA6: Premotor cortex (frontal); BA 44/45: Broca's area; BA22/42: Wernicke's areas; BA47: orbital area.

1.3 Speech perception

Speech perception is a fundamental natural and basic skill that usually develops continuously and automatically from gestation until linguistic maturity is reached to an adult-like level, typically during childhood (Hansson et al., 2020). This skill can become cognitively demanding in complex language processes that require higher-order cognition (such as semantic processing, reading processing, or during the process of learning a new language) or in the case of atypical development. Speech perception consists of several steps, from detecting and perceiving the auditory signal, categorizing and memorizing the speech sound, to extracting the meaning. Research has identified two different mechanisms – speech perception and word recognition – and studied them separately, although the two are fundamentally connected (Ghitza 2011; Jusczyk & Luce 2002; Werker & Yeung 2005). Speech perception was defined as the process that transforms speech input into a phonological representation, whereas word recognition was defined as the process of identifying the words in the stream of speech input (Samuel 2011).

Early research on speech perception focused on analyzing and mapping the acoustic signal properties to the linguistic elements (phonemes, phonetic cues, etc.) (e.g., Liberman, 1957; Peterson & Shoup, 1966). These early studies showed that mapping between the linguistic units and the speech signal is highly complex because of sequential or/and simultaneous activations of different brain areas (Kober et al., 2001). Articulations, for example, were shown to play an important role in speech perception, and these cannot be explained by a simple relationship (Lindblom, 1996). The brain mechanisms involved in these processes have been actively investigated, continuously offering an updated view of the language network (Fridriksson et al., 2016; Hodgson et al., 2021; Lipkin et al., 2022).

Speech perception is based on the mapping of basic auditory information into specific phonological units by identifying acoustic features and their boundaries (Goswami, 2008; Schulte-Körne & Bruder, 2010). Recognizing spoken words involves identifying segments and features from the acoustic-phonetic properties present in the speech signal (for reviews, see Quam & Creel, 2021; Weber & Scharenborg, 2012).

Previous studies have suggested an initial universal speech system that allows newborns and infants to distinguish all phonetic contrasts, including those that are not present in their linguistic environment (Gómez et al., 2014; Kuhl et al., 2014; Werker, 2018). However, this ability is limited by the so-called "critical window" or critical period (CP), where humans are born with a biological auditory perceptual system open for all possible sounds of any language, but only for a limited period (Kuhl et al., 2005; Werker & Hensch, 2015). During the first six months of life, perception skills gradually become narrowed by environmental factors and language exposure, and only specific speech sounds and language items that were present during the early developmental phase remain active (Kuhl et al., 1992). Less is known about speech development during childhood, although important events occur during early and middle childhood, such as the development of a larger vocabulary, and, somewhat later, learning new skills such as reading or learning a second/foreign language when the child starts attending school. Continuous exposure to the native language may have an important influence on the perceptual establishment. However, second-language learning research showed that the phonological system remains flexible to foreign sounds until approximately 5–7 years of age (Walley & Flege, 1999), and then decreases dramatically by the adult age (Newport, 1990). This flexibility differs between individuals depending on different factors such as motivation and individual learning strategies (Segalowitz, 1997; Schneiderman & Desmarais, 1988) and depends on the language's similarities and differences.

Learning to read may also impact phonological representations, as phonemes and graphemes show bidirectional relationships (Goswami, 2000). Several studies have shown a link between early auditory and speech perception abilities measured during the first year of life to the later emergence of reading difficulties (e.g., Guttorm et al., 2010; Leppänen et al., 2010; Lohvansuu et al., 2018; Molfese et al., 2000; Schaadt et al., 2015).

1.3.1 Event-related potentials in speech processing

Several speech perception studies have used the event-related potential (ERP) technique to investigate speech processing. ERP is an accurate measure of brain processes based on the temporal electrical activity measured at the scalp, reflecting the cortical brain dynamics of different processes. This technique is well known for its very high temporal accuracy and possibility to obtain a relatively good spatial localization, with an accuracy that varies from millimeters to centimeters, via the source reconstruction methods (for more details, see Unnvongse et al., 2023). The source reconstruction technique uses scalp electrical information and source reconstruction algorithms to compute the neural origin of the brain activity by solving the inverse problem (identifying the intracranial sources) with a proper head model (MRI-based) (Michel & Brunet 2019).

ERPs are identified as components with specific electrical properties (latency, polarity, electrical scalp distribution, and amplitude). They are believed to reflect specific processes, such as sound detection, feature extraction, or sound categorization (Hickok & Small, 2015, p. 89; Näätänen et al., 2000; Näätänen et al., 2014; Schulte-Körne & Bruder, 2010). As speech processing uses the sensory auditory pathways, it is evident that speech processes and auditory processes share common neural networks. In the context of reading and reading difficulties (or dyslexia), the neural correlates of speech perception have been investigated with different oddball paradigms by manipulating the stimulus type, such as vowels or more complex speech items such as consonant-vowel (CV) syllables, or words (Kujala & Näätänen, 2001; Leppänen et al., 2019; Lohvansuu et al., 2018; Pakarinen et al., 2013; Partanen et al., 2013; Winkler et al., 1999; Ylinen et al., 2019). The findings from adult and children data showed a mixture of results that, despite being sometimes contradictory, overall showed atypical brain responses in RD (for a review, see Schulte-Körne & Bruder, 2010).

The current dissertation focuses on investigating what type of auditory speech processes are affected in the context of reading difficulties. Investigating different auditory brain processes can reveal whether these differences occur only in discriminatory processes (reflected in MMN and LDN components) or whether the early basic speech sound processing (P1-N250) may also be affected. These ERP responses are commonly studied in auditory speech research and a solid literature background is available. These particular responses were chosen for investigation because they make it easier to compare the current results with previous findings in the literature, but also because they make it possible to reach conclusions by reporting any new findings.

1.3.2 Early obligatory brain responses – P1 and N250

The early P1 response (peaking around 100 ms in children and 50 ms in adults) belongs to the so-called P1-N1-P2 complex. It is an obligatory response identified as a physiological marker of sound detection (Maurer et al., 2002; Alain & Tremblay, 2007; Han et al., 2010; Durante et al., 2014: Hämäläinen et al., 2015) and phoneme identification (Frederici, 2017, p. 20). These brain responses are known to be sensitive to the variations in sound properties such as frequency, duration, or intensity (Alain & Tremblay, 2007; Wagner et al., 2017; Kalaiah, 2017). The responses have been shown to be sensitive to changes occurring in speech, such as consonant-vowel transitions (Doellinger et al., 2011; Manca & Grimaldi, 2016). In some studies, the P1, N1, and P2 were also labeled as the auditory change complex (ACC) (Braun et al., 2008; Han, 2010; Kim, 2015; Wagner et al., 2017). Those studies focused on the consonant-vowel transition in naturally produced syllables, reflecting the phonological speech contrast detection, and showed its efficacy in assessing auditory discrimination ability in children (Boothroyd, 2004). Previous literature has suggested differences between typical and dyslexic readers in the obligatory brain responses between 100 and 250 ms (Bonte & Blomert, 2004a; Hämäläinen et al., 2007; Lovio et al., 2010; Khan et al., 2011; Stefanic et al., 2011; Hämäläinen et al., 2013; Hämäläinen et al., 2015).

Another early obligatory ERP response that is known to occur in response to speech items is the N250, which occurs at the same latency as the mismatch (MMR) response. The N250 component in syllable processing and speech perception studies was proposed to be part of the basic auditory processing complex P1-N250 (Vidal et al., 2005; Hommet et al., 2009; Hämäläinen et al., 2018, Wass et al., 2019). The N250 is known to be associated with the sound representation formation of a repeated stimulus (Karhu et al., 1997), where more frequent repetition resulted in a stronger response.

1.3.3 Discriminatory brain responses – The MMR and LDN

The main targeted response when using the oddball paradigm is the mismatch component. It is commonly labeled as mismatch negativity (MMN) or mismatch response (MMR) and is known to reflect the involuntary discriminatory detection appearing as a neural response to pattern regularity violation (Garrido et al., 2009; Näätänen, 2000; Näätänen et al., 2007; Näätänen et al., 2014; Winkler, 2007). The MMN/R, which has been studied extensively in the context of auditory and speech processing, is expressed as a negative peak in the case of MMN (or less typically positive in the case of MMR for mismatch response), emerging between 100 ms and 250 ms visualized by subtracting the response to the deviant stimulus from the response of the frequently repeated standard stimulus.

The MMN/R component is largely investigated in the auditory domain (for a review, see Näätänen et al., 2007) and frequently used in language processing research (for a review, see Bishop, 2007). It also has been studied extensively in relation to reading and reading difficulties (Hämäläinen et al., 2015; Hämäläinen et al., 2018; Leppänen et al., 2019; Lohvansuu et al., 2014; Oliveira et al., 2013) and in foreign language learning and processing (Winkler et al., 1999; Ylinen et al., 2019; Zevin et al., 2010).

A second ERP response that is frequently reported in the oddball paradigm, and co-occurring with the MMN/R response, is the so-called late discriminative negativity or LDN (Čeponienė et al., 2004; Cheour et al., 2001; Halliday et al., 2014; Hämäläinen et al., 2015; Alonso-bua et al., 2006; Jakoby et al., 2011; Korpilahti et al., 2001; Leppänen et al., 2019). This late response usually emerges at a time frame between 300 ms and 600 ms (Korpilahti et al., 2001; Maurer et al., 2002) and has been reported to reflect higher auditory discriminative and complex cognitive processes (Cheour et al., 2001; Hämäläinen et al., 2015; Leppänen et al., 2019; Schulte-Körne & Bruder, 2010). This late response remains poorly understood compared to the MMN/R, although an increasing number of studies have started to give importance to it, where several questions remain to be answered (Cheng & Lee 2018; David et al., 2020; Hong et al., 2018; Leppänen et al., 2019; Virtala et al., 2022; Zeng et al., 2022).

1.3.4 Speech perception in foreign language

Earlier research suggested that native and foreign language processing share common neuronal correlates with a possible phonological transfer between the two languages. The cross-linguistic phonological transfer, mainly investigated in bilingualism and multilingualism studies, has been shown to occur from the first/native language (L1) to the second language (L2) (or even to L3) by transferring the phonological properties from one language (mainly L1) to the other(s). This transfer includes prosody, phonological awareness, and letter knowledge (Marx & Mehlhorn, 2010; Rasier & Hiligsmann, 2007; Simon, 2010; Sun-Alperin & Wang, 2011; Wawire & Kim, 2018). Thus, shared phonological processes may explain why the quality of native language processing may affect the foreign language skills (Cisero & Royer, 1995; Dehaene-Lambertz et al., 2000; Durgunoğlu et al., 1993; Łockiewicz et al., 2018). Although this relationship has been repeatedly reported in behavioral research, it remains ambiguous from a neurophysiological perspective.

Foreign language speech perception has only been investigated to a low degree in the context of reading difficulties. However, there is an idea of a general phonological processing deficit in the context of dyslexia. This idea has raised the assumption that both native and foreign languages may show similar processing difficulties in the context of reading problems because they share similar neural bases (Cisero & Royer, 1995; Helland & Kaasa, 2005; Hermans et al., 1998; McTaggart & Beatty, 2009; Nation, 2003). The brain mechanisms involved in this phonological transfer are still not fully understood and are poorly supported, where research lacks brain-based evidence (Goswami, 2000; Helland & Kaasa, 2005; Soroli et al., 2010).

1.4 Language and reading

Current linguistic theories based on network analysis suggest the presence of hierarchical processing of speech and language and have divided them into three main processes: phonological processing, semantic processing, and syntactic processing (Yuan et al., 2022). These processes are performed by different subnetworks that are functionally flexible, distinguishing two main streams: a dorsal stream, which is engaged mainly in phonological processing, and a ventral stream, which is engaged mainly in semantic processing (Hodgson et al., 2021; Wagley & Booth 2022). For example, the meta-analysis conducted by Hodgson and colleagues (2021) suggested that the left dorsal inferior frontal gyrus (dIFG) and left posterior superior temporal gyrus (pSTG) are the main parts of the network involved in phonological processing and that the left ventral inferior frontal gyrus (vIFG) and left posterior middle temporal gyrus (pMTG) are the main parts of the semantic processing network.

Reading is the ability to decode print into meaning by converting visual symbols into speech sounds and then into meaning. Unlike spoken language, reading is not a natural ability, but a skill acquired through an explicit learning process. This skill derives from the human capacity for language (Dehaene et al., 2015) and involves different processes. Reading acquisition usually occurs at an early age, where the child progressively learns how to decode a written text into a spoken form, and then into a meaning via an indirect strategy known as phonological decoding (Diáz et al., 2009; Horowitz-Kraus & Hutton, 2015; Li et al., 2021; Ziegler et al., 2020). This strategy relies heavily on the reader's auditory perception skills. By developing reading skills through time, a second strategy takes place, whereby a skilled reader can decode, in an automated manner, the written words directly into their meanings through fast visual word recognition (Ventura et al., 2020; Levy et al., 2010; Khateb et al., 2014). Both strategies are fully developed in the adult brain and can be simultaneously active in a reading process. The basic (first) strategy is mainly used by learners in the early learning phases (Goodman 2013), but is also utilized, even by skilled readers; for example, to decode unfamiliar or pseudo words (Elsherif et al., 2022).

1.4.1 The reading network

Reading requires the recruitment of different brain regions specialized in different processes, where it relies primarily on the language network (see Figure 1), but also requires the recruitment of the visual network (phonological processing, visual processing, linguistic information processing). In addition to these regions, coordination structures are needed for effective communication between the different brain regions (Broce et al., 2019). The reading network has been extensively investigated in the literature, showing that different lobes of the brain work together in a reading process via different pathways. This network mainly includes brain areas of the language and visual networks, both of which are essential for reading processes. Using functional MRI, researchers have identified what is called a "classical pattern of activation" in the typical reading brain, with three main regions being highly active in the decoding phase: the left IFG in the frontal lobe, the left temporoparietal cortex (TPC) and the left occipito-temporal region (OTC). These regions interact to link printed words to sound and meaning (Kearns et al., 2019); see Figure 2 for an illustration.

Neurophysiologically, a clear overlap is observed between the language network and the reading network. This anatomical overlap reflects the existence of shared functional mechanisms between the two systems (Broce et al., 2019; Rueckl et al., 2015). Glezer and colleagues (2015) investigated the phonological and orthographic selectivity across the reading network using the fMRI rapid adaptation technique. The authors found a specific sensitivity of brain areas to specific stimuli (orthography versus phonology) in adults and showed that the TPC was exclusively sensitive to phonology (speech), whereas the OTC and the d IFC were exclusively sensitive to orthography (print).

The reading network in the context of foreign language learning has rarely been investigated. However, recent evidence from an adult study has shown that the network goes through a reorganization during the first three months of learning a new language and remains stable after the establishment of the new network (Kuper et al., 2021). In a longitudinal study using fMRI, Kuper and colleagues tracked functional changes in the reading network during the automatization process of reading in a foreign language. After the first month of instructed learning, the main language areas (the left inferior frontal gyrus, the left precentral gyrus, and the bilateral supplementary motor cortex) and cognitive areas (left inferior parietal lobe and bilateral anterior cingulate cortex) showed higher brain activations compared to the activation at the beginning of the learning process, both in semantic and lexical decision tasks. This activation remained stable in the following six months and in the follow-up period of three months. The authors found a continuous extension of the overlapping network between native and foreign languages over the Broca's area from the beginning until the end of the training.

Furthermore, the interaction between the two systems showed not only that language shapes the reading skill, but also that reading and literacy change the brain and the language network (Dehaene et al.,2010; Chyl et al., 2018). Together, all of this evidence suggests that foreign language learning, both foreign speech perception, but also foreign language reading, may affect native language processing.

Deficiencies or dysfunctions at different levels of these networks are possible, which may cause reading difficulties with different origins.

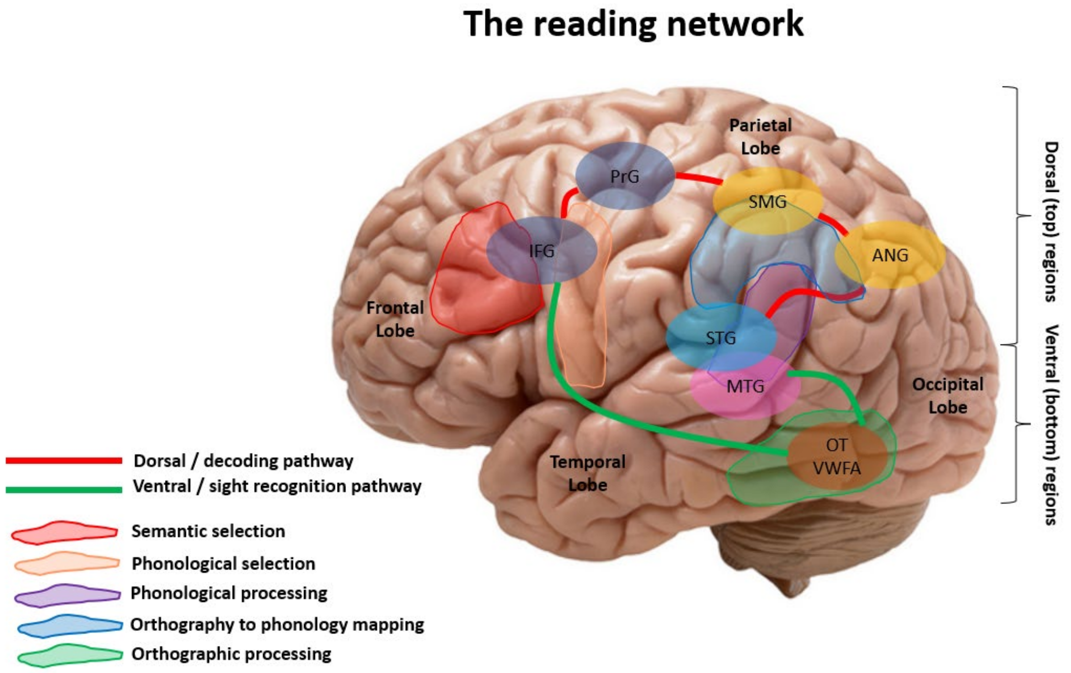

FIGURE 2 The reading network (based on Kearns et al., 2019; Broce et al., 2019)

1.4.2 Reading, reading difficulties, and speech perception

Problems in language processing, and specifically in speech perception, such as difficulties in phonemic awareness or altered ability to manipulate the elements of spoken language, are commonly reported in children who have reading difficulties (Breier et al., 2002). Previous studies have documented altered or disrupted networks in phonological and orthographic processing in the context of reading problems (Temple et al., 2000). Due to difficulties in building proper representation, which can be a consequence of the inability to store or retrieve speech sounds, phonological processing deficit was long considered a core deficit in dyslexia (Ramus, 2003; Gu & Bi, 2020). Dyslexics usually show difficulties in speech perception that affect their ability to build phonological representations leading to phonological processing impairment (Schulte-Körne et al., 1999; Noordenbos & Sernicleas, 2015). This theory assumes an association between the phonological awareness deficit and the deficit in acoustic speech structure processing (Schulte-Körne & Bruder, 2010).

Foreign language processing is more complex. Foreign phonemic sound perception is thought to rely on the identification of native representations (Best & McRoberts, 2003; Obleser et al., 2003; Werker & Tees, 1984), but these representations may also develop in an independent system when the foreign speech sounds do not exist in the native language (Winkler et al., 1999). The allophonic theory suggests that, in the case of dyslexia, the brain maintains its sensitivity to irrelevant speech contrasts. This over-sensitivity disturbs the development of neural networks responsible for the establishment of categorical speech perception (Hornickel & Kraus, 2013; Noordenbos et al., 2012; Serniclaes, 2018; Serniclaes & Seck, 2018; Soroli et al., 2010). This theory suggests that the over-sensitivity to irrelevant phonological contrasts may be the origin of the reading difficulty due to a failure to establish robust phonological representations, which may induce instability of the grapheme-phoneme connection. It may also explain the higher sensitivity observed in subjects with RD to the foreign speech sounds, as the phonological representations remain flexible in a similar neural state as during the critical period.

The current research has investigated the phonological representation of different linguistic items, both native and foreign, by studying different brain responses in typically developed children and in children with reading difficulties. Moreover, the high sensitivity was inspected in the RD group.

1.5 Dyslexia and reading disorders

Poor reading skills were shown to be linked to speech perception abilities in foreign languages and in second-language learning (Litt & Nation, 2014; Soroli et al., 2010; Ylinen et al., 2019). Language and reading processing difficulties in foreign language learning and how they are linked to native language in reading difficulties context remain topics of debate. Investigating brain responses and activity in response to foreign languages can reveal the possible defective mechanisms that may cause these learning weaknesses in this specific context (Łockiewicz et al., 2018; Soroli et al., 2010).

The following sub-sections present the main different theories that were proposed to explain the origin of reading disorders and how they are related to the current research work.

1.5.1 The phonological decoding deficit and the letter-speech sound mapping impairment in reading disorders

Various skills, such as reading speed, reading accuracy, or spelling, may affect word decoding. Deficits in these skills were frequently reported in reading difficulties (Hulme & Snowling, 2014; Siegel, 2006; Snowling 2001; Vellutino et al., 2004). The phonological theory proposed two possible main defective mechanisms to explain reading disorders: altered connections among phoneme-grapheme neural representations, or speech signal inadequate neural representations. According to this theory, weak or unstable connections between sounds and letters eventually lead to reading problems (Goswami, 2002; Noordenbos et al., 2012; Vogel et al., 2013). The deficit may occur when decoding single letters, letter clusters, or words in a reading process, which may lead to an alteration of the decoding process in the phoneme-grapheme correspondences (Goswami, 2000; Prestes, 2017). Studies have shown that reading processes and reading skills are strongly linked to speech processing (for reviews, see Duncan, 2018; Pennington & Bishop, 2009; Price, 2012; Zhang & McBride-Chang, 2010). Moreover, deficits in speech and phonological processing have been frequently reported in several studies investigating brain responses in children with reading difficulties (Castles & Freidmann, 2014; Catts et al., 2017; Ramus, 2014; Snowling, 1998).

The literature has strongly suggested that an impairment in letter-speech sound mapping (grapheme-phoneme connection establishment) is the origin of reading difficulties (Ehri, 2005; Fraga-González et al., 2015; Maurer et al., 2010; Žarić et al., 2014). Letter-sound mapping has been investigated in typical readers and in subjects with reading difficulties, and a relationship between the visual and auditory modalities has been proposed. Cross-modality (visual and auditory) network coactivation during the grapheme-phoneme association process has been described as the key factor for developing fluent reading, typically occurring in the early learning stages of reading (Ehri 2005; Fraga-González et al., 2021). This process was shown to rely on enhanced brain visual areas involved in print decoding when presented with letter-speech sound correspondences. In support of this theory, EEG studies showed that the MMN and LDN amplitudes, for example, were enhanced when speech sounds were presented simultaneously with letters in typical readers. Furthermore, this effect was shown to be absent in dyslexic readers, suggesting a weak binding between letter-speech neural representations (Froyen et al., 2009). Similar findings were reported by Blau and colleagues (2009), who showed reduced audiovisual integration in dyslexics when compared to good readers. The audiovisual integration deficit was linked to an activity reduction of the superior temporal cortex, reflecting a deficit in auditory speech processing.

In addition to the EEG/ERP evidence, several fMRI studies have shown the importance of the auditory cortex in the letter-speech sounds integration, both in adults and in children (Holloway et al., 2015; Van Atteveldt et al., 2004; Yang et al., 2020). Yang and colleagues (2020) studied via fMRI the audiovisual neural basis in letter-speech integration and showed a less-developed correspondence of orthographic and phonological information matching in dyslexic children than in controls. That study reported a difference in the left superior temporal gyrus (STG), corresponding with previous findings in literature, and a reduced functional connectivity of the left angular gyrus and the left lingual gyrus. These brain structures and areas are known to be involved in the integration processes (Richlan et al., 2020; Yang et al., 2020).

1.5.2 The print processing deficit in reading disorders

The links between visual and auditory information processes in the context of reading and speech processing remain unclear. Visual processing deficits have been frequently reported in the context of reading difficulties (Archer et al., 2020; Eden et al., 1996; Giofrè et al., 2019; Lobier et al., 2012; Lobier et al., 2014) at different levels, such as sensory, temporal, and attentional, but also in memory (Boets et al., 2008; Conlon et al., 2011; Facoetti et al., 2006; Farmer & Klein, 1995; Goswami, 2015; Snowlilng, 2001; Wright & Colon, 2009). The main brain area of the reading network, with a relationship to speech processing, was identified in the left occipitotemporal cortex, and located at the visual word form area (VWFA) (Brem et al., 2010). Brem and colleagues showed the critical role of the VWFA in sound-print mapping during the early phases of reading acquisition. They reported clear co-activation of the visual and auditory networks during the coding-decoding learning process. In ERP research, this brain area activation has been associated with the visual N170 component, an ERP response that is known to be sensitive to print (Cheviet et al., 2022; Mahé et al., 2013; Maurer et al.,2005; Maurer et al., 2010). The neural activation of the N170 response in reading was shown to differ between typical and dyslexic children (Pleisch et al., 2019). Visual-language network dysfunctions were proposed as a possible origin in the development of dysfluent reading (Pleisch et al., 2019).

1.5.3 N170 the ERP component in reading and the visual word form area (VWFA)

In reading research, the N170 is defined as an ERP component that is elicited in response to print and occurs between 150 and 200 ms, with a peak around 170 ms and with a temporo-occipital negative topography (Maurer et al., 2005; Rossion et al., 2002; Sanchez-Vincitore et al., 2018). It has been shown to be a reliable physiological marker of reading processes when left lateralized (Hasko et al., 2013; Lin et al., 2011; Lochy et al., 2016; Maurer et al., 2005; Maurer et al., 2008; Zhao et al., 2014) and an indicator of reading development in children (González et al., 2016). Atypical N170 was previously reported in the dyslexic group compared to controls (Fraga-González et al., 2014; Mahé et al., 2012, Mahé et al., 2013).

The ERP response becomes a strong indicator with which to study the visual cognitive processes and dynamics of reading when the brain responses are locked to the saccadic time of eye movements during the reading process, which is typically measured via a combined eye-tracking-EEG method. This method is known as fixation related potentials (FRPs), where average waveforms are extracted from the EEG, time-locked to the onset/offset of the eye fixations. Several brain responses of reading were investigated using this method, such as P1, N1/N170, N400, etc. (for a review, see Degno & Liversedge, 2020).

A good candidate response for this type of method is the N170, ERP marker of print processing, which has been frequently investigated in the context of reading and reading disorders (e.g., Dimigen et al., 2011; Dimigen et al., 2012; Dimigen & Ehinger, 2021; Kornrumfp et al., 2016; Loberg et al., 2019). A recent systematic review by Amora et al. (2022) summarized the last 30 years of research conducted on the N170. The authors summarized the findings on amplitude, latency, and lateralization in different age groups: young children, school-age children, and young adults. Good adult readers were consistently found to show responses with shorter latency and a larger N170 amplitude compared to adults with reading difficulties. The authors interpreted this enhanced negativity in good readers as reflecting an efficient visual orthographic processing. For the latency, similar processing time was found between good readers and dyslexic children; however, some findings showed longer latency in good young readers compared to those with reading difficulties. Lower N170 amplitude and longer latency in dyslexics were interpreted as consequences of failure in visual print identification and proposed to be the origin of the slower reading.

Moreover, atypical bilateral activation was also previously reported in adults with reading problems compared to a left-hemispheric activation typically found in control subjects (Waldie et al., 2017). However, for typical school-age children, a more right-lateralized N170, a reduced left lateralization or bilateral activation have been reported in literature (Sacchi & Laszlo 2016; Emmorey et al., 2017). This late finding was interpreted as possibly reflecting the immature brain response in young individuals; however, it is difficult to reach any conclusions on the N170 typical laterality at this developmental stage, as the findings were inconclusive and further evidence is needed.

Several studies of the N170 neural origin used fMRI combined with EEG or MEG (Brem et al., 2006; Maurer et al., 2005; Maurer et al., 2008; Mahé et al., 2013). The results showed that the main origin of the N170 is located in the visual word form area (VWFA). Moreover, there is strong evidence in the literature that the activity of the N170 component recorded on the scalp level has the VWFA as the main source generator identified via source localization, which confirms the fMRI results (Mahé et al., 2013; Maurer et al., 2005b; Proverbio et al., 2018).

The VWFA was identified as a specialized area in print processing (e.g., Brem et al., 2020; Centanni et al., 2017; Chyl et al., 2018; Maurer et al., 2011; Van der Mark et al., 2009) and part of the reading network (e.g., Nakamura et al., 2012). Previous MRI studies of dyslexics and CTR reported atypical activation of the VWFA in the RD group such as an under-activation of the left VWFA and an overactivation of the right hemisphere (e.g., Mahé et al., 2012).

1.6 Source localization of EEG activity

Advancements in EEG technology have upgraded this technique, making it an appropriate tool with which to explore both temporal and spatial characteristics of the brain electrical signal. Technological progress and the development of the source localization algorithms has made it possible to obtain accurate source estimations using high-density EEG combined with appropriate brain anatomical models.

The propagation of the electrical flow induced by the post-synaptic potential of neurons activated in synchrony creates a potential difference between electrodes placed on different scalp position according to Poisson's equation (Michel & Brunet, 2020). This propagation is affected by factors such as scalp and skull thickness, head shape, and tissue conductivity, inducing a heterogeneous and attenuated signal at the scalp level. The first step in source localization is the forward modeling, where the signal distortion by all these factors is estimated and modelled by computing the obtained potential at different electrodes when the signal is generated by a known source. The second step is the inverse problem, where the source of EEG potentials is applied via the head model to compute the source origin of the neuronal signal (Michel & Brunet, 2020).

In the current study, CLARA (Classical LORETA Analysis Recursively applied in BESA Research ®) algorithm was used as the source reconstruction method. It was shown to offer a better focal solution than other algorithms (Beniczky et al., 2016; Scherg et al., 2019). CLARA is an iterative application of LORETA in the brain volume, commonly applied in EEG/ERP source reconstruction studies (Beniczky et al., 2016).

1.7 The attention network in speech perception

Effective speech processing requires the contribution of a complex system comprising perceptual, linguistic, and attentional networks (Agmon et al., 2022). The functional neuroanatomy of the auditory attention system studies based on neuroimaging techniques revealed the involvement of a distributed fronto-temporal network (the ventral stream) and a fronto-parietal network (the dorsal stream) depending on the task requirements. The fronto-temporal stream was associated with the attention allocation driven by the stimulus, whereas the fronto-parietal stream was associated with the voluntary attention in tasks requiring selective or active attention (Tóth et al., 2019). The following model (illustrated in Figure 3) summarizes the attention network based on these different studies and including the frontal, fronto-cerebellar, and language networks.

In a previous study, the brain activation patterns of adult participants in selective attention versus distributed attention were compared in two different speech perception tasks (Agmon et al., 2022). Similar brain networks were found in both strategies (selective versus distributed) with an activation of the auditory cortices (bilateral STG/STS) and the activation of higher-level speech and attention processing regions (bilateral IFG, right MFG, and left IPS). The activation in these areas depended on the attention strategy required by the task, with a higher activation of the fronto-parietal area in the task requiring selective attention (Agmon et al., 2022).

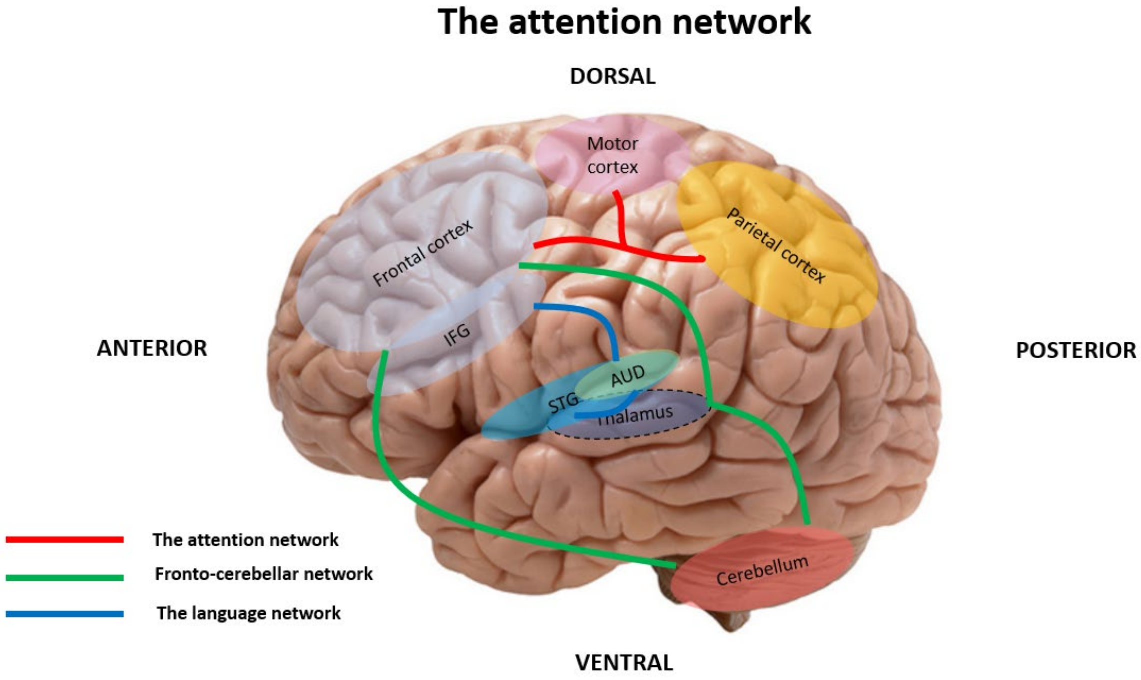

FIGURE 3 Schematic representation of the attention network. The main brain areas involved in speech processing include the basic attention network, the fronto-cebellar network, and language network involved in attentional processes (based on Purper-ouakil et al., 2011)

In a functional connectivity analysis, the functional brain activations involved in voluntary vs involuntary attention shifting were compared (Rossi et al., 2014). The study reported an increase of the fronto-parietal region activation in the voluntary attention context. An increase of the activations in the auditory cortices, in the bilateral anterior IFG, in the left posterior IFG, SMG, and in the posterior cingulate cortices were reported in the involuntary attention orienting context. A main contribution of the dorsal network in voluntary attention and a main contribution of the ventral (fronto-parietal) network in the novelty detection or involuntary attention shifting were concluded (Rossi et al., 2014).

1.7.1 Attentional deficit in speech processing

The auditory research has commonly reported central auditory processing impairment among individuals with AD/HD in the auditory research (Gomez & Condon 1999; Lanzetta-Valdo et al., 2016; Blomberg et al., 2019). Auditory or language/speech impairment co-occurrence with AD/HD is frequently reported in clinical evaluations (Cohen et al., 2000; Bruce et al., 2006; Wassenberg et al., 2010). Despite the frequent overlap between the disorders (Kim & Kaiser, 2000; Weiss et al., 2003; Mueller & Tomblin, 2012; Michalek et al., 2014; Hawkins et al., 2016; Söderlund & Jobs, 2016; Redmond, 2020), several questions related to speech processing and speech deficits in the context of attention disorder remain unanswered. Neuropsychological assessments were frequently used to investigate language processing in attention deficit disorder (e.g., Carte et al., 1996). The link between language and auditory/speech deficits and the attention deficit in AD/HD remains unclear, especially in developmental research (Weiss et al., 2003; Michalek et al., 2014; Jafari et al., 2015; Hawkins et al., 2016).

Blomberg et al. (2019) investigated cognitive processes in natural speech processing in AD/HD adolescents. Speech perception skills in AD/HD adolescents were reported to differ from the control group, where participants with attentional disorder required a higher signal-to-noise ratio in order to understand speech signals (Blomberg et al., 2019). As an interpretation of the high frequency of the attention and language disorders co-occurrence, a key role of the attention deficit mechanisms was proposed as a possible cause of the language and speech impairment in the attention deficit context (Cantwell & Baker, 1992). However, this finding remains speculative due to the absence of sufficient evidence with brain data.

Attention has been shown to play a facilitation or an inhibition role depending on the task directed attention (Asbjornsen & Hugdahl, 1995). Furthermore, scans of the brain activations in speech attention tasks in functional magnetic resonance imaging (fMRI) showed the modulatory role that attention plays in passive and active speech processing via directed attention (Hugdahl et al., 2003). A deficit in temporal neural encoding in speech and non-speech processing was reported in the subcortical brain activity of AD/HD children compared to those of typically developed children (Jafari et al., 2015).

1.7.2 The P3a ERP component in auditory and speech processing in attention deficit context

In the present study, the automatic attention shifting process was investigated in children with and without attentional problems, by analyzing the P3a response to different speech items. The P3a response is an ERP component that is known to reflect pre-attentive brain process (Light et al., 2007; Shestakova et al., 2003; Virtala et al., 2018). This ERP response is a positive component that peaks between 250 ms and 400 ms and is known to reflect involuntary attention shifting to novel items or deviant stimuli presented within a stream of repeated standard stimuli (Berti, 2016; Light et al., 2007). The P3a is sensitive to the physical differences between the standard and the deviant stimuli, and is typically expressed as larger positivity for the deviant items (Wass et al., 2019; Wronka et al., 2012). It has been investigated in the context of language/speech (Linnavalli et al., 2018; Shestakova et al., 2003) and reading and reading disorders (Hämäläinen et al., 2008; Lovio et al., 2012) within the MMN-P3a complex (Savill & Thierry, 2012; Virtala et al., 2021; Ylinen et al., 2016). Earlier studies reported enhanced P3a amplitude to foreign language stimuli in typical subjects when learning a foreign language (Jakoby et al., 2011; Shestakova et al., 2003). On the other hand, diminished P3a response was found in some children with reading difficulties (e.g., Leppänen et al., 2019). In young adults, the top-down attention was shown to modulate the neural response of the P3a response in typical subjects, although this modulation was weaker in AD/HD subjects (Kwasa et al., 2023).

1.8 Aims of the research

This thesis investigates the brain responses reflecting speech processing in the context of reading disorders and attention problems in 11–13-year-olds using electroencephalography (EEG) methods. This dissertation investigated different brain responses in reading and attentional processes and how they interact with the language network and reports new findings.

The main idea is to investigate how speech processes are linked to (other) higher cognitive skills such as reading and attentional processes, in the context of typical development, and how they may be affected in the context of learning disorders. In two of this dissertation's studies (Studies I and III), specific brain responses to speech sounds – presented in a two-sequence oddball paradigm – were investigated in typically developed children and in children with reading or attention disorders. Speech processing was examined in native and in foreign language contexts. The thesis also investigates the early visual reading process in the context of reading difficulty. Study II examines the neural correlates of speech and reading by combining different techniques: EEG, source reconstruction and eye-tracking (ET) and using two different tasks (a passive speech perception task and a reading task).

The aims and research questions of each study are presented below.

Study I:

Study I investigated brain responses to native and foreign speech sounds in typically developed children (CTR) and in children with reading difficulties (RD), tested in a two-sequence two-deviant auditory oddball paradigm. The paradigm was previously used by Ylinen et al. (2019), who focused on the MMN response. The current study included both discriminatory ERP responses, MMR and LDN, in the analysis. The discriminatory auditory processes (reflected in MMR and LDN components) were investigated to study how the neural dynamics differed between RD and CTR groups in native and foreign speech processing. The age group investigated in this study was two years older than the original study. This group was expected to show stronger neural representation of the foreign speech items compared to the younger group (the group investigated in the original study) due to the longer exposure to the foreign language. The relationship between speech perception in both languages and reading was also investigated. Previous literature supports the idea of weaker brain activations in foreign language processing due to a lower quality of the phonetic representations. Diminished brain responses were reported in dyslexics, both in native and foreign speech sound processing (Ylinen et al., 2019; Leppänen et al., 2019; Alonsó-Bua et al., 2006).

Both MMR and LDN responses are expected to show diminished ERP activations as a consequence of the weaker neural representations in the foreign language compared to native language processing for the CTR group and in both languages for the RD group compared to the CTR group (Schulte-Körne & Bruder, 2010; Neuhoff et al., 2012; Hommet et al., 2009). However, as this is a replication of the original paradigm in Ylinen et al. (2019), similarities are expected with the previous results, even if they may seem contradictory to previous literature. The results of this study are also expected to show some developmental effects. Ylinen's study found no group differences between the CTR and RD groups in processing native words and foreign pseudowords. The authors reported a smaller MMN response only in familiar second-language words. A correlation between the amplitude of the MMR response for familiar foreign-language and the reading skills in native language was reported (Ylinen et al., 2019). The brain responses to different contrasts (containing vowel vs vowel, vowel vs diphthong, native vs foreign sounds) were investigated within the groups in order to better understand the phonological brain representation in the context of good and poor reading. The results were compared to previous findings in order to understand the origin of the group differences and the deficiencies in processing native and foreign language in reading difficulties.

Study II:

Study II investigated basic ERP responses to speech, the P1 and N250, and the visual FRP response during reading, the N170, and the association between these basic speech perception brain responses and the reading score in the same children. In school-aged children, who have an established reading network, speech processes remain associated with the basic processes of reading. The neural activity was investigated to determine how these brain responses may reflect the reading skills. A new approach was used to investigate this question of how the visual process of print and the auditory speech processes may be interlinked and linked to reading skills. This approach combines different methods: ERP, FRP, and CLARA source reconstruction.

Auditory and visual modalities were investigated using two paradigms: a speech perception paradigm and a sentence reading paradigm. The source reconstruction and correlation analyses were used to identify the link(s) between reading skills and auditory processes, reading skills and visual processes, and to investigate the neuronal activity of the two modalities. The speech (P1 and N250) responses (e.g., Bonte & Blomert, 2004a; Lohvansuu et al., 2018) and the visual N170 response are expected to correlate with reading skills (Mahé et al., 2013; Maurer et al., 2008; Fraga-Gonzalez et al., 2014). A relation between the speech processes P1 and N250, and the visual N170 (over the VWFA) are expected to correlate within the same subjects in the two tasks.

Study III:

Study III investigated ERP brain responses in typically developed children (CTR) and in children with attentional problems (AP) in response to speech sounds when processing native and foreign languages. The aim was to investigate the attentional mechanisms that interfere with speech processing in the context of attention deficit by studying the brain dynamics in native and foreign language processes. The main ERP component known to reflect attentional shifting processes is the P3a response (Gumenyuk et al., 2001; Polich & Criado, 2006; Stige et al., 2007; Yang et al., 2015). In addition to the ERP analysis and the statistical cluster-based permutation tests, the analysis comprised two other methods for investigating the relationship between speech perception and the attentional mechanisms. One method was a correlation analysis to investigate whether the behavioral evaluation of attention problems reflected the brain activity, and the other was a source reconstruction analysis to investigate the neural sources of the speech attentional processes in children with or without attentional deficit.

Differences in the brain responses of the P3a between AP and CTR groups are expected in the language processing. Foreign language processing was also investigated in these groups as an exploratory question since no clear evidence on the effect of attentional difficulties on the foreign language brain processes is available in the literature. Based on some previous observations in AD/HD studies with children, group differences are expected (Ferrari & Palladino 2007; Leons et al., 2009; Liontou 2019). The alteration of the attentional mechanisms in native language processing, as reflected in the P3a response, are also expected to be altered in the foreign language. The attention score, obtained by behavioral evaluation, was tested to determine whether it is a reliable marker of the attentional brain processing. A correlation analysis was conducted between the attention score (ATTEX) and the ERP (P3a) responses. As some previous reviews have concluded, altered attentional networks may be the origin of the difference in brain activity (Konrad & Eikhoff 2010; Cao et al., 2014). The P3a source reconstructions in both groups (CTR and AP groups) were compared to reveal the neural origins of these attentional processes and how they differed in the context of attention deficit.

Overall, the goals of this dissertation are to provide a coherent view of brain responses to speech processing of native and foreign language, and also to provide new evidence by delineating the spatial and temporal characteristics of the neural processes in two neurodevelopmental disorders, reading and attentional deficits, compared to typical development.

2 METHODS

2.1 Participants

The sample comprised 159 participants, who were invited to be part of the EEG recording and the behavioral assessments in the three studies included in this research (Studies I, II, and III). These children were selected from eight different schools around the city of Jyväskylä in central Finland. They initially participated in the eSeek project (Internet and learning difficulties: A multidisciplinary approach for understanding reading in the new media (eSeek), project number (274022)) (Kiili et al., 2018). The demographic details of the different groups investigated in each study are summarized in Table1.

All participants were school-aged children, native Finnish-speaking, with no history of neurological disorders or head injuries, and no hearing or vision problems, based on the parental reports. They were all studying English as a foreign language in school and exposed to the English language daily through TV channels or the Internet.

TABLE 1 Summary of the demographic information of the participants included in Studies I, II, and III.

Study	Groups	Number of participants	Gender	Age range (years)	Age average (years)
Study I	CTR	86	M=43; F=43	11.78–12.84	12.36
	RD	26	M=18; F=6	11.84–12.94	12.31
Study II	CTR	60	M=30; F=30	11.88–12.84	12.37
	RD	20	M=14; F=6	11.84–12.94	12.34
Study III	CTR	86	M=43; F=43	11.78–12.84	12.36
	AP	17	M=16; F=1	11.95–12.74	12.30

Note: M: male; F: female

The participants were classified based on a reading fluency score derived from three reading tasks (see detailed description below) and the Attention and Executive Function Rating Inventory (ATTEX in English, KESKY in Finnish), which evaluated their attentional problems. An additional requirement to be part of the study was a score above 15 points in the shortened Raven's progressive matrices test.

The studies in this thesis were conducted in compliance with the Declaration of Helsinki, and the study protocols were approved by the ethics committee of the University of Jyväskylä, Finland. All methods used were performed in accordance with university guidelines and regulations. The participants and their parents provided signed informed consent prior to the study.

2.2 Stimuli and tasks

2.2.1 Studies I and III

Studies I and III investigated the auditory responses obtained with a passive oddball paradigm divided into two blocks: a Finnish language block presented first, then an English language block. The total duration of this experiment was ~20 min. The stimuli (summarized in Table 2) were recorded by a bilingual male native speaker of Finnish and English languages. The stimuli were pronounced in a neutral way. The auditory recordings were checked for any bias in pronunciation by native Finnish and English speakers. Praat 5.1.45 was used to equalize and normalize in segmental durations, pitch contours, and amplitude envelopes the stimuli recordings (Boersma & Weenink, 2010). The recordings were then shortened and resynthesized using the overlap-add method (for a detailed description of stimuli preparation, see Ylinen et al., 2019).

2.2.1.1 Auditory stimuli

The stimuli consisted of Finnish and English consonant-vowel-vowel (CVV) syllables, as summarized in Table 2. The English items can be easily identified as a foreign language from the onset of the word, as the Finnish phonology does not include the sound /ʃ/ (Lennes et al., 2010). The foreign English stimuli were expected to differ due to their daily frequency use: "she" is well known and the most frequent of the stimuli, whereas "shoe" and "shy" are known but less frequent, according to the British national corpus (Leech et al., 2016). The Finnish items were chosen as the phonetic equivalents to the English items, not according to their frequency of use. For the Finnish stimuli, "sai" is the most frequent item "suu" is less frequent, and "sii" is the most infrequent, according to the Finnish language bank (Huovilainen, 2018). For details, see Ylinen et al. (2019). The CVV syllable type occurs at a rate of 12.7 percent in the Finnish language (for details, see Suomi et al., 2008, p. 65).

The stimuli were presented in a pseudorandomized order within each block, always presenting at least two standard stimuli (and maximum) between the two consecutive deviant stimuli. The inter-stimulus interval varied randomly between 850 ms and 1000 ms. The stimuli were presented via a loudspeaker located on the ceiling approximately 100 cm above the participants' ear positions, and were presented at approximately 65 dB(A). The volume level of each stimulus sound was tested with an audiometer before each recording. The sound level meter (Type 2235, Brüel & Kjaer system) was used on a pedestal device at the participant position (settings: sound incidence = frontal; time weighting = fast; ext filter = out; frequency weighting = A; range = 40–110 dB; display = max).

TABLE 2 Summary of the auditory stimuli presented in the oddball paradigm.

Stimulus		Duration (ms)	Stimulus type	Word/Pseudo word	Number of repetitions	Analyzed
Finnish Block						
Suu	[sʊ:]	401	Standard	Word (“mouth”)	800	200
Sai	[saɪ]		Deviant	Word(“got”)	100	100
Sii	[s̲i:]		Deviant	Pseudoword	100	100
English Block						
Shoe	[ʃʊ:]	401	Standard	Word	800	200
Shy	[ʃ̲aɪ]		Deviant	Word	100	100
She	[ʃ̲i:]		Deviant	Word	100	100

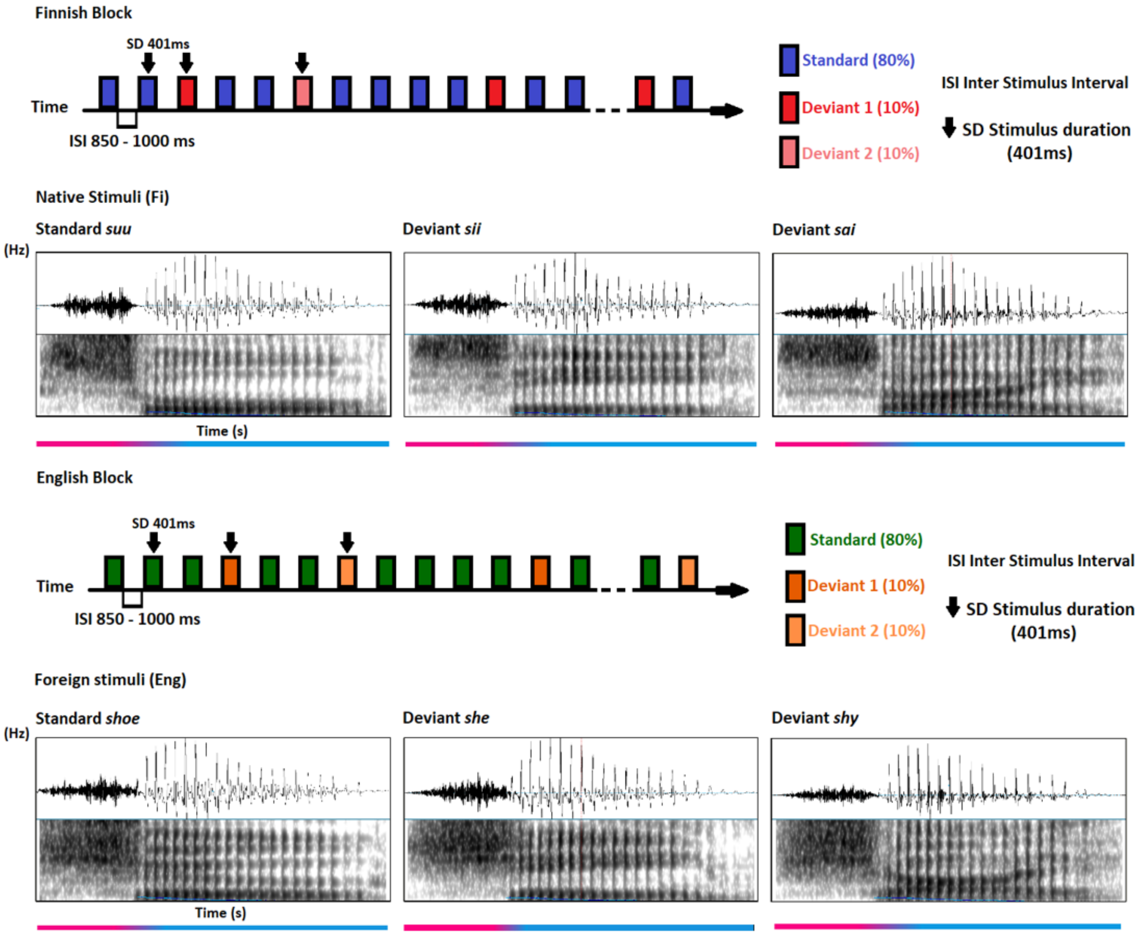

FIGURE 4 Schematic illustration of a two-deviant auditory oddball paradigm showing the two sequences: Finnish (top panel) and English (bottom panel). In each sequence, one standard and two deviants (D1 and D2) are presented in a randomized order. The spectrograms of the speech items are presented below each block. The spectrogram axes are time (in seconds (s)) and frequency (in Hertz (Hz)). The color bar below the Time axis shows the transition from the fricative (in pink) to the vowel(s) (in bleu).

2.2.2 Study II

2.2.2.1 Auditory stimuli and stimulus presentation

The auditory stimulus used for this study was extracted from the passive oddball paradigm described in Study I. The target stimulus for Study II is the standard stimulus. This stimulus was presented 800 times in the paradigm; however, only 200 trials, pre-deviant standard stimulus responses, were used in the analysis. The stimulus consisted of the Finnish monosyllabic word *suu*.

2.2.2.2 Sentence stimuli

In the free-reading task, the sentences were presented in 20-point Times New Roman font on a computer screen. A total of 200 sentences with five to nine words, (median length of six words), were used as the visual stimuli in this task. The FRP analysis comprised 912 words, with a length varying from five to 13 letters.

The materials for this paradigm were part of a previous study. For a detailed description, see Loberg et al. (2019). The following sentences are examples extracted from the reading paradigm.

Kuumaa kesäistä päivää helpottaa kostea

(A hot summer day eased by humidity)

Erittäin vakavan kolarin aiheutti hölmö

(A very serious crash was caused by a fool)

Suuren juhlan kunniaksi leivottiin makea

(To celebrate the big feast, a sweet was baked)

2.2.3 Selection criteria and tests

2.2.3.1 Reading score

Principal factor analysis (PAF) was computed to estimate the participants' reading skills, based on the following three tests: the Word Identification Test, a subtest of the standardized Finnish reading test ALLU (Lindeman, 1998); the Word Chain Test (Nevala & Lyytinen, 2000); and oral pseudoword text reading (Eklund et al., 2015). These tests were loaded to the fluency factor as follows: Word Identification Test (0.683), Word Chain Test (0.872), and oral pseudoword text reading (0.653).

The Word Identification Test included 80 pictures with four alternative words presented for each picture. The task was to identify the correct picture–word pairs. The score was computed based on the number of correctly identified pairs within two minutes.

The Word Chain Test consisted of 25 chains of words. Each chain comprised four words that were connected to each other, without any spaces. The task was to find the word boundaries and to identify the four words. The score was based on the number of correctly separated words within the 90 seconds.

The Oral Pseudoword Text-reading Test consisted of 38 pseudowords (a total of 277 letters) that were embedded in a short passage. The task was to read the passage aloud as quickly and as accurately as possible. The score was computed based on the number of correctly identified pseudowords divided by the total reading time, in seconds.

(For a detailed description of these tests, see Kanniainen et al., 2019).

The PAF factor McDonald's omega reliability coefficient was .79 (Kanniainen 2022).

2.2.3.2 Attention and Executive Function Questionnaire

The ATTEX questionnaire, filled out by teachers, was used to evaluate the attention problems. It includes 55 items designed to screen and measure students' degree of attentional and executive function problems in the school environment.

All participants who scored more than 30 points and had been identified with attention deficit (according to their teacher's rating) were identified as exhibiting attention problems (for details, see Klenberg et al., 2010). The McDonald's omega reliability coefficient in this test was .94 (Kanniainen, 2022).

2.2.3.3 Cognitive non-verbal assessment

This test is a modified version of version of Raven's progressive matrices test, including 30 items (Raven, 1998). The task was to identify the correct solution from six options for partially uncompleted pictures (six possibilities to complete the pattern). The time taken to give a correct answer was recorded, with a maximum of 15 min to accomplish the task. Participants who scored below the 10th percentile (a score equal to or below 15) in the nonverbal reasoning task testing were excluded. This test McDonald's omega reliability coefficient was .76 (Kanniainen, 2022).

2.2.4 Data acquisition

2.2.4.1 Auditory EEG recording and pre-processing

For Studies I, II, and III, the EEG recording was performed in a sound-attenuated and electrically shielded laboratory room located at the University of Jyväskylä. Participants were instructed to sit comfortably on a chair and to listen passively to the auditory stimuli, while watching a muted cartoon playing on a computer screen. They were instructed to minimize their movements to reduce the possible artifacts in the EEG recording. The recording session was continuously monitored by the experimenters using a video camera placed inside the recording room.

Data were recorded using 128 Ag-AgCl electrodes net (Electrical Geodesic, Inc.) with online reference at Cz. NeurOne ® software and a NeurOne ® amplifier (MegaElectronics Ltd, new designation: Bittium) were used for the recording. The online sampling was set at 1,000 Hz. The high pass filter was set at 0.16 Hz, and the low pass filter was set at 250 Hz during the recording. Impedances were kept under 50 kΩ, with a continuous online monitoring of the data quality. To ensure the best recording quality, breaks were taken between the blocks to adjust or correct the impedance, as the electrodes may dry over time.

Offline data pre-processing and averaging was performed in Brain Electrical Source Analysis (BESA) Research 6.0® and BESA Research 6.1®. Bad channels were selected and discarded from the data (mean number of bad channels: 5.6; range: 1–13). Independent component analysis (Infomax applied on a 60 s segment of the EEG; Bell & Sejnowski, 1995) was conducted to correct the blinks from each participant's data. The epochs were set from −100 ms (pre-stimulus baseline) to 850 ms. Artifact detection was set to a maximum threshold of 175 µV for amplitude fluctuations within the total duration of the epoch. A high pass filter of 0.5 Hz, zero phase was set before the averaging. Interpolation was performed for all bad channels with noisy data using the spherical spline interpolation method (Ferree, 2006). The data were offline re-referenced to the average reference and averaged individually and separately for each stimulus type. Difference waveforms were calculated by subtracting the response to the standard stimulus prior to the deviant stimulus from the deviant response (that is, deviant response–standard response). The preprocessing analysis comprised all trials for the deviant stimuli and the trials before the standard stimulus.

2.2.4.2 Reading data measurements and preprocessing

For Study III, the eye-movement data acquisition for the reading task was performed with the Eyelink 1000 with 2000 Hz upgrade (SR research) version and applying a 1000 Hz sampling rate. The sentences were presented on a Dell Precision T5500 workstation with an Asus VG-236 monitor (1920 × 1080, 120 Hz, 52 × 29 cm). The synchrony between the beginning and the end of each trial was ensured with a mixture of transistor-to-transistor logic pulses (to EEG) and ethernet messages to eye tracking (ET). The reading task was divided into four blocks (228 sentences in each). The participants were instructed to read as quickly as possible and held their heads fixed on a chinrest during the measurements. A 13-point run of fixation dots calibration routine was performed before each block and before each trial. The calibration was redone every time the fixation diverged from the calibration by more than one degree. The experiment's trial did not start until the experimenter had manually approved the calibration. Once the task started, participants were able to press a button to move to the next trial (for details, see Loberg et al., 2019). Corrections and recalibrations were performed as many times as needed to maintain the quality of the EEG and the ET recordings throughout the experiment. Breaks were taken when necessary or upon the participant's request.

In both experiments, the participants were informed that they could terminate the experiment at any time in the case of discomfort.

EEGLAB (v14.1.2) with an EYE-EEG (0.85) add-on applied in MATLAB ® were used for the EEG-ET data co-registration. A high-pass filter at 0.5 Hz and a low-pass filter at 30 Hz were applied. The raw gaze position data and the EEG data were synchronized using shared messages in both data streams at the beginning and the end of each trial. All gaze positions outside the screen and all zero-gaze positions resulting from blinks and between trial gaps in the recordings were automatically discarded from the analysis. All fixations corresponding to all the words within the sentences, except for the last word, during a first-pass reading were used to compute the FRP estimates. The responses were locked to the first fixation of each word, mean word length of 8, and saccade amplitude of 1.8798. Before and after these values, a time window of 100 ms was set as bad data. A binocular median velocity algorithm for detecting fixations (and saccades) was applied to the remaining gaze positions.

2.2.5 Data analysis

2.2.5.1 Studies I, II, and III

2.2.5.1.1 Euclidean distance and center of gravity

The Euclidean distance (ED) and center of gravity (COG) were computed to measure the phonological distance between the different speech items (distance between the fricatives and vowels) in order to estimate the degree of differences or similarities between the speech items and to investigate whether this somehow affects the ERP responses.

Computation of the Euclidean distance (ED) is widely done in speech perception and language studies investigating phonological distancing. ED is defined as the scalar sum estimating the difference in phonological/acoustic features between two spoken vowels/items. ED is applied to a bidimensional acoustic space based on tongue position during speech production that correlates with its first (F1) and second (F2) formant frequencies in each item (Vakulenko, 2022). With the acoustic method, the formant frequencies (F1 and F2) were determined using Praat® software version 6.0.49, and the distance was computed using Excel® 2016 software version 16.0.6742.2048 by applying the following formula:

$$d(p,q) = \sqrt{\sum_{i=1}^{n} (q_i - p_i)^2}$$

Note: p,q: two distinct points in the Euclidian space; q_i ,p_i: Euclidian vectors; n: n-space

For fricative consonants, computing the center of gravity (COG) is the most used method. The COG is the phonetic cue in fricative perception consisting of the magnitude weighted average of frequencies present in the fricative spectrum. The COG allows us to distinguish the sibilant fricatives with different places of articulation (/s/ vs. /ʃ/) (Chodroff & Wilson, 2020). Importantly, the COG characteristics of a fricative change according to the preceding vowel (for example, the value for /s/ is lower before a rounded vowel, such as /u/, than it is before a non-rounded vowel, such as /i/) (Yu, 2019).

2.2.5.1.2 Statistical analyses

Each ERP epoch was divided into time windows that were defined based on the literature and a visual inspection of the grand average waveforms. In Study I, the windows were set from 150 to 300 ms for the MMN/R response and from 450 to 850 ms for the LDN response. In Study III, the window was set between 300 and 400 ms for the P3a response.

Statistical differences between the responses to the deviant and standard stimuli were estimated within each group, between the two groups, and between languages using BESA Statistics® 2.0, with the nonparametric cluster-based permutation tests on the four time windows computed separately (BESA®, Germany; for the principles of nonparametric cluster-based permutation tests in M/EEG data; see, e.g., Maris & Oostenveld, 2007). The number of permutations was set to 1000 for each contrast, and the channel neighboring distance was set to 4.5 cm (with 129 electrodes). False discovery rate (FDR) correction was applied across the permutation tests (Benjamini & Hochberg, 1995) to correct the p-value (FDR correction with p = 0.05) performed for the research question: for the within-CTR group comparisons, within-RD group comparisons, between-language comparisons (Finnish vs. English), and between-group comparisons (CTR vs. RD). The obtained channels and millisecond values of the clusters are viewed as rough estimates; they do not reflect the exact range where the processing differs between the stimuli. Thus, the usage of this method does not allow any conclusions to be made about the exact latency or localization of the difference observed between the groups or conditions (for more details about the interpretation of this method, see Sassenhagen & Draschkow, 2019).

The same settings were used for the Study III statistical analysis. The analysis was performed for the within-CTR group comparisons, within-AP group comparisons, between-language comparisons (Finnish vs. English), and between-group comparisons (CTR vs. AP).

2.2.5.1.3 ANOVA

A 2 [Finnish, English] × 2 [CTR, RD] mixed ANOVA was performed to investigate whether the CTR and RD groups process the Finnish and English stimuli differently in Study I. The interaction term in an ANOVA model was examined. For each ERP component (same time windows as described above), the mean voltage was calculated over the different time windows and over the selected electrodes located at the fronto-central area: E4, E5, E10, E11, E12, E16, E18, and E19 (for details of the electrode locations in the Geodesic Sensor Net - Technical manual 2007, p. 125). The ANOVA was performed for the different conditions depending on the function of the component: only on the standard for the obligatory components (for P1 and N250) and on the difference waves (deviant stimulus and standard stimulus) for the discriminative (MMR and LDN) and attentional components (P3a).

2.2.5.2 Study II

2.2.5.2.1 Deconvolution modeling of the FRPs

For estimating the FRPs in Study II, the UNFOLD toolbox (Ehinger & Dimigen, 2019) was used. The FRPs were calculated via a generalized linear model used for response estimation and the correction of overlaps between the responses with a generalized additive model for non-linear predictors (Loberg et al., 2019). The modeled response ranged from -700 ms to 500 ms from fixation onset. Only first pass fixations on the target words were included in the analysis.

2.2.5.2.2 Source reconstruction and spatial filtering

Source analyses were performed using BESA Research® 6.1 and 7.0 to identify the source location for the different components obtained in the speech processing and reading tasks. A distributed source model in the brain volume—classical LORETA analysis recursively applied (CLARA) restricted to the cortex—was used to estimate the neuronal source origin. For accurate forward head modeling, a FEM head model for 12-year-old MRI average provided in the BESA software was implemented in the analysis. In Study II, model solutions were created based on the ERP brain source reconstructions for the CTR+RD (or combined CTRD) group, and for each brain component. The grand average model of each component was then applied as a filter on the individual data to extract the individual source activity.

In Study II, source locations were calculated for P1, P1-2, N250, and N250-2 (for an illustration of the ERP auditory responses, see Figure 8). Model solutions were similarly computed for the reading data based on the N170 component FRP estimates for the whole group.

The source analysis was performed approximately 10 ms before the peak for all components. This time point was chosen after thorough visual inspection of the global field power (GFP), where the model showed the most adequate solution for the source activity (based on residual variance). This was performed manually and individually for each component. The final model only included the neural sources that were valid in the common group (CTRD). A regional dipole was seeded at the maxima for each CLARA source identified. The power sum of the three orthogonal orientations of the regional sources was extracted and used as spatial source filter applied on individual data. The application of the filter generated individual source waveforms for each participant. A mean scalar value for each subject was computed for the source activity measures of all time points within a time window between 20 or 30 ms around the peak, specified for each component. The time windows were fixed so that the peak was always located in the middle of the window. The descriptions of these time windows are detailed below.

2.2.5.2.3 Source activity and reading score correlations

In Study II, correlations between source activations in each modality, and the reading scores (PAF) were examined across the CTRD group using Pearson's correlation coefficients. For each source activity, the mean value was calculated around the peak using MATLAB R2019b (Mathworks ®), as described above. Four main components were found in the auditory ERP response: P1, a second P1 or P1-2, N250 and a second N250 or N250-2. The time windows used to calculate the mean values for the auditory data were as follows: 80–110 ms for P1, 150–180 ms for P1-2, 230–250 ms for N250, and 360–390 ms for N250-2. For the visual data, the time window used to calculate the mean value of the N170 component was 180–210 ms.

Pearson's correlation coefficients were calculated between the average source activity and the reading score of the participants using IBM SPSS statistics 26 (IBM Corp), version 26.0.0.1, and applying a false discovery rates (FDR) correction of q = 0.05 (Benjamini & Hochberg, 1995) for the brain-to-behavior correlations and the brain-to-brain correlations. Correlations between auditory and visual source activities were computed. A partial correlation (controlling for reading skills/ PAF) between the source activity in the reading and speech processes was also performed.

2.2.5.3 Study III

2.2.5.3.1 Brain response and attention score correlations

The correlations between the ATTEX score and the brain responses over the target time window were estimated using BESA Statistics 2.0. from the difference waves (deviant stimuli – standard stimuli) with channel neighboring distance set to 4.5 cm, α set at 0.05, and 1000 permutations for each computation. In a second step, MATLAB R2019b (Mathworks ®) and the IBM SPSS statistics version 26 software were used to determine the r-value of each significant correlation obtained in the BESA statistics. The average amplitude over a specific time window and specific electrodes based on the clusters found in the statistical analysis were computed with a MATLAB script. Pearson correlation results were reported in the results. A short summary description of the specific parameters used to compute the r-value is available within the results section.

2.2.5.3.2 Source analysis

For Study III, BESA research® 7.1 software was used with a distributed source model in the brain volume: classical LORETA analysis recursively applied or CLARA. This approach was performed to define the source origin related to the attentional processing of speech items on the grand average difference waves. The high cut-off filter was set at 20 Hz and the analysis was conducted over the same time window as used earlier for the correlation analysis (see description above). The window duration was set to the 150 ms showing the strongest correlation results and the most stable topographic maps in the correlation analysis. The CLARA solution was obtained with 1 percent regularization and 0.005 percent SDV cutoff, applying a 7 mm voxel size in the Talairach space and unweighted image. An age-appropriate MRI template (age 12 y 0mo) with a 3-D brain template model provided by the BESA® software was used to calculate the estimations of the cortical sources. The source reconstructions were performed in a comparative manner to investigate the possible differences in cortical brain activations between the AP and CTR groups over the statistically significant conditions only as defined in the statistical analysis.

3 RESULTS

3.1 Study I – Discriminatory brain responses to native and foreign language in children with or without reading difficulties

Within the *CTR* group analyses and in native language processing, the ERP results showed typical discriminatory responses. The MMR response in the time window [150–300 ms] was less pronounced for the *sai* deviant than for the *sii* deviant stimuli, with statistically significant cluster-based permutation analyses for both contrasts *sii-suu* and *sai-suu* ($p<0.001$, $p<0.001$ respectively). In the late time window [450–850 ms], the LDN response was statistically significant for both contrasts ($p<0.02$ and $p<0.001$ respectively). In the foreign language contrasts, the waveforms showed weaker MMR response with a diminished amplitude than that found in the native phonologically equivalent conditions. The polarity of MMR response showed a positivity or a tendency toward a positivity in the foreign language processing. The cluster-based permutation tests showed statistically significant difference between deviant and standard in the contrasts s*he-shoe* and *shy-shoe*, revealing an MMR response ($p<0.02$ and $p<0.001$, respectively). The results in the late time window were similar to those described in the native conditions with a typical LDN response. The deviant-standard difference was significant in both foreign contrasts ($p<0.005$ and $p<0.001$, respectively). The LDN was more pronounced for the second foreign contrast *shy-shoe* than for *she-shoe*.

Within *RD* group analyses and in native language processing, the ERP results showed similar patterns to those reported in the *CTR* group. Although the MMR difference for the *sai-suu* contrast was statistically significant ($p<0.001$), the MMR response to the *sii-suu* condition did not show a significant difference between the standard and the deviant stimuli, unlike in the *CTR* group. On the other hand, the LDN difference between deviant and standard stimuli did not reveal any statistical differences for the native contrasts in this group. The analysis of foreign stimuli in the *RD* group showed similar responses to those in the *CTR* group, but with enhanced amplitudes. The cluster-based permutation test in the MMR time window showed significant differences in both the *she-shoe* (p<0.005) and *shy-shoe* (p<0.001) contrasts. Again, the LDN was not significant for either foreign contrast in this group.

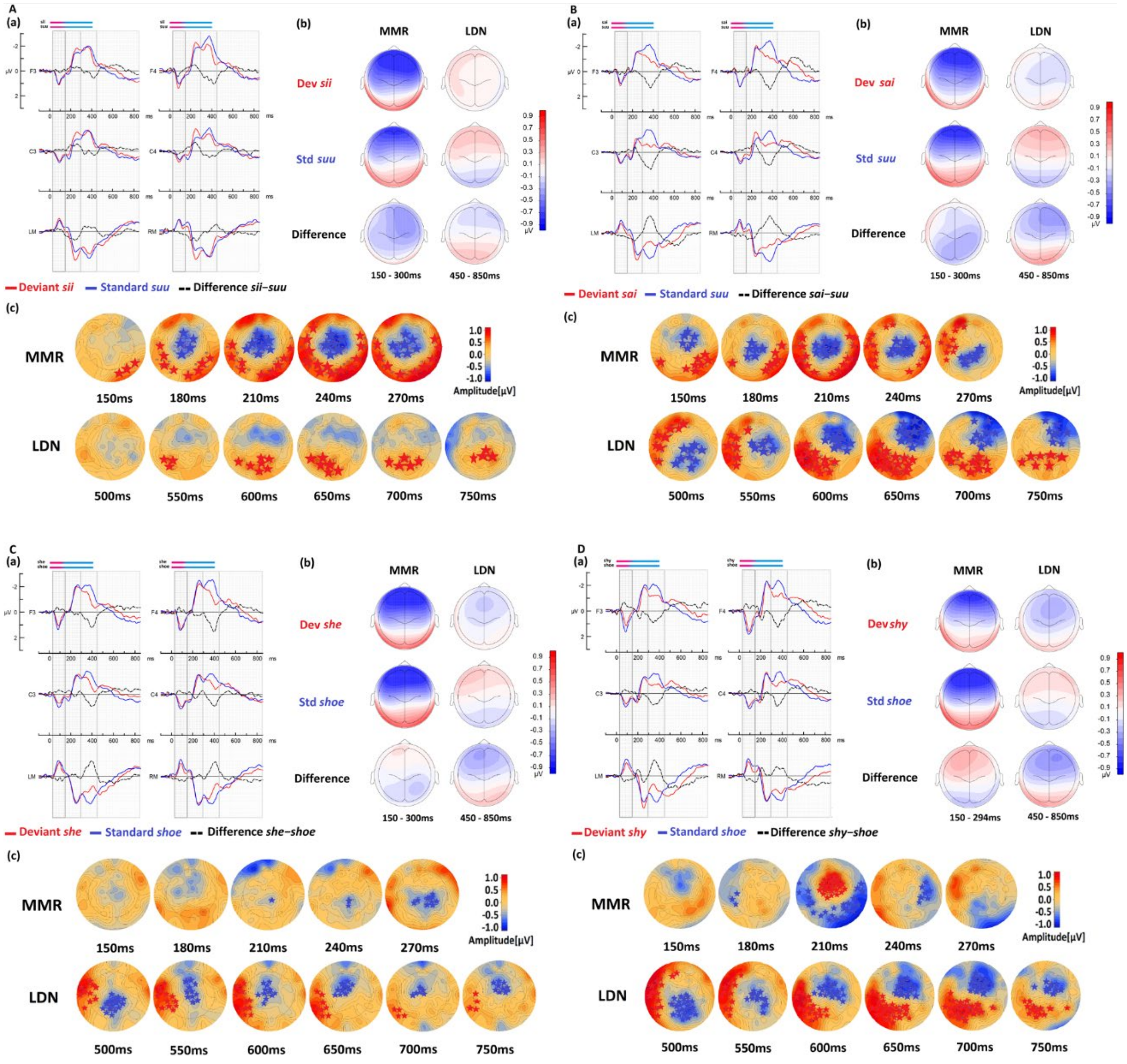

FIGURE 5 ERP waveforms and statistical results of the within-CTR group analysis. Grand average brain responses of the control (CTR) group to conditions (A) *sii-suu* and (B) *sai-suu* (C) *she-shoe* and (D) *shy-shoe*. Panel (a) illustrates the different waveforms: The deviant ERP waveforms are shown in red, the standard ERP waveforms in blue, and the difference ERP waveforms in black. The MMR and the LDN time windows are presented with black boxes. Panel (b) illustrates the average topographic maps for MMR and LDN time windows. Panel (c) illustrates the statistical cluster-based permutation test results (every 50 ms) between the responses to the deviant and standard stimuli indicated with stars (blue for negative and red for positive) significant clusters.

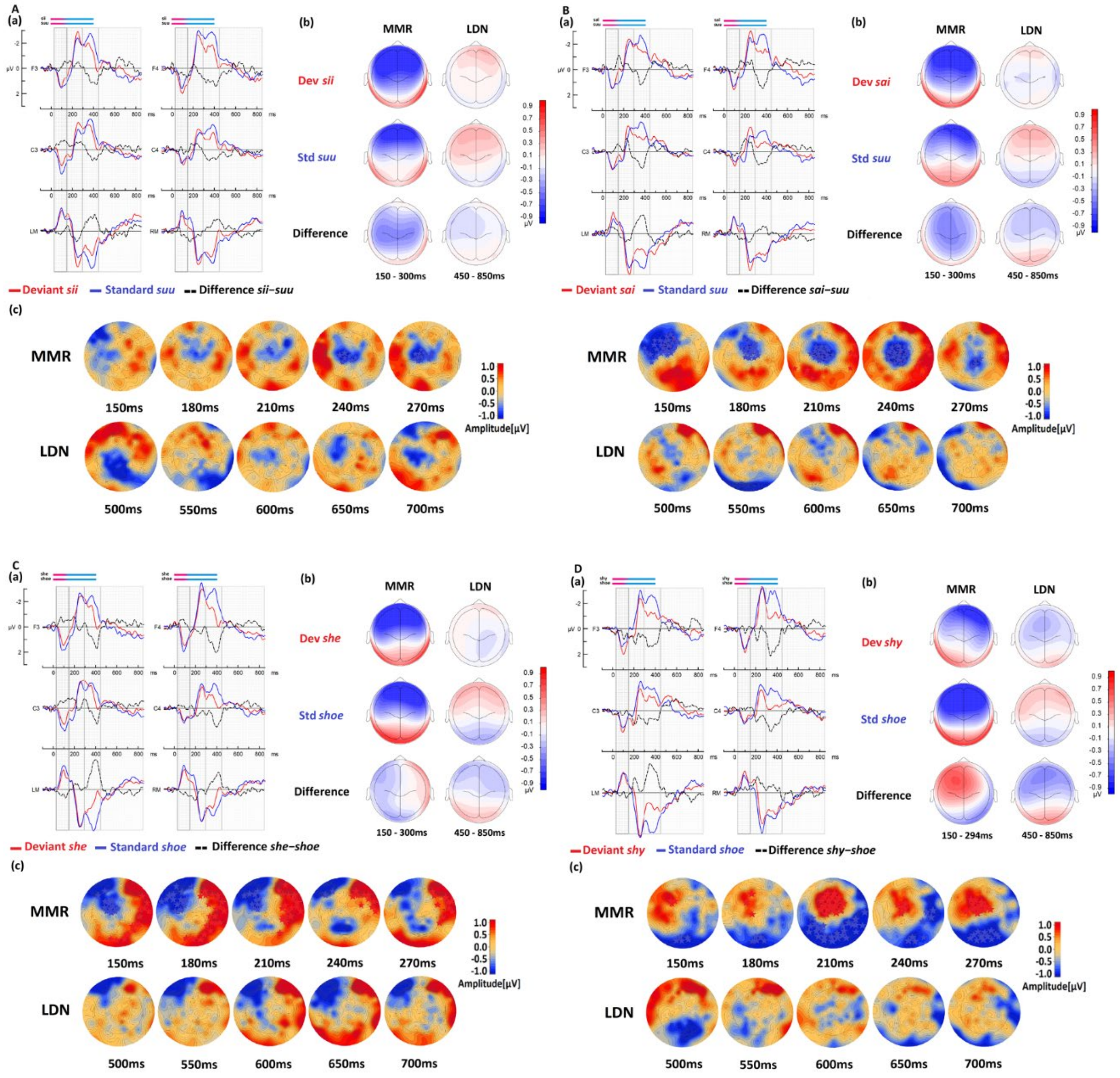

FIGURE 6 ERP waveforms and statistical results of the within-RD group analysis. Grand average brain responses of the reading difficulty (RD) group to conditions (A) *sii-suu* and (B) *sai-suu* (C) *she-shoe* and (D) *shy-hoe*. Panel (a) illustrates the different waveforms: The deviant ERP waveforms are shown in red, the standard ERP waveforms in blue, and the difference ERP waveforms in black. The MMR and the LDN time windows are presented with black boxes. Panel (b) illustrates the average topographic maps for MMR and LDN time windows. Panel (c) illustrates the statistical cluster-based permutation test results (every 50 ms) between the responses to the deviant and standard stimuli indicated with stars (blue for negative and red for positive) significant clusters.

In the language comparison and within the *CTR* group, the cluster-based permutation tests of the difference waves between the English and the Finnish contrasts (*she-shoe* vs *sii-suu* and *shy-shoe* vs *sai-suu),* showed a statistically significant enhancement in the MMR response (~150–300 ms), with a clear effect at the mastoids (p<0.001 and p<0.001, respectively). In the late time window (~450–850 ms), no statistical difference was found for the LDN response. A similar result was observed for the *RD* group with a statistically significant difference between native and foreign language in the MMR time window (p<0.005 and p<0.002, respectively). In the same contrast comparisons, the responses to the foreign language were larger than those to the native language, and no statistical difference was found in the LDN time window within both groups.

The group comparison *(CTR* vs. *RD)* of the difference waves (deviant–standard) within each contrast (*sii-suu*, *sai-suu*, *she-shoe*, and *shy-shoe*) did not show any significant group differences.

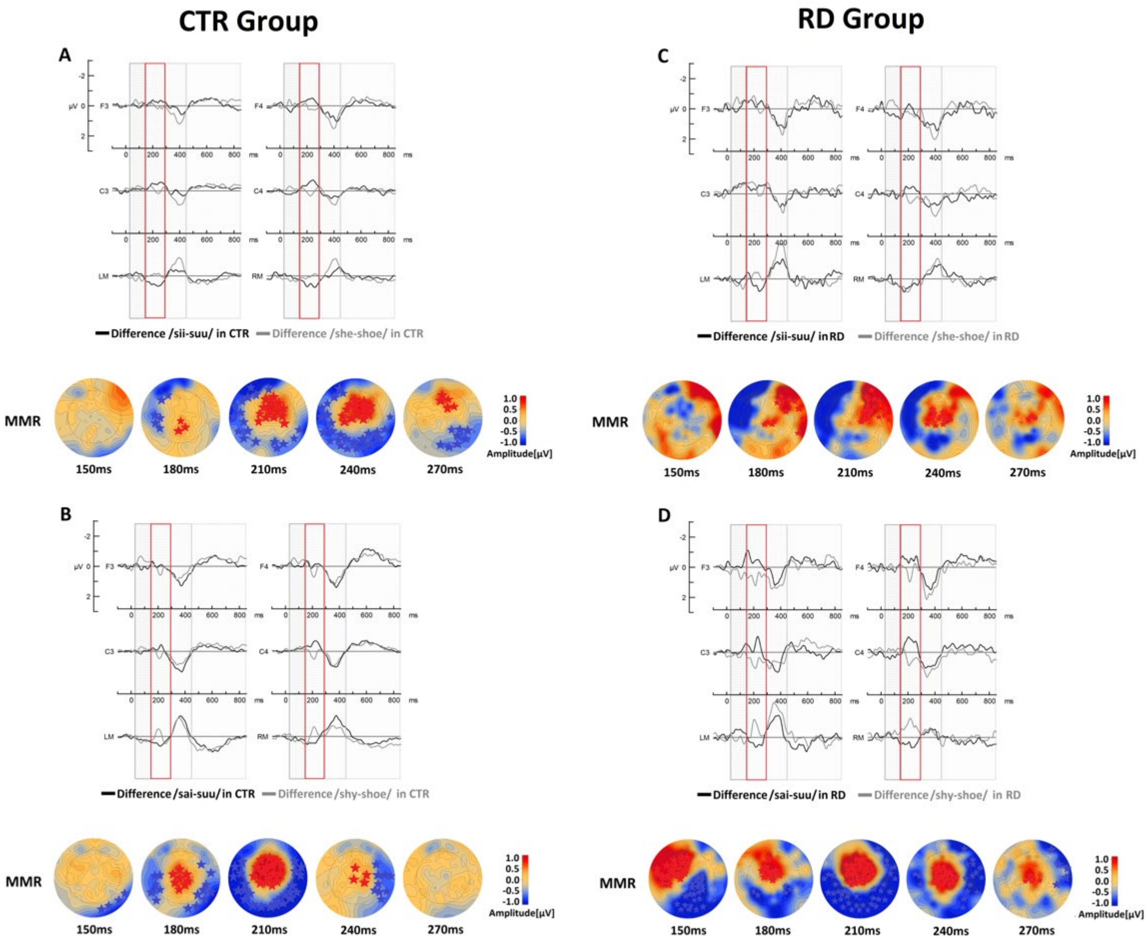

FIGURE 7 Statistical results of the between-language comparison with the CTR and RD groups. The CTR group difference waveforms are illustrated in the left panel. (A) the top left panel shows the difference for *she-shoe* (in gray) vs. *sii-suu* (in black) and (B) the bottom left panel shows the difference for *shy-shoe* (in gray) vs. *sai-suu* (in black). The statistical cluster-based permutation result maps of the difference (English–Finnish) for this group are presented below their difference waveforms. The RD group difference waveforms are illustrated in the right panel. (C) the top right panel shows the difference waveforms for *she-shoe* (in gray) vs. *sii-suu* (in black) and (D) the bottom right panel (D) shows the difference for *shy-shoe* (in gray) vs. *sai-suu* (in black). The statistical cluster-based permutation result maps of the difference (English–Finnish) for this group are presented below their difference waveforms. The significant clusters are highlighted with stars. F= Frontal; C= Central; ML = left mastoid; MR = right mastoid.

A 2 × 2 ANOVA tested the language × group interaction effect for the two time windows MMR and LDN. The results did not show any group × language interaction in any of the time windows. However, the results did reveal a language main effect.

3.2 Study II – Brain source correlates of speech perception and reading processes in children with and without reading difficulties

The auditory grand average ERP waveform revealed the presence of four components that emerged in response to the auditory stimulus: A P1 response peaking at around 90 ms, a second P1 (P1-2) with a peak at around 170 ms, a N250 with a peak at around 250 ms, and a second N250 (N250-2) with a peak at around 370. The grand average of the FRPs waveform revealed the presence of the visual N170 response with a peak at around 200 ms. For an illustration of these responses, see Figure 8.

The group-based cortical source reconstruction (applying CLARA) for each of these ERP/FRP responses showed the following sources. The source reconstruction for the auditory P1 component (performed at 80 ms) shows an activation of the auditory cortices (A1). The reconstruction of P1-2 (at 160 ms) shows slightly larger activity covering a larger area than that found in the first P1 response in the auditory cortices (A1) and with an activation over the central region. The source reconstruction for N250 response (at 230 ms) revealed the activation of left and right temporal lobes, at the superior temporal area (STA), the inferior frontal area (IFA) in the left hemisphere, and the middle frontal area in the right hemisphere. The source reconstruction for the N250-2 response (at 370 ms) showed the activation of four sources: the left and right STA, the right IFA, and the central right area of the motor cortex.

The activity from the bilateral auditory sources across the different components was used to run the correlation analysis in order to investigate the relationship between the auditory speech perception processes and the reading processes at both behavioral and neuronal levels. The additional sources were not examined because they may be part of other processes, such as attentional or semantic processes based on previous literature.

The group-based cortical source reconstruction of the visual response in reading, reflected in the N170 (at 190 ms), showed the activation of two sources over the left and right occipital areas (the middle occipito-temporal area and the right visual cortex). Moreover, two other sources were found to be active over the left frontal area: left orbitofrontal area and the left prefrontal area. Only the sources of the occipital areas were included in the correlation analysis to investigate the reading processes. The frontal sources may reflect other processes that are mainly related to attentional processes.

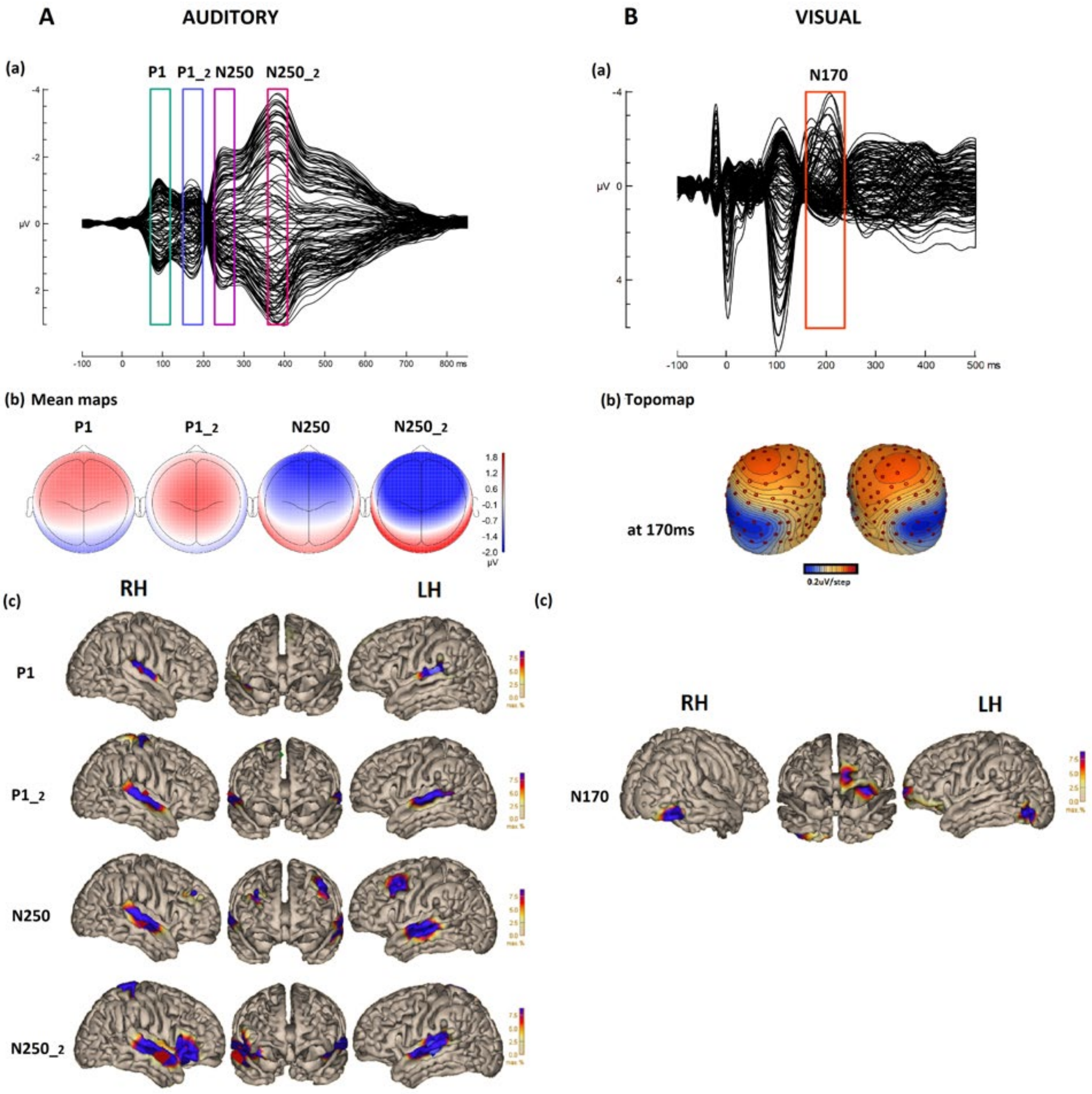

FIGURE 8 Speech and print brain responses. Panel A. (a) The top left panel presents a butterfly illustration of the group (N = 80) grand average waveform, of the speech ERPs. The main components (P1, P1-2, N250, and N250-2) are highlighted within the boxes. (b) The center left panel presents their corresponding 2D topographic mean maps at the 70–120 ms, 150–200 ms, 230–280 ms, and 360–410 ms time windows, respectively. (c) The bottom left panel shows the cortical CLARA source reconstruction results for each of these components. Panel B. (a) The top left panel presents a butterfly illustration of the group (N=80) grand average waveform, of the print FRPs. The main component N170 is highlighted with an orange box. (b) The center right panel presents its corresponding 3D topographic map, at 170 ms. (c) The bottom left panel shows the cortical source CLARA source reconstruction result for this component.

The correlation analysis between the scalar values of the cortical source activity and the reading score (PAF) showed a significant negative correlation between the P1 source activity of the left A1 and the reading score, whereas the right source activity did not reveal any significant results. Neither the right nor the left brain activity of the P1-2 or the N250 sources correlated with the reading scores. A significant negative correlation was also found between the N250-2 source activities and the PAF score in both the left and right temporal areas (STA).

The correlations between the scalar values of the visual sources and the PAF showed that the left occipital source activity over the left occipital area (L VWFA) negatively correlated with the PAF. However, this last correlation became non-significant after multiple comparison corrections.

In the brain-to-brain correlations between the scalar value of the visual N170 source and the auditory source activities, the auditory P1-2 source in the left STA correlated significantly with both active sources of the N170 over the left and right hemispheres. The auditory N250 sources in the left and right STA correlated significantly with the left VWFA of the N170 response. Overall, in the brain-to-brain correlation analysis, the higher the source activity in one modality, the higher the source activity in the other modality.

The partial correlations when controlling for the reading scores factor in the brain-to-brain correlations did not reveal any change in the correlation results.

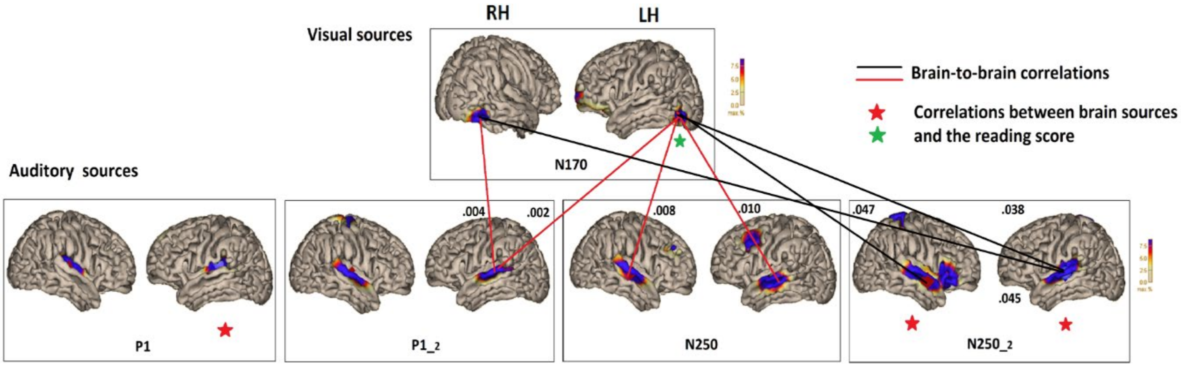

FIGURE 9 Summary results showing correlations between the source activity in speech processing and reading in the brain-to-brain analysis (indicated by stars) and in the brain-to-behavior analysis (indicated by lines). The top panel represents the visual sources, and the bottom panel represents the auditory sources. All correlations that remained significant after the multiple comparison's correction are highlighted in red.

3.3 Study III – Auditory P3a response to speech in children with or without attentional deficit

The statistical cluster-based permutation test of the difference waves (deviant-standard), comparing the control group (CTR) and the attention problem group (AP), over the P3a window (300– 450 ms) was investigated. In the native contrasts *sii-suu* and *sai-suu*, the statistical analysis shows a significant difference only in the *sai-suu* condition (p-value<0.005). Larger difference wave responses were found in the AP group than in the CTR group. However, lower amplitudes in both deviant stimuli (*sii* and *sai*) were found in the AP group than in the CTR group. The main group difference was found over the right frontal area (for an illustration see Figure 10). The AP group showed a more positive P3a response than that of the CTR group. The statistical cluster-based permutation test of the group difference in the foreign language (English) contrasts (between the deviant stimulus and standard stimuli) over the P3a window (300–450 ms) for the conditions *she-shoe* and *shy-shoe* did not reveal any statistically significant results.

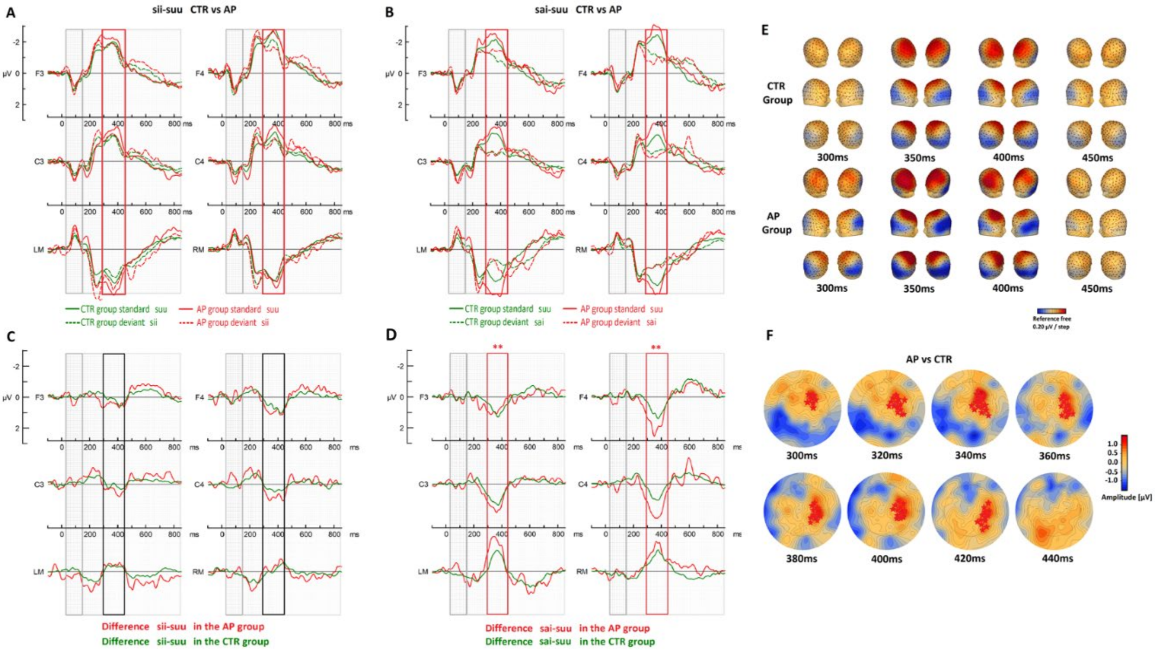

FIGURE 10 The difference waves of the CTR and AP groups in native conditions and their statistical results. The top panel shows the ERP waveforms of the standard and the deviant stimuli (dashed lines) in the CTR group (green) and the AP group (red). The native conditions are presented in Panel (A) (suu and sii) and Panel (B) (suu, and sai). Panel (C) illustrates the difference waveforms of the CTR group (in green) and the AP group (in red) for the *sii-suu* contrast, and (D) *sai-suu* contrast. Panel (E) shows the P3a topographic maps of the CTR and AP groups between 300 and 450ms for the difference *sai-suu* (the only statistically significant condition). Panel (F) shows the cluster-based permutation test results of the between-group comparison (AP vs CTR groups) for the *sai-suu* difference wave and at the P3a time window. Red stars indicate the significant clusters.

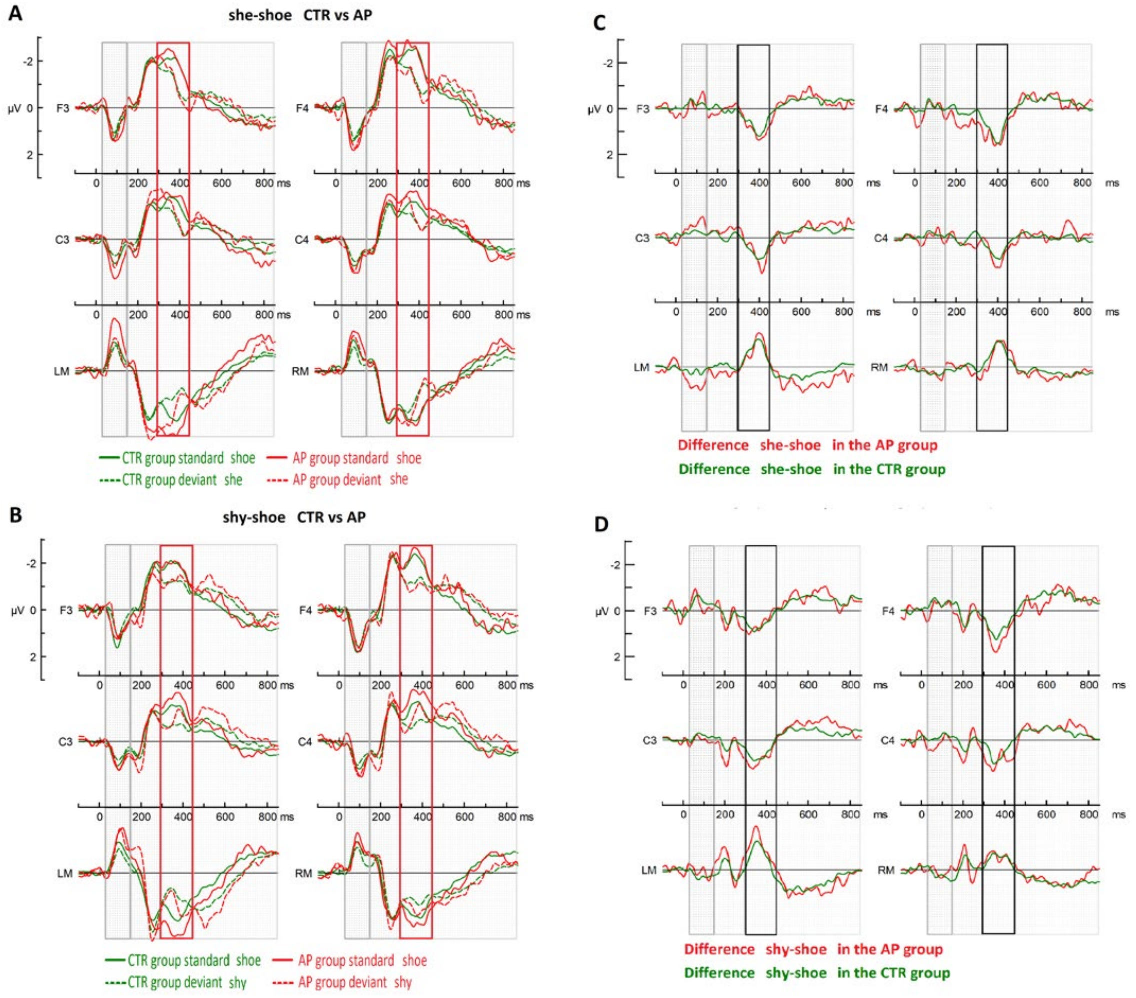

FIGURE 11 The difference waves of the CTR and AP groups in foreign conditions. The ERP waveforms of the standard and the deviant stimuli (dashed lines) in the CTR (green) and AP (red) groups are presented in the left side. Panel (A) shows the waveforms to the standard stimulus *shoe* and deviant stimulus *she*. Panel (B) shows the waveforms to the standard stimulus *shoe* and deviant stimulus *shy*. The difference waveforms of the CTR group (green) and the AP group (red) for the (C) *she-shoe*, and (D) *shy-shoe* contrasts.

In the within-group analysis and in the native language context, the ERP responses to standard stimulus *suu* in both contrasts *sii* vs *suu* and *sai* vs *suu*, showed higher amplitudes than that to the deviants in both native conditions within the AP group. In the P3a time window, the difference amplitude between the deviant and standard stimuli was larger in the *sai-suu* condition than in the *sii-suu* condition in the AP group. Similar results were also found in the CTR group. The permutation test results of the P3a response within the CTR and AP groups to native language contrasts (*sii-suu* and *sai-suu*), over the P3a time window, show a statistical difference in both groups (with p<0.001, p<0.001 for the CTR group and p<0.013, p<0.001 for the AP group).

In the within-group analysis and in the foreign language context, responses were similar to those observed in the native language. The cluster-based permutation test results of the P3a response within the CTR and AP groups in a foreign language context, and within the P3a time window, showed a statistically significant difference within both contrasts. In the AP group, a clear statistical difference for the *she-shoe* and *shy-shoe* contrasts was found (with a p<0.001 and p<0.001, respectively) in the CTR group and (with a p<0.001 and p<0.001, respectively).

The correlation analysis between the attention score and the ERP amplitude of the P3a in the native (Finnish) language showed statistically positive correlations for both the *sii-suu* and *sai-suu* conditions. In the *sii-suu* contrast, a positive correlation was found over the right hemisphere with a p<0.02, explaining ≈12 percent of the brain activity (between 340 and 360 ms). The result was significant in the Pearson (p-value<0.001) and Spearman's rho (p-value<0.02) correlations (see Figure 12).

In the *sai-suu* contrast, a positive correlation was found over the right hemisphere, with a p-value<0.03 explaining ≈17 percent of the variability of the brain activity (between 380 and 400 ms). The result was significant in the Pearson (p-value<0.001) and Spearman's rho (p-value<0.002) correlations (see Figure 13).

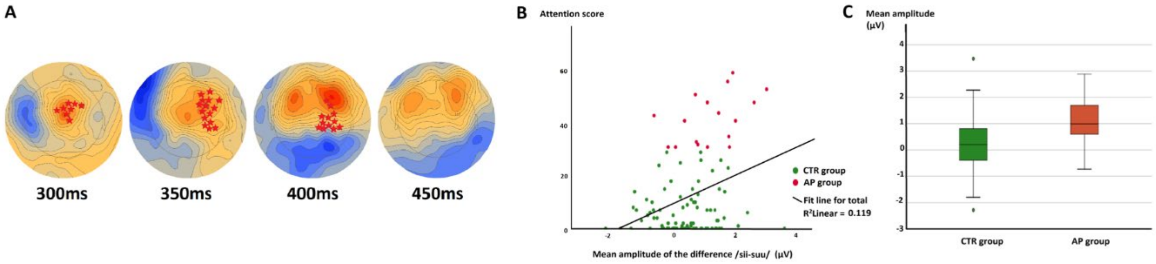

FIGURE 12 Correlation test results between the mean amplitude of the difference waves *sii-suu* and the attention score (ATTEX/KESKY) in CTR and AP groups. Panel (A) shows the significant cluster maps between 300 and 450 ms (red stars). Panel (B) illustrates the scatterplot for CTR group (green) and AP group (red) with correlation between the mean amplitude of the difference *sii-suu* between 340 and 360 ms over the significant cluster for the electrodes (E 3 102 103 104 110 116 117 122 123 124). Panel (C) displays the box plot of the mean amplitude [340–360 ms] distribution in both CTR (green) and AP (red) groups for the same correlation analysis.

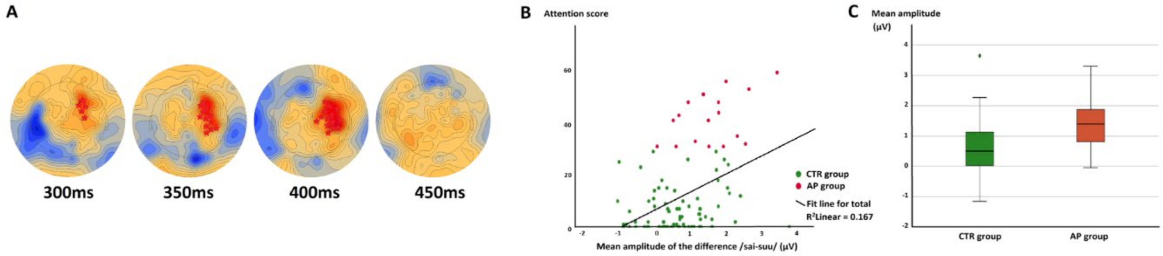

FIGURE 13 Correlation test results between the mean amplitude of the difference waves *sai-suu* and the attention score (ATTEX/KESKY) in CTR and AP groups. Panel (A) shows the significant cluster maps between 300 and 450 ms (red stars). Panel (B) illustrates the scatterplot for CTR group (green) and AP group (red) with correlation between the mean amplitude of the difference *sai-suu* between 380 and 400 ms over the significant cluster for the electrodes (E 92 93 98 102 103 104 105 110 111 116 117). Panel (C) displays the box plot of the mean amplitude [380–400 ms] distribution in both CTR (green) and AP (red) groups for the same correlation analysis.

The correlation analysis between the attention score and the ERP amplitude of the P3a in the foreign (English) language did not reveal any statistically significant results for any of the contrasts (neither *she-shoe* nor *shy-shoe*).

The grand average source reconstruction results for the CTR and AP groups of the *sii-suu* and *sai-suu* native language conditions for the difference waves between ≈ 300 and 450 ms showed a significant correlation between the P3a brain responses and the attention scores. The activated sources in the AP group seemed to show stronger activations and slightly more posterior than the CTR group.

For the *sii-suu* contrast, the CTR group source reconstruction showed five sources active in the following approximate areas: the L Brodmann area (BA)36 (left inferior temporal region), the R BA48 (the right retrosubicular/ hippocampal area), the R BA36 (the fusiform area in the right temporal region), the L BA23 (the ventral posterior cingulate gyrus (vPCG) in the left hemisphere), and the L BA1 (the left frontopolar/anterior prefrontal cortical area (APC)). The AP group source reconstruction for the same contrast showed equally the activations of five sources with the same sources over the L BA36 and the R BA48. On the other hand, activation of the BA10 and the BA23 was found in the opposite (right) hemisphere (R BA10 and R BA23), located in the left hemisphere in the CTR group. Moreover, an activation of the L BA48 was also found in the AP group, while the R BA36 was found in the CTR group. See Figure 14.

For the *sai-suu* contrast, the CTR group source reconstruction showed four active sources: the L BA36, the R BA48, the R BA23, and the R BA10. The AP group source reconstruction for the same contrast showed the same activations in three sources – the L BA36, the R BA48, and the R BA10 – with only a difference in the fourth source, R BA23, that did not show activation in the AP group. See Figure 14.

Overall, the source activations were stronger in the AP group than in the CTR group. Similar brain areas were found to be active in both groups for both native conditions, with mainly a bilateral activation of the temporal regions and the activation of the frontal and posterior areas of the cingulate gyrus.

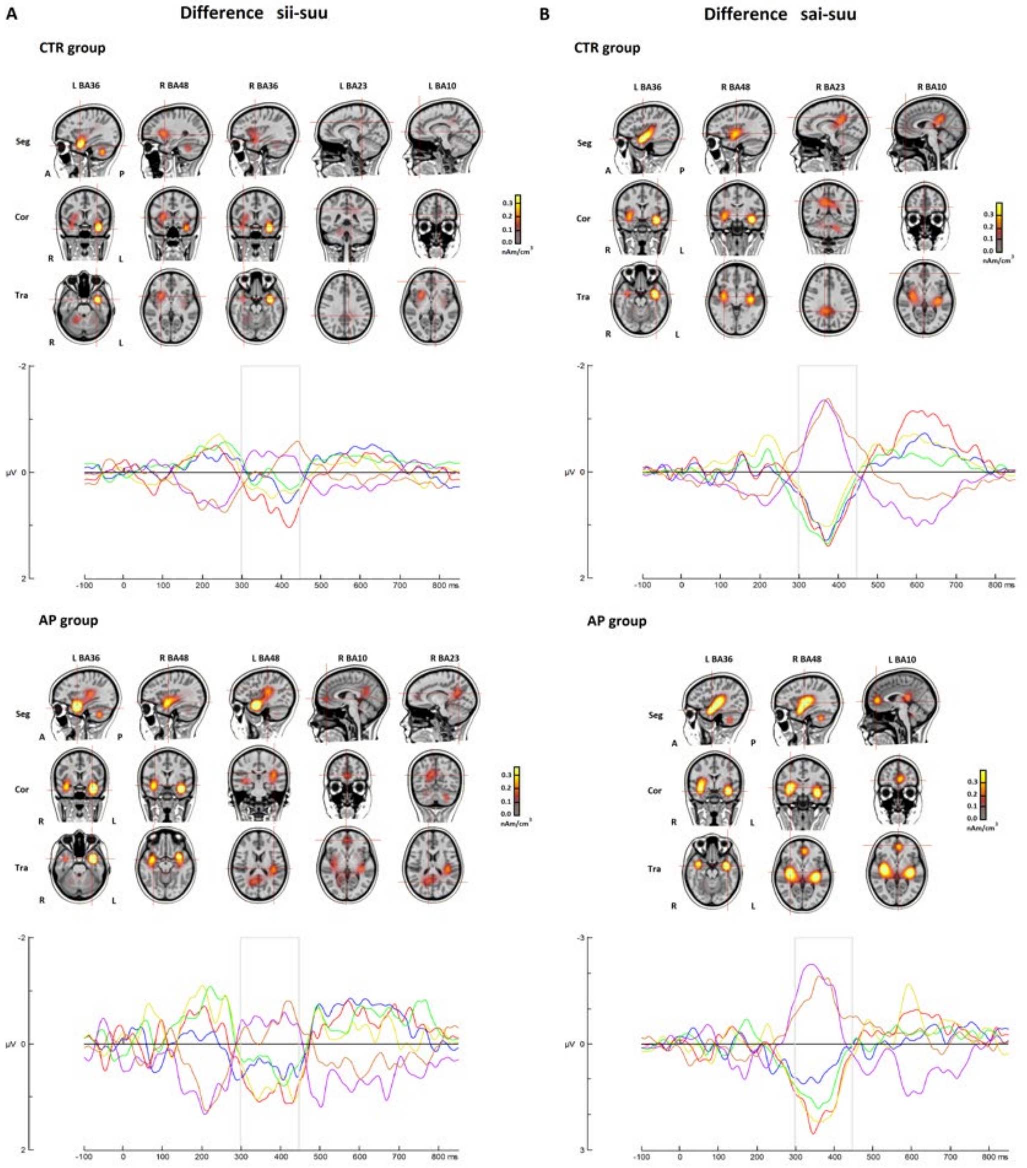

FIGURE 14 CLARA source reconstruction results for the CTR group (top panel) and the AP group (bottom panel) for the statistically significant time windows according to the correlation analysis. (A) The active sources between 300 and 450 ms (time window highlighted with the light grey box) in the difference *sii-suu*, (B) and in the difference *sai-suu*. The difference waveforms for the F3 (blue), F4 (red), C3 (green), C4 (yellow), RM (orange), and LM (purple) electrode are illustrated below their corresponding condition and group.

Note: A (anterior), P (posterior), R (right), L (left), Seg (segmental), Cor (coronal), Tra (transversal).

4 DISCUSSION

This dissertation investigated brain responses to speech and how they are linked to reading and to attentional processes in typical development and in reading or attentional difficulties. The discriminatory brain responses to speech items in native and foreign languages were studied in typical and in poor readers (Study I). This dissertation also investigated how the basic speech processes were linked to reading skills, both in the sensor level by studying the brain ERPs and at the source level (Study II). Studies I and II both focused on the brain responses to speech and their relation to reading skills, where both typical readers and children with reading difficulties were investigated. Attentional shifting in speech processing was also investigated using ERP/FRP analysis and the source reconstruction method (Study III). The attention shifting response, both in typical children and in those with attentional problems, was investigated to better understand the relationship between attentional difficulties and speech processing (Study III). Moreover, Studies I and III both investigated language processing in native and foreign language contexts.

In Study I, the results of the within-group analysis revealed that only MMR, but not LDN, was significant in the language comparison in CTR and RD groups. The RD group showed similar MMR responses to those found in the CTR group; however, this group did not show any significant LDN response in any of the contrasts, either native or foreign. Significant MMR and LDN responses were found in the CTR group and for all contrasts. However, the MMR showed a smaller amplitude in foreign language processing and the LDN response was weaker in the contrasts with vowels than in those with a diphthong. Moreover, both groups showed a typical negative MMR (between 150 and 300ms) with a lower amplitude within contrast (deviant–standard) in native language processing compared to the foreign language condition. On the other hand, the results revealed an atypical positive MMR to foreign stimuli in both groups. In the direct comparison between the two group (CTR vs RD) discriminatory responses, no differences were found for either MMR or LDN responses.

In Study II, the results showed a correlation between the brain activity of the P1 and N250-$_2$ components with the reading scores. The N170 activity in the left hemisphere over the left VWFA correlated significantly with the reading score but did not survive the statistical correction. Significant correlations between the brain source activations in speech processing and in reading were found when correlating the source activities of both modalities. The source activation of the P1-2 and the N250 correlated significantly with the N170 source, which is in line with previous findings.

The results in Study III showed the presence of a P3a component in the CTR and AP groups, with a larger P3a amplitude in the AP group. This group difference was found in the P3a time window only in the native contrast with a deviant carrying a diphthong (*sai-suu)*. The attention scores and the P3a response in native contrasts correlated significantly. The results also revealed the role of the right frontal area on the attentional processes. The source reconstruction of the P3a revealed the neural activation of the temporal fusiform areas, the temporo-parietal junction area, the ventral posterior cingulate area, and the frontopolar/anterior prefrontal cortical area. The CTR and AP groups both showed similar source activations with enhanced and larger source activity observed in the AP group. This enhancement was found in both native conditions and on both hemispheres, especially in the second condition (*sai-suu)*. The frontal source in particular showed enhanced neural activation in the AP group. A tendency for an opposite frontal hemispheric activation was observed in the AP group when compared to the CTR group in the first condition (*sii-suu*). No correlation was found between the P3a response and the attention score in foreign language processing.

4.1 Discriminatory brain processes to native and foreign languages in children with or without reading difficulties (Study I)

In the CTR group, the within contrasts (deviant–standard) analysis of the native language showed similar discriminatory brain responses to those reported in the literature (Alonso-Búa et al., 2006; Čeponienė et al., 2004; Cheour et al., 2001; Zeng et al., 2022) except for the first contrast *sii-suu*, which showed a weaker MMR response compared to other contrasts. Although the analysis of the foreign language processing within the CTR group revealed the presence of MMR and LDN responses, the MMR response was very weak and atypical compared to the MMR response in the native language. This effect is somehow linked to the presence of the foreign sound [ʃ] at the onset of the English speech items. A coarticulation effect of the following vowel/diphthong is also thought to affect the ERP response, as the stimuli (syllable in this case) is probably processed as a "unit", where both the fricative and the vowel are linked and affect each other, as described in literature (Chen, 2015; Ohde, 2011). This makes the foreign stimuli more salient than the native ones, not only because the foreign nature of the onset sound, but also because the effect of the onset sound is also present in the coarticulation and beyond. It is likely that the early discriminatory response may have overlapped with a highly active attentional component (probably a P3a) generated in response to the foreign features, where the sum of both responses created a positive MMR. Although this result is different from the negative MMR found in the original study (Ylinen et al., 2019), it may be explained by more attentional processes engaged to foreign stimuli in this group sample, who became more sensitive to the foreign sound after longer exposure. Moreover, the effect of the stimulus features was examined by inspecting the stimuli Euclidean distance (ED) (for vowels) and center of gravity (COG) (for fricatives), where the acoustic distance effect on the MMR response was checked. The MMR was previously shown to be sensitive to acoustic distance (Savela et al., 2003), so the ED/COG may explain the difference in ERP responses. The ED results revealed that English and Finnish vowels were acoustically distinct and that the ii ([i:]) deviant was acoustically further in ED from the standard uu ([ʊ:]) than the deviant ai ([aɪ]) (see Figure 15). The ED/COG may partially explain how the MMR responses behaved within the CTR group, where in native language processing the larger the ED between deviant and standard vowels, the larger the MMR response. However, the difference between the two MMR responses in (*sii-suu*) and (*sai-suu*) remained minimal. The ED/COG did not seem to play the same role in the case in foreign language processing, as the ED/COG was not linked to the ERP responses. These results suggest that a different mechanism was engaged in processing speech foreign items, showing the specificity of the brain response to the nature of the stimuli.

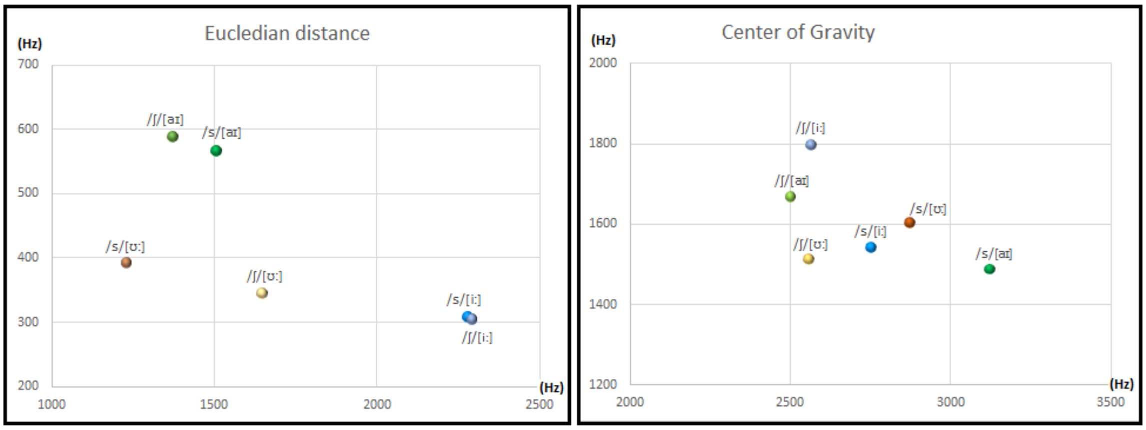

FIGURE 15 Illustration of the physical ED between the different vowels of the Finnish and English stimuli (left panel). Illustration of the physical COG of the different fricatives of the Finnish and English stimuli (right panel). The unit is Hertz (Hz).

The LDN response was significant in all the contrasts within the CTR group. Its topography showed a tendency towards the right hemisphere for both native contrasts. This was also the case for the foreign *shy-shoe* contrast, whereas the topography in the *she-shoe* contrast showed a tendency to the opposite, left hemisphere. The amplitude of the LDN response varied in the different contrasts.

The role of this late component remains a subject of debate (Wetzel et al., 2014; Wu et al., 2019). However, it has been suggested to be linked to different processes, such as the stimulus phonological complexity (David et al., 2020), higher cognitive processes such as the semantics or the stimulus type (noun, verb, adjective, etc.) (Korpilahti et al., 2001), and attentional processes (Choudhury et al., 2015). It may also indicate a delayed effect of the coarticulation that may have induced a stronger LDN response, when overlapping with later processes, in the case of stimuli carrying a diphthong (/ai/). The stimulus type/ semantics may have also contributed to the ERP response, as the discriminatory processing of words and pseudo-words was earlier shown to differ (Jacobsen et al., 2004). This could be the case because both of these types of stimuli are present in the current paradigm, where the syllables are suu and sai, which are also full words in Finnish language with their own meanings. Sii could be considered as a pseudoword, as it could be a part of a word but does not have its own meaning. Larger responses were interpreted to reflect more robust memory traces. Lexically meaningful items were also shown to affect the ERP response compared to non-meaningful items, where the meaning was shown to modulate the ERP response with a processing advantage of the meaningful items (Jacobsen et al., 2021).

Overall, the results of the discriminatory responses in the CTR group reveal the presence of two different mechanisms engaged specifically for each language type (native vs foreign).

In the RD group, and within contrast analysis, significant MMR responses were observed for most of the contrasts, except for the *sii-suu* contrast, which is the same contrast reported above to show the weakest MMR in the CTR group. Interestingly, this is the only contrast comprising a pseudo-word. This may reflect a different encoding strategy adopted for pseudowords compared to word processing, as proposed above. The RD group also showed a positive MMR response in foreign language processing that was similar to the CTR group. Although the RD group overall showed the presence of the discriminatory responses, the activation pattern revealed differences compared to the CTR group. The late discriminative component in the RD group, the LDN, did not show any significant response in any of the contrasts. The lack of an LDN significance in the RD group may suggest weaker discriminatory brain processes than those in the CTR group (Cheour et al., 2001; Schulte-Körne & Bruder, 2010). Reduced LDN responses in RD have been reported in previous studies (Hommet et al., 2009). As well as being described as a discriminatory response, LDN was also proposed to be a maturation marker of the later attentional processes that are dependent on the stimulus complexity (Čeponienė et al., 2002). This may suggest that the RD group results reflected a lack of maturity in processing the stimulus complexity, especially that the lack of LDN was valid for all the stimuli, where none of the contrasts showed a significant response. This could be a valid explanation as the RD group commonly showed immature brain responses in literature (e.g., Hämäläinen et al., 2007; Stephanics et al., 2011).

In the language comparison, discriminatory brain processes of native and foreign languages were investigated in the CTR and RD groups. The MMR response, in both groups, showed enhanced brain responses in foreign language processing compared to native language. Moreover, the MMR response showed a typical negative response over the fronto-central area in the native processing, whereas it tended toward a positivity in the same electrodes in foreign language processing. This result may indicate the effect of the engagement of specific processes and neural mechanisms that seem to be language-dependent. The instability of the brain responses in the MMN time window, as observed in the enhanced response and the polarity change (shift of the polarity into positivity instead of the typical negativity), may reflect the instability of the foreign speech items neural representation compared to a well-established representation of the native speech. This polarity shift of the MMR is typically described in the literature as a marker of immaturity, mostly described in earlier childhood (Virtala et al., 2022). This larger response may be explained by the recruitment of additional brain resources as a corrective mechanism to the instability. This mechanism is probably triggered by the first sound [ʃ] present at the onset of the foreign (English) stimuli, which is salient due to the absence of this sound from the native (Finnish) phonology. The foreign nature of the stimuli may engage additional attentional processes and thus activate a larger attentional response (P3a) that may overlap with the MMR response and produce a shift of the polarity as proposed above. The LDN brain response in this language comparison did not reveal any significant differences between the processes of both languages in none of the groups.

In the direct group comparison (CTR vs RD), no statistical differences were found between the groups neither for MMR nor for LDN responses, reproducing results that are similar to those reported by the original study (Ylinen et al., 2019). However, a difference between Ylinen's study and the current one was Ylinen reported weaker MMR in the RD group when processing a second language familiar word (the word *she*), which was not observed in the results of the present study. The absence of this finding may be explained by a change in the neural representations of the foreign language as a result of a longer exposure to foreign speech at this age compared to that at a younger age. In other words, it could be explained by the development of the brain representations due to age difference between the two tested groups (nine-year-olds in Ylinen's study vs 12-year-olds in the present study). No direct significant group differences were found in the LDN response. A similar result, with no group differences in either MMR or in LDN, was previously reported in a vowel discrimination task investigated by Froyen and colleagues (2011). This result differed from other studies, which typically reported differences in the MMR responses between CTR and RD groups (for a review, see Volkmer & Schulte-Körne, 2018). These contradictory findings could be explained by the different stimuli, the different paradigms, and the different age groups tested in the studies (e.g., Peltola et., 2003; Halliday et al., 2014; Virtala et al., 2018). The lack of the group difference in this case may be explained by the possible effect of the artificial reduced sensitivity of the statistical method. This is because the computation compares the difference (RD-CTR) of the difference (deviant-standard). This method may "wash away" the presence of any small differences, if they exist.

The literature does not include any evidence about the LDN response on foreign speech processing and in the context of reading difficulties. The results of the current study showed a tendency towards larger LDN response in the RD group than in the CTR group. Larger ERP responses in the RD group compared to those in the CTR group have been described in the literature and interpreted as greater processes used as a compensatory mechanism for the less efficient linguistic performance in discriminatory processes in the context of reading difficulties (Bishop, 2007; Lohvansuu et al., 2014; Liu et al., 2014). This neural over-sensitivity may also be linked to the allophonic theory, which assumes a continued sensitivity to contrasts that do not exist in the native language in RD subjects, who typically show higher sensitivity to foreign speech sounds (Serniclaes et al., 2018).

4.2 Brain source correlates of speech and reading processes in children with and without reading difficulties (Study II)

In Study II, the brain-to-behavior relations between the speech processes and reading skills were investigated via correlations of the reading score (PAF) and the brain activity of the visual word form area (VWFA). Brain-to-brain correlations of the neural activity in basic speech processing and in reading processes were investigated in a group of children comprising poor readers and good readers. Source reconstruction was conducted for both processes and used for the correlation analysis. The results and their interpretations are detailed below.

The ERP analysis to the speech perception task, computing the grand average of the ERP responses to the stimulus suu, showed two main components: a P1 and an N250. The P1–N250 complex has been previously described in the literature as part of the basic auditory response (Čeponienė et al., 2005; Gansonre et al., 2018). The P1 is known to be an obligatory response that is suggested to reflect sound detection and phoneme identification (Durante et al., 2014; Hämäläinen et al., 2015; Kuuluvainen et al., 2016), whereas the N250 has been suggested to reflect phonological processing (Eddy et al., 2016), or memory trace formation (Karhu et al., 1997; Čeponienė et al., 2005; Khan et al., 2011; Hämäläinen et al., 2013). Interestingly, the results from the present study showed responses with double-peak components, which are believed to reflect the complex structure of the stimulus as a CV syllable. Similar responses to syllable stimuli have been previously reported in the literature, showing the brain responses to consonants and vowels (Yaralı & Yağcıoğlu 2018). The P1 frontal positive peaks emerged at approximately 80 ms and at 170 ms, reflecting the P1 and P1-2 responses, respectively. The first peak was a typical P1 response that emerged for the onset sound of the syllable (the fricative) /s/, whereas the second component, P1-2, seems to emerge as a response to the second part of the syllable (the vowel) /uu/. The same response pattern was also found for the N250 component, with two fronto-central negative peaks at around 250 ms and 370 ms reflecting the N250 and N250-2 components as the second response to the fricative and to the vowel, respectively. In this second response, the N250 components are believed to comprise the processing of both the onset sound and the coarticulation as it showed enhanced response compared to that of the P1 components. Earlier studies showed the consonant-vowel transition effect on response to syllables in children (Boothroyd, 2004). This larger response may also be related to the repetition effect, as the repetition has been shown to induce stronger response (Karhu et al., 1997), to the nature of the word stimulus, its meaning or to its familiarity and frequency (Jacobsen et al., 2021). The early auditory responses (P1–N250) were shown to be linked to reading skills (Parviäinen et al., 2011; Hämäläinen et al., 2015; Kuuluvainen et al., 2016). Earlier studies reported a difference between typical and dyslexic readers showing different responses in the early time window between 100 and 250 ms in each group (Bonte & Blomert, 2004b; Hämäläinen et al., 2007; Khan et al., 2011; Hämäläinen et al., 2015).

In the reading task, the FRP analysis revealed a typical visual N170 response. This component has been shown to reflect the process of objects and face recognition (Rossion et al., 2002; Collin et al., 2012; Hinojosa et al., 2015). In the reading literature, this component was shown to typically have a left lateralization as a result of print processing and was extensively investigated in the context of reading and reading difficulties (Maurer et al., 2005; Maurer et al., 2008; Mahé et al., 2013; Sacchi & Laszlo, 2016; Loberg et al., 2019).

The source reconstruction showed similar brain activations in both P1 components, reflecting similar processes within the double peak. Similar brain areas to those described in this analysis have been reported in previous studies of the P1 response in adults and children (Godey et al., 2001; Shahin et al., 2004; Ruhnau et al., 2011). The A1 has been shown to play a fundamental role in speech perception and in phoneme identification (Mesgarani et al., 2008). A recent study by Hamilton and colleagues (2021) using electrocorticography (ECoG) showed that speech processing in the auditory cortices is a parallel processing of the speech information, engaging primary and non-primary areas in a parallel process. The source reconstruction of the N250 response also showed similar brain areas as previously reported in the literature (Parviainen et al., 2011; Hämäläinen et al., 2015). The activation of the superior temporal areas (STAs) has been linked to phonological processing (Hickok & Poeppel, 2007; Trébuchon et al., 2013). The process of speech sound encoding of the phonetic acoustic features at the superior temporal gyrus (STG) was summarized and discussed in the review by Yi et al. (2019). The source reconstruction of the P1-N250 complex showed more anteriorly located activations across time. Although the sources of the P1 and N250 responses were anatomically very close, the results showed more anterior and ventral sources in the N250 reconstructions, reflecting a different process than in the early P1 responses. The emergence of the frontal sources, in addition to the sources located over the temporal areas in the N250 responses, may reflect a later higher and more complex cognitive process of the speech sound. As suggested above, the P1 components seem to reflect basic processes and the N250 components seem to reflect more complex processes, which may explain the activation of specific sources in each of these processes.

The source reconstruction of the N170 response revealed the activation of bilateral occipital areas over the VWFA and the activation of the left frontal area. These findings support previous results, which show the same areas as generators of the N170 (Maurer et al., 2005a; Maurer & McCandliss, 2007; Maurer et al., 2011; Mahé et al., 2013). Interestingly, a bilateral activation over the occipital areas can be observed, whereas earlier studies showed a left lateralization of the N170 sources in reading (Maurer et al., 2008). Bilateral activation was reported as an immature response and mostly found in young children (Uno et al., 2021), but also in subjects with reading problems. As the group comprised both good and poor readers, and considering that dyslexics were shown to lack this hemispheric lateralization of the N170/VWFA (Maurer et al., 2005b), the bilateral activation observed in the source analysis of the N170 probably comes from the subgroup of poor readers. The separate group analysis reinforced this suggestion, as the results showed a more bilateral brain activation in the RD group than in the CTR group. This result reflects the immature or the atypical reading response of this sub-group.

In the correlation analysis, although the N170 response showed a correlation with the reading scores, it did not survive the statistical correction for multiple comparisons. This correlation result was expected based on previous literature (Maurer et al., 2005a; Hasko et al., 2013). However, the source reconstruction method used in this study may be the reason for this statistical result, as the correlation was based on a group average response. Different subjects showed different source activities due to the individual variability. The high variability of the brain activation that may be present within the group (between subjects) and the variability of the reading stimuli eliciting the N170 response (average reconstruction on 912 words) may also play a major role in these correlation results, as the source activity may be dispersed.

The correlation analysis between the P1 source activity at the left auditory cortex and the reading score (PAF) showed a significant negative correlation between the source activity and the reading skills. The negative correlation indicated a reverse effect, where the more active the brain was, the lower the reading skills were – this contradicts previous results (Shaywitz et al., 2002; Meyler et al., 2007) – as typically lower activation was linked with processing efficacy. The maturity of this response was often linked to a smaller response to repeated stimulus in the adult-like processing. Thus, this negative response is an indicator of immaturity and probably linked to the developmental stage of this process. No correlations were found in the right hemisphere. The left lateralized effect observed in this correlation analysis could be linked to previous findings showing that the left auditory cortex is involved in processing time cues and temporal acoustic information (Ladeira et al., 2011; Heimrath et al., 2016). These roles are the same as those previously shown to be played by the P1 ERP response in stimulus processing (Hamilton et al., 2021).

The source activation of the N250-2 over the STAs in both hemispheres showed significant negative correlations with the reading scores. The STAs are known to be part of the language processing network (Albrecht et al., 2000; Mody et al., 2008; Proverbio et al., 2011) and have been shown to reflect low-level speech encoding in speech processing (Hullet et al., 2016; Berezutskaya et al., 2017; Yi et al., 2019). Previous evidence also showed the role of the STAs in relation to phonological processing in reading (Simos et al., 2000; Mesgarani et al., 2014).

Overall, the results showed that the more active the brain was, the lower the reading skills were; this result was valid for all of the components. Higher brain activation maybe due to the recruitment of additional resources as an adaptive or corrective mechanism (Lohvansuu et al., 2014), or it may be linked to the inverted U-shaped developmental trajectory. This model of development assumes that the development of the visual expertise depends primarily on the perceptual learning in the early phases of learning and then gradually declines with the development of the expertise (González et al., 2016). Previous studies have shown this developmental trajectory typically in the development of reading expertise (Chyl et al., 2021; Dehaene-Lambertz et al., 2018). The present results showed that this interpretation seems to be valid for both visual and auditory modalities at this age, which may explain the negative correlations reported across this analysis (González et al., 2016). This inverted U-shaped trajectory was also reported in speech perception developmental trajectory across a lifespan (from five to 89 years), where the results of forced-attention consonant–vowel dichotic listening paradigm revealed an inverted U-shaped association of age and performance. The authors concluded that cognitive control of speech follows a similar trajectory in different domains, like the one often reported in the visual domain (Westerhausen et al., 2015).

The brain-to-brain correlation analysis produced significant results. The left STA source activity of the P1-2 response correlated significantly with both N170 sources (VWFA) in both hemispheres. Both superior temporal areas activity of the N250 response correlated only with the left N170 source (L VWFA). Overall, these results suggest a strong relationship between the left occipital source VWFA in the reading processes and the auditory processes in both hemispheres, supporting the proposed hypothesis, in which the auditory and reading processes are interlinked. The positive correlation results found in the brain-to-brain analysis suggest that the two modalities behave similarly, reflecting a compensatory or a complementary system that act consistently across the two modalities. This implies that a smaller N170 reflects more efficient print encoding, a result that is in line with previous literature (González et al., 2016; Mahé et al., 2012; Maurer et al., 2006).

Reading level did not affect the correlation results, as indicated by the partial correlation suggesting that both modalities (visual and auditory) are directly linked. This may suggest that both processes may share some common functional and structural networks with each other. The partial correlation indicates that the reading skills does not affect the correlation effect, although it does remain a strong reflector of these processes at the behavioral level. Earlier findings have revealed the presence of associations between the modalities (Garcia et al., 2019; Pugh et al., 2013), but further investigation is required. From these results, it became possible to show the direct relation between the two routes visual and auditory, suggesting a link between the VWFAs and STAs.

4.3 Auditory P3a response to speech in children with or without attentional deficit (Study III)

The third study compared brain dynamics of speech processes, and how they are associated with the attention-switching response (P3a), between children with attentional problems (AP) and typically developed children (CTR).

A significant difference between the CTR and the AP group at the P3a time window was found in the native language processing (in the *sai-suu* contrast). This result is in line with earlier studies (Barry et al., 2003; Van Mourik et al., 2007; Tsai et al., 2012). Larger P3a response in participants with attentional problems compared to typical participants has been consistently reported in the literature (Van Mourik et al., 2007; Gumenyuk et al., 2005; Oja et al., 2016). However, significant group differences were found only for brain responses in the native condition *sai-suu*. This may indicate specific attentional processes related to the stimulus phonological structure. The specificity of this contrast is the presence of a native fricative /s/, followed by a diphthong in the deviant /ai/. It is possible that the combination of this specific phonological structure engaged a higher attentional response compared to the other native contrast, where the deviant carries a vowel /ii/, which is a simpler structure than the diphthong.

When contrasted to the physical properties, as indicated by the ED/ COG (see Figure 15), the results showed that the difference found in brain responses was not only related to the stimuli phonological features; other processes may be involved in this response such as attentional processes related to the complexity of the stimuli (for example, diphthong vs vowel). The sound complexity on ERP responses was shown in earlier literature (Čeponienė et al., 2002). Moreover, the phonological brain mapping of the vowels may have contributed to this response, where the differences in vowel mapping (between /u/ /i/ and /ai/) may have generated larger differences in brain processes for one deviant stimulus compared to the other when contrasted to the standard, creating a clearer group difference, as reported above (Lennes et al., 2010). Another contributing factor could be the semantic differences between the different stimuli. The contrasts between syllable-word and word-word may create different attentional processes. There is previous evidence that brain processes differ between words and pseudowords (Ziegler et al., 1997), where both semantic and attentional processes interact, not only in native language, but also in a second language

(Trofimovich 2008). Both processes were shown to affect overall the final brain response (Shtyrov et al., 2012). Shtyrov and colleagues (2012) reported larger P3a response to pseudowords than to words; they explained this result as an indicator of the neural processes of lexical search facilitation increased via higher attentional engagement. This result indicates that the brain processes may differ in words and pseudowords processing, despite contradicting the current finding, as the current results showed higher P3a to *suu-sai,* which is the contrast with real words. In a second-language context, Trofimovich (2008) reported that more experienced L2 learners showed higher sensitivity to phonological details of the foreign language; however, the attention to word meaning may affect this sensitivity, causing its elimination independently of the experience level. Thus, and based on previous results, the P3a response could represent a combination of different processes (Wronka et al., 2012), such as attentional, semantic, and phonological processes, as suggested above.

The group difference found in the contrast *sai-suu*, at the sensor level (see Figure 10), was located over the right frontoparietal area. The role of the frontal cortex in the attentional processes has been shown in previous research (Michalka et al., 2015) and was suggested to play a role in directing the attention (Foster et al., 1994; Daffner et al., 2000).

The AP group showed CTR-like brain responses in the foreign language context, with a typical P3a response in the within group-analysis. Statistically, no group differences were found between the AP and the CTR groups in foreign-language processing. A possible explanation of the absence of a group difference is the effect of the semantic processes. Meaning processing was earlier proposed to generate higher brain activation of the attentional processes, especially in a foreign language context (Trofimovich, 2008). This could be the case with the current stimuli, as they may have engaged higher semantic processes because they are relatively new linguistic items compared to the native language. In this case, the participants may have engaged more automatic attentional processes, in processing the meaning of the foreign items, detected as such since the onset of the stimuli due to the distinct first sound (/sh/). This higher activation may hide the group differences of the attentional processes that may become undetectable due to this semantic effect. This may occur when the brain response to the meaning is larger than the attentional response (Trofimovich 2008). Some evidence in the literature points in this direction as the P3a response was shown to be affected by the meaning of the stimuli (for a review, see Parmentier, 2014). Moreover, the unstable phonetic representation of foreign speech sounds, in both groups, may also be a second reason for the absence of clear group differences in attentional processes. As both groups lack neuronal maturity, similar brain responses may result in both groups, making it difficult to observe any differences between the groups.

The correlation analysis between the ERP amplitude and the attention score (ATTEX) showed a significant positive correlation in the P3a time window for both native contrasts (*sii-suu* and *sai-suu*). The P3a response and the ATTEX both acted in the same direction, which may indicate that both measures successfully captured the same neuronal attentional processes; this may indicate the validity of the behavioral evaluation to measure the attentional processes. However, this was only valid for the native language processing, as no significant correlations were found between the attention score and the P3a response in the foreign language context. This may indicate this behavioral test specificity, but also supports the idea of weaker foreign language neural representations, as suggested by the ERP results above.

Interestingly, these correlations showed an effect in the right fronto-parietal region, which is the same brain area that showed significant differences within and between AP and CTR groups. Previous literature has shown the role of this area in the selective attention network (Ptak, 2012), suggesting a top-down input of the frontoparietal area in modulating the auditory cortex during selective attention in speech processing (Lesenfants & Francart, 2020; Wikman et al., 2021). Thus, these results represent evidence that the P3a response reflects the attentional processes with a main contribution of the frontoparietal right area, but also with the contribution of additional generators located in the temporal areas, as revealed by the source reconstruction analysis.

The source reconstruction analysis of the P3a response showed a diffused neural network including sources in the auditory areas. The areas that were revealed to be active in the CTR group were the temporal, parietal, and frontal regions, with a main activation in the temporal areas (bilateral fusiform areas). Similar brain areas and similar activations were found in the AP group source reconstruction analysis, with higher neural activations found within this group than in the CTR group. Overall, the source reconstruction analysis revealed that the attention network had similar brain activations to those described in the literature, both in typical (Ptak, 2012; Lesenfants & Francart, 2020) and in AD/HD participants (Bush 2010; Salmi et al., 2018), with a strong similarity between the results of the current study ant the results reported by Wronka et al. (2012). Previous studies and the current study reported source origins of the P3a in the temporal, parietal, and frontal regions. The selection of sensory stimuli was shown to be mediated by the dorsal fronto-parietal network, whereas the saliency detection was processed by the ventral fronto-parietal network (Corbetta et al., 2008). The additional sources (located in the thalamus, cingulate cortex, and the temporo-parietal junction) were also documented in previous studies (Konrad et al., 2005; Xuan et al., 2016). It has been suggested that both dorsal and ventral systems were functionally altered in the context of attention deficit (Cortese et al., 2012; Castellanos & Proal 2012; Cao et al., 2014; Rubia et al., 2014), with larger neural activity of the default mode network (Salmi et al., 2018).

In addition to its role in attentional processes, the frontoparietal area was shown to play a role in working memory (Ptak, 2012; Polich, 2007). Previous studies by Knight (1984 and 1996) showed that the hippocampal and prefrontal areas contribute to the P3 response. This evidence indicates a possible effect of the working memory (WM) on the ERP results. The working memory was earlier shown to play a role in holding the temporary information via the activation of the dorsolateral prefrontal cortex while processing the stimuli in the animal models and human neuroimaging studies (Wronka et al., 2007). The contribution of the WM to the attention-switching P3a response was also investigated by Berti (2016) in a visual task. The results of that study showed that the P3a response reflected the initial processes of information selection in WM, but not in the updating of the WM itself. Frenken and Berti (2018) also studied attention shifting in WM within the P3a component, highlighting that attention shifting in WM was an internal process that was hard to disentangle. A similar contribution of the WM could also be present in the processing speech stimuli; thus, this interpretation remains possible. Moreover, a recent study showed the effect of WM training on both P3a and P3b responses in children (Xu et al., 2021). The literature has also suggested that the latencies and amplitudes of the P3a and the P3b may represent the performance of the WM function (Xu et al., 2021). The literature showed the presence of a relationship between the P3a and working memory; however, further investigations are necessary to clarify this idea in a speech-processing context.

Overall, evidence from the literature supports the findings of source reconstruction and correlation analysis, both of which suggest a major role of the right frontoparietal area in the attentional processes, in typical subjects and in those with attentional problems.

The source activity in the CTR group varied between the two native contrasts, showing different brain activities for each difference (deviant–standard). This difference could be related to the engagement of different brain areas depending on the physical properties of the stimuli. The source activity in the AP group showed activations (higher activations) in similar brain areas to those found in the CTR group in native language processing. Differences in source activity between CTR and AP participants have been reported in previous studies, showing abnormalities in the frontal and temporoparietal areas (Bush et al., 2011; Goepel et al., 2011; Janssen et al., 2016). This enhanced source activity of the AP group reflects the larger P3a ERP amplitude observed at the scalp level within the same group. An enhanced activity was equally reported in AD/HD subjects investigated via fMRI technique in auditory discrimination task (Salmi et al., 2018). The source activity results remain in line with the ERP interpretations.

4.4 General discussion

This dissertation examined the brain correlates of speech processing within the context of reading and attentional difficulties in 11–13-year-old children via various methods. The interactions of reading and attentional brain dynamics with the language network via speech processing were thoroughly investigated.

Studies I and III investigated brain responses to speech sounds in typically developed children and in children with reading or attentional difficulties. Both studies used the auditory oddball paradigm and applied ERP and source analysis methods. Moreover, both studies examined native and foreign language processing via the analysis of the discriminatory (MMN and LDN in Study I) and attentional (P3a in Study III) brain responses.

The auditory oddball paradigm was used differently in Study II, as the focus was on the speech perception, where only the standard stimulus was investigated. Study II also used a reading task to investigate the visual reading response in typical and poor readers. The neural correlates of speech and reading were investigated via ERP, source reconstruction, and EEG-eye-tracking /FRP methods. The common ideas and conclusions between these studies are discussed and detailed below.

In Study I, the results of the discriminatory responses within the CTR group suggest the activation of distinct mechanisms in processing a native and foreign language. This result seems contradictory to the phonological transfer theory, which proposes a transfer mechanism between the two languages, as this result is more in favor of a language specific processing than a shared mechanism. Furthermore, the ANOVA results of Study I provide additional support for this language effect.

Studies I and II investigated the cortical responses to speech items in two different contexts. Study I investigated the ERP discriminatory responses (MMN and LDN), both in native and foreign speech processing, in CTR and RD subjects. Study II investigated the basic auditory processes (P1– N250) of speech perception in native language within the same subjects (CTR+RD combined in one group in Study II). These auditory responses were correlated with the visual brain response to print as reflected in the component (N170). In Study II, the early basic auditory responses (P1– N250) showed strong evidence of the phonological brain processing of syllable-words (CV) items, with the presence of double-peak responses in both P1 and N250, reflecting the sensitivity to the phonological units (the consonant and the vowel) and showing that the physical properties had a clear effect on the early obligatory brain responses. The effect of the coarticulation was also interpreted as a cumulative response, mainly observed in the N250 components, which showed higher amplitudes. Interestingly, the same coarticulation effect was also suggested to affect the MMR response in the discriminatory processing. This expectation was approved by the findings in Study I. As Studies I and II used the same stimuli and investigated the brain responses of the same subjects, combining the results from the two studies may suggest that two types of processing – a coarticulation effect and a discriminatory effect – probably co-occur within the same time range, depending on the cognitive needs of the task. This could be evidence of the shared neural mechanism between the two systems involved in these processes.

Within Study II, the P1–N250 complex response showed continuous brain responses, reflecting a relationship between the different processes and their continuity. The ERP results of this second study hints at the existence of parallel processes (phonological identification, coarticulation effect, syllable processing, memory trace formation, and even semantic processing) occurring during the first time window (between 30 ms and 250 ms). This parallel processing was earlier suggested in the literature via the dual stream model (e.g., Hickok &

Poeppel, 2007; Fridriksson et al., 2015). In the current findings, this processing continuity was indicated by the ERP response pattern, but also observed in the source reconstruction of the P1–N250 response (see Figure 8). Similar neuronal sources were observed between the different components in favor of the parallel processing; however, additional sources also emerged across time, reflecting different processes but also additional cognitive engagement through time, in favor of the continuity idea. This also reflects the high sensitivity of the brain to the various features carried within the stimulus that may require different processes.

The N250 sources were more anteriorly and ventrally located than the P1 sources. The dorsal stream (here reflecting the P1 sources) has earlier been proposed to be mainly engaged in phonological processing, whereas the ventral stream (mainly N250 sources) was described as being more involved in the semantic processing (Hodgson et al., 2021; Wagley & Booth 2022). The current interpretations support the previous models proposed in literature. The source analysis of the obligatory responses, conducted in Study II, showed that different brain areas were involved in speech perception, supporting earlier findings with the activation of the A1s, STAs, and left IFAs as main source generators of the obligatory responses (P1–N250). This result was in line with previous evidence on the language network (see Introduction) and as illustrated above in Figure 1 and Figure 2.

Study II also investigated the reading processes via the analysis of the visual reading component N170 on the scalp and on the source levels. The main source generator of the reading N170 was found over the VWFAs with a bilateral activity. The literature has proposed that bilateral brain activation or a dominant brain activation of the right VWFA reflects the atypical visual brain response in reading among subjects with RD (Brem et al., 2020; Fraga-Gonzáles et al., 2014). The neural activation of this area has been shown to correlate with the reading skills, an idea that is in line with previous findings (Brem et al., 2010; Simon et al., 2013).

In Study I, although both discriminatory responses (MMN and LDN) did not show any statistical group differences in the direct group comparison of the difference waves, there were some hints of a grouping effect (depending on reading skills) based on the inspection of brain responses of each group. The ERP results showed higher brain activations in the RD group with the complete absence of the LDN effect within this group. However, the LDN effect was present in the different contrasts within the CTR group, although this went undetected in the group comparisons.

To further investigate these results, a more direct analysis was conducted via the brain-to-behavior correlations within the same subjects in Study II**.** The results of Study II were supportive of the suggestion from Study I**,** which clearly showed the brain responses correlating with the reading scores in the brain-to-behavior analysis. Although Studies I and II investigated different processes, the results led to the same conclusions of a group effect and that the brain responses were affected by the reading skills. A second confirmatory result of this speech-reading relationship was the presence of significant correlations between the source activity in the speech perception task and the source activity of the reading task. This result showed the neural continuity of the auditory and visual modalities in the reading context and approved previous models and theories proposing shared neural networks (Broce et al., 2019; Kearns et al., 2019; Rueckl et., 2015) between the two modalities (see Figure 2) in a bidirectional relationship between speech and reading (Goswami, 2000) as commonly proposed in developmental research (Guttorm et al., 2010; Leppänen et al., 2010; Lohvansuu et al., 2018; Molfese et al., 2000; Schaadt et al., 2015). Thus, the current result represents new evidence for the continuity theory by showing a direct relationship between the two modalities in the context of reading and reading disorder – a tie that remains present despite being tested in two independent tasks. These results represent evidence of continued reliance on the auditory system, even after several years of exposure to print; this reflects the dependence of the visual reading system on the auditory system. Furthermore, the results showed the brain dynamics of the two processes and revealed the direct relation between the STAs and the left VWFA.

Studies I and III investigated foreign language processing and compared the brain activation in the two languages (Finnish vs English) in two target samples: RD and AP, respectively. Study III revealed no significant group differences between the CTR and AP groups in a foreign language context. Similarly, Study I found no group differences in a foreign language context between CTR and RD groups. In both studies, brain representation of the foreign language was hypothesized to be weaker than that of the native language. The absence of significant group differences between the groups in the two studies may be interpreted as similar brain responses in both typical and atypical populations. The exposure time still appears to be insufficient to build a native-like representation at this age group, as these children were exposed to a foreign language (English) indirectly (through TV and media) and for a short period at school. This finding confirms the hypothesis that neural representation of the foreign language probably did not reach maturity in neither of the groups at this age.

Moreover, Studies I and III revealed a language effect. In Study III, a language effect was found based on the brain activity and the correlation analysis showing significant correlations between the attention scores and the brain activity only in a native language context. Study I showed a clear language effect, as concluded from the cluster-based permutation tests and found clearly in the ANOVA results.

The other similarity found between these two studies (Studies I and III) is related to the conclusion from comparing the Euclidean distance effect between the different speech items on brain responses. Both studies showed brain sensitivity to the stimuli phonological variations in contrast processing, which were partially related to the physical features of the different stimuli. However, the ED was shown not to be the only factor involved in these brain responses. Although the ED may play a role, further processes clearly affected the final ERP responses. For example, coarticulation, semantic and memory processes were proposed in Studies I and III to be part of the discriminatory and attentional processes, which seem to occur in parallel to the stimuli feature processing.

The source reconstruction in Study III showed the activation of diffused neural networks, in both CTR and AP groups, with a main activation in the temporal, parietal, and frontal regions. This result closely reproduces previous findings in the literature describing the attentional fronto-prietal network (Ptak, 2012; Lesenfants & Francart, 2020; Wronka et al., 2012) and approves the current attention network as illustrated in the recent model (see Figure 3). Interestingly, the current results indicate that the right frontal area seems to play a key role in the attentional processes involved in speech processing, which may also be specific to the current study context and stimuli.

Studies I and III showed enhanced brain responses in atypical populations (RD and AP) compared to controls as observed via higher amplitudes in the ERP analyses and stronger brain source activity in the source reconstruction analyses. Interestingly, this observation is in line with the comorbidity theory and with previous evidence suggesting a similar neural basis in the RD and AP disorders. This finding may be explained by the existence of common or similar mechanisms in these two disorders, where both groups showed what seems to be a compensatory response via enhancing the brain neural activation.

In conclusion, this dissertation investigated different axes of the relationship between speech, reading, and attentional processes in children with and without reading or attentional difficulties. Studies I, II, and III all tap into different processes and brain mechanisms, where the investigation applied a variety of methods and techniques based on brain and behavioral measures. The overall findings provide new evidence and extend the current knowledge on both reading and attentional disorders and allow a better understanding of the brain dynamics underlying speech processing in different learning disorders (RD and AP), but also in different linguistic contexts (native vs foreign language). This research provides further insight into the most reported neuro-developmental disorders reported in school-age children.

4.5 Limitations

All of the studies used a two-deviant two sequence auditory oddball paradigm to investigate the different brain processes in native and foreign languages and in different populations of children with or without learning disorders. This paradigm was used to replicate the original paradigm designed by Ylinen and colleagues (2019). However, the paradigm used in the current studies (Studies I and III) kept only two of the three deviants from the original paradigm, which contained three deviants in each language block. The three deviants were designed to maintain the balance of words and pseudowords in each language. It was not possible to maintain this balance in the current research because the length of the experiment was relatively long for the participants. The experimental series that each participant had to perform during one visit in the laboratory had a duration of 3.5–4 h; therefore, the decision was made to reduce the length of the paradigm by discarding one of the conditions. This decision could have affected the interpretation of some results, especially for the pseudowords, because the foreign language block does not contain any pseudowords. This makes it difficult to reach any conclusions on the role of semantic effect on the foreign language processing.

Another limitation of this experiment is the fixed block design. Although it again altered the balance of the experiment, the choice was to maintain a fixed-order presentation of a first native (Finnish) and second foreign (English) block, for two reasons. The first reason is related to a possible effect of the foreign language memory traces on the native language processing in case the foreign block was presented first. As English language items are phonologically salient and distinct from the native language due to their onset phonological item, they could affect the processing of the next block after some exposure. The second reason is to obtain at least one full data set (here, the native language data) to be able to compare the brain responses between the different groups, in case the data quality was not sufficient, or the number of participants was not enough. In this case, the fixed balance made it difficult to conclude a clear language effect as the effect of language was confounded with the order effect.

Another limitation in these stimuli choices is the use of two types of languages; one is a transparent language (the Finnish language), and one is an opaque language (the English language). The opacity of language may affect some processes in speech processing and in reading. Although the reading system is known to be universal across languages (Feng et al., 2020; Li et al., 2022; Rueckl et al., 2015), it has been shown that the bilingual brain forms language specific networks for the reading mechanisms for each language by activating neuronal responses differently according to the language in use (Marks et al., 2022). This means that the brain networks may also be somehow activated differently between the two languages due to this factor (transparency), not only due to the nativeness of the language.

Studies I and III, the group sizes were not equally distributed among the CTR group and the groups with learning difficulty (with RD or AP). This may have created some differences in the group analysis because the signal-to-noise ratio was different for each group. Although the small group sizes (RD and AP) may show lower statistical power, the results remained satisfactory. Despite the drawback of noisier signals, the atypical populations group sizes remain acceptable for EEG research. Furthermore, the target ERP brain responses were clearly present on the group averages.

In addition to the group size limitation, the gender group ratio (male: female) was different within the three studied groups. Although this ratio was respected in the CTR group with equal number of boys and girls (1:1), it was not possible to maintain in the RD (3:1) and AP (6:1) groups. One factor that directly affected this ratio was the natural occurrence of these disorders in males and females, where males are known to be more affected by these developmental disorders. As a random sample of school children was included in these studies, this factor was not controlled. Consequently, these data sets did not make it possible to conduct any gender analysis or to make any conclusions about the gender effect on the obtained ERP responses.

Another limitation of this research is the use of an indirect method to estimate the brain areas in Studies II and III. As is well known, the source reconstruction is an indirect method that uses the electrical scalp information to reconstruct the neural sources via specific algorithms. This method remains reliable, as this reliability has been shown in previous studies, and by the frequent clinical applications (Beniczky et al., 2016); also, Studies I and III both successfully reproduced previous findings using source reconstruction methods in EEG and MEG studies and reporting similar sources. Furthermore, the results of most of the reconstructed source localizations revealed similar brain areas to those found in other studies using, for example, fMRI. Without claiming that this method is equivalent to MRI, the source reconstruction does have high value to answer some research questions related to the activity of brain areas. However, this method carries the very high temporal resolution of the EEG method, that other methods (such as MRI) cannot achieve, along with a good/acceptable source localization result. Within this same limitation, there is also the fact that a standard template offered by software was used for the source reconstruction. Although the template was age-appropriate, future studies could improve this application by using the participants' MRI scans for better localization accuracy.

A final limitation is related to the correlation analysis interpretations. The results of Studies II and III showed the presence of significant correlations, both in brain-to-behavior and brain-to-brain, highlighting the different relationships between the different processes and brain areas. However, it was not possible to know the casualties (direction) of these relationships as the current experimental design and analysis do not allow such conclusions.

4.6 Future directions

As introduced in the introductory part of the dissertation, reading and attentional difficulties are both known to often show comorbidity and to share behavioral, neural, and genetic similarities in a high percentage of children diagnosed with reading difficulties. Thus, it will be interesting to investigate a comorbid group with both attentional and reading problems and to study these same brain responses, such as the processes investigated in Studies I, II, and III in this group. It will be even more interesting for the same study to include a direct comparison between the RD and AP groups (so far investigated separately in the studies in this dissertation) and compare that with the comorbid group. This will not only bring complementary information to the current dissertation, but also to the existing literature, as this area requires further investigation and additional evidence to the comorbidity science.

Another interesting future research is to use this EEG data in a functional connectivity analysis in order to elucidate the relationship between the different brain areas and to explore their directionality in each group; this was not possible to conclude in the current research due to the methodological limitations. As high cognitive functions require functional integration of neural networks, this method is appropriate for this type of investigation. Functional connectivity analysis in EEG is known to be one of the most informative methods for investigating brain dynamics, as it makes it possible to investigate the processes and dynamics on the millisecond scale.

Finally, future research could also combine different methods to more profoundly investigate these groups' brain activity; for example, it would be interesting to use MRI/fMRI, magnetic resonance spectroscopy (MRS), or diffusion tensor imaging (DTI) to better understand the relationship between the reading and attention networks and their neural mechanisms within different contexts. It would also be interesting to investigate the genetic background of these different groups and link that to their brain responses and behavioral evaluations, as there is already evidence in the literature on a genetic effect. This type of multi-methodological study allows better identification of individual profiles, understanding the functional and structural dysfunctionalities in the case of disorders, which can offer a better ground for clinical evaluation and facilitate the diagnosis process or offer possible target therapies in clinical application.

YHTEENVETO (SUMMARY)

Aivoaktivaatio äidinkielisen ja vieraankielisen puheen ja painetun tekstin prosessointiin sellaisillalapsilla, joilla on lukemisen tai tarkkaavaisuuden vaikeuksia

Lukivaikeudet ja tarkkaavaisuushäiriöt ovat yleisimmin raportoituja oppimishäiriöitä kouluikäisillä lapsilla. Mittavasta tutkimuksesta huolimatta useisiin näiden oppimisvaikeuksien aivoperustaan liittyviin kysymyksiin ei olla vielä saatu vastausta. Tässä väitöskirjassa tutkitaan puheen prosessoinnin, visuaalisen lukemisen prosessoinnin ja auditiivisen tarkkaavaisuuden prosessoinnin neuraalisia korrelaatioita tyypillisesti kehittyneillä lapsilla ja lapsilla, joilla on lukemisen tai tarkkaavaisuusden vaikeuksia. Tutkimuksessa käytettiin aivovasteita (ERP), fiksaatiopotentiaaleja (FRP, silmänliikkeisiin aikasidottuja aivovasteita) ja aivoaktivaation lähdemallinnusmenetelmiä. Lisäksi tutkimuksessa käytettiin käyttäytymistason mittareita täydentämään aivojen tuottamaa tietoa. Tutkimuksessa I tutkittiin aivojen esitietoista erottelua mittaaviaprosesseja, poikkeavuusnegatiivisutta (MMR) ja myöhäistä erottelunegatiivisuutta (LDN) äidinkielen (suomi) ja vieraan kielen (englanti) puheärsykkeisiintyypillisesti kehittyneillä lapsilla (kontorlliryhmä, CTR, N=86) ja lapsilla, joilla oli lukemisen vaikeuksia (RD, N=26). Lukivaikeusryhmässä havaittiin epätyypilline erottelua heijastava aivovaste ollen suurentunut sekä äidinkielisiin että vieraskielisiin puheääniin. Lisäksi aivovasteet poikkesivat toisistaan äidinkielen ärsykkeisiin verrattuna vieraan puheen ärsykkeisiin kummassakin ryhmässä. Tutkimuksessa II tutkittiin puheen havaitsemiseen liittyviä aivojen perusvasteita ääniin (ns. P1-N250 komponenttia) ja niiden yhteyksiä lukemisen perusprosesseja heijastaviin visuaalisiin aivovasteisiin (ns. N170 komponenttiin) lähteen paikannusmallinnuksen avulla. Kuulotiedon ja puhetiedon käsittelyä heijastavien aivoaktivaatiolähteiden välillä havaittiin yhteyksiä. Aivojen ohimolohkon kuulo-ja puhealueiden aktivaatiolla oli selkeä yhteys sanantunnistusta heijastavaan aktivaatioon ohimo-ja takaraivolohkojen liittymäkohdan läheisyydessä olevalla ns. visuaalisella sanan tunnistamisalueella (VWFA). Lisäksi puheen prosessointia heijastava aktivaatio oli yhteydessälukutehtävässä suoriutumiseen. Tutkimuksessa III tutkittiin tahattoman huomion suuntaamista heijastavaa aivovastetta (ns. P3a) sekä äidin että vieraan kielen puheärsykkeisiintyypillisesti kehittyvillä lapsilla ja lapsilla, joilla oli tarkkaavaisuuden pulmai (N=17). Tulokset osoittivat, että P3a-vaste äidinkielisiin puheääniin erotteli ryhmiä ja oli yhteydessä tarkkaavaisuutta mittaaviin opettajan arviointeihin. Vieraan kielen prosessointia heijastavilla aivovasteilla ei havaittu olevan yhteyksiä tarkkaavaisuuteen. Tarkkaavaisuuden hermoverkkoa tutkittiin myös lähteenpaikannus analyysin avulla. Tarkkavaaisuuspulmaisten ryhmässä havaittiin suurentuneita aivovasteita sekä lähdeaktivaation että sensorien (päänpinnalta) mitattavien aivovasteiden tasolla. Kaiken kaikkiaan tämän väitöskirjan tulokset osoittivat eroja tyypillisesti kehittyvien lasten ja oppimisen vaikeuksista kärsivien lasten sekä eri kielisiä ärsykkeitä heijastavien aivovasteiden välillä.

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ORIGINAL PAPERS

I

DISCRIMINATORY BRAIN PROCESSES OF NATIVE AND FOREIGN LANGUAGE IN CHILDREN WITH AND WITHOUT READING DIFFICULTIES

by

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Article

Discriminatory Brain Processes of Native and Foreign Language in Children with and without Reading Difficulties

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Abstract: The association between impaired speech perception and reading difficulty has been well established in native language processing, as can be observed from brain activity. However, there has been scarce investigation of whether this association extends to brain activity during foreign language processing. The relationship between reading skills and neuronal speech representation of foreign language remains unclear. In the present study, we used event-related potentials (ERPs) with high-density EEG to investigate this question. Eleven- to 13-year-old children typically developed (*CTR*) or with reading difficulties (*RD*) were tested via a passive auditory oddball paradigm containing native (Finnish) and foreign (English) speech items. The change-detection-related ERP responses, the mismatch response (MMR), and the late discriminative negativity (LDN) were studied. The cluster-based permutation tests within and between groups were performed. The results showed an apparent language effect. In the *CTR* group, we found an atypical MMR in the foreign language processing and a larger LDN response for speech items containing a diphthong in both languages. In the *RD* group, we found unstable MMR with lower amplitude and a nonsignificant LDN response. A deficit in the LDN response in both languages was found within the *RD* group analysis. Moreover, we observed larger brain responses in the *RD* group and a hemispheric polarity reversal compared to the *CTR* group responses. Our results provide new evidence that language processing differed between the *CTR* and *RD* groups in early and late discriminatory responses and that language processing is linked to reading skills in both native and foreign language contexts.

Keywords: speech perception; native language; foreign language; reading difficulties; MMR; LDN

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1. Introduction

Dyslexia is a frequent developmental impairment when learning to read and spell; it appears independently of any sensory impairment or other neurological disorder with a prevalence ranging from 5–10 percent [1–5]. Reading difficulties may appear despite an average or above-average level of general cognitive skills and linguistic performance in spoken language and vocabulary [6]. Dyslexia has been linked to problems in developing well-defined phonological representations [7,8] or to problems in accessing them [9–11]. These problems have been thought to occur in a large percentage of dyslexic readers [12]. Poor phonological processing skills in dyslexics have been linked to speech perception abilities in a foreign language, including second-language learning [5,13,14]. Despite the phonological processing difficulties behind problems in foreign language learning and its relation to the native language in dyslexia, the background of learning challenges remains poorly understood. Studying brain responses in foreign language processing may make it easier to understand the origin and possible defective mechanisms that may cause learning difficulties in such a context [14,15]. Therefore, the present study aims to a better understand the relationship between native and foreign language processes and to investigate the possible link between language processing and reading difficulties. We are particularly interested in investigating how the discriminatory processing of native and foreign spoken language at the level of brain responses differs between school-aged children with reading difficulties when contrasted to typically reading control children of the same age.

1.1. Language Development and Speech Processing in Typical Readers and in Dyslexics

Speech perception is based on mapping basic auditory information into specific phonological units by identifying acoustic features and their boundaries [16]. The perception of foreign speech sounds may rely on the identification of well-established native representations [17–19]. However, these representations may also develop independently when the speech sounds of the foreign language do not exist in the native language [20]. Allophonic theory suggests that, in dyslexia, the brain maintains its sensitivity to irrelevant speech contrasts, which may disturb the development of neural networks for categorical speech perception [2,7,14,21,22]. Several studies have shown the link between early auditory and speech perception abilities measured during the first year of life to the later emergence of reading difficulties [23–27]. Researchers from the Jyväskylä Longitudinal Study of Dyslexia [28–30] have reported associations between brain activations at six months, preschool-age cognitive skills, and reading development up to 14 years of age [25]. In line with these findings, the longitudinal project of the Dutch Dyslexia Program showed a correlation between early event-related-potential (ERP) responses to speech sounds at the age of two months and later reading skills measured between seven and nine years of age [31–33].

1.2. Native and Foreign Language Acquisition in Dyslexia

Previous studies on native and foreign language learning have suggested that proficiency in the first language affects second language learning skills highlighting the presence of a possible link between processing the two languages [34,35]. Other studies have suggested possible phonological awareness transfer mechanisms across languages [15,36–38]. This question has been addressed mainly from a bilingual point of view [39]. The speech perception of foreign language has been rarely studied in the context of reading difficulties. If difficulties in phonological processing are independent from the language–that is, universal–the processing of both the native language and a foreign language is likely to be deficient in the case of dyslexia. However, it is not fully clear how compromised speech perception skills in the first language may affect the learning of a foreign language [40–42]. Learning a foreign language remains challenging for typical readers as some difficulties may emerge when the foreign language contains speech sounds that do not have equivalent representations in the native language. For example, the English sound [ʃ] does not have an equivalent in the Finnish phonology [5]. These difficulties are amplified in the context of reading problems.

Studies with behavioral assessments, mainly in adults, have shown differences between typical readers and individuals with dyslexia in processing of foreign or second language. For example, Soroli and colleagues explored the speech perception of native and foreign languages in adult dyslexics and showed that word stress discrimination was deficient in dyslexic participants in foreign language processing [14]. Several works have supported the view that first-language deficits may affect second-language learning in dyslexics and normal readers [36,41,43,44], but the brain mechanisms involved are not fully understood. Previous findings on the neural level suggest that the brain activations differ in processing native and foreign language, not only in adults but also in typically developed children to [45–48] (46, p. 150). In a study by Ylinen and colleagues, no atypicalities were found in the brain activations for native language words or in second language speech sound processing in nine- to 11-year-old school children [5]. However, weaker brain activations in the right temporal cortex of dyslexic participants were found in the processing of familiar second-language words. This brain area has been previously reported to play a role in word form learning [49].

The current study adopted a modified version of the two-sequence two-deviant oddball paradigm used by Ylinen and colleagues [5]. The present study investigates the brain responses to native and foreign language processing in 11–13-year-old children with and without reading difficulties. Formal instruction of English (foreign language) started when the Finnish participants of Ylinen et al. and the current study were aged eight and nine. Therefore, we expect this age group to have stronger neural representations for the foreign speech sounds as they have longer exposure to the foreign language compared to Ylinen et al. [5], which was conducted with 9–11-year-old children. The investigation of an older age group may give us a clearer view on foreign language processing in children with reading difficulties and a better understanding of the possible differences in discriminatory brain responses between typical readers and those with reading difficulties.

1.3. Phonological Deficit and Dyslexia in ERP Research

Several studies have shown that speech perception and reading ability are mediated by phonological awareness [12,40,50–53]. The poor categorization of speech sounds, reflecting deficient internal phonological representations, could be the reason for the developmental deficiency in phoneme identification [54–58]. For example, several behavioral studies have shown that children with dyslexia have poor categorization abilities of consonants [2,59,60].

The ERP components obtained in response to speech stimuli are believed to reflect different processes, from sound detection and feature extraction to categorization [16,61–63] (61 p. 89, 62 pp. 14–17). Studies of the neural correlates of auditory and speech perception in dyslexia have applied the auditory oddball paradigm in different versions using different types of stimuli [5,20,25,64–67]. Some of these studies used, for example, consonant-vowel (CV) syllable stimuli. They were conducted in adults and children and showed atypical mismatch response (MMR) and a late discriminative negativity (LDN) response in individuals with dyslexia [16]. The results showed consistently diminished MMR response in both children and adults with dyslexia when processing difference of tones durations and frequencies. An attenuated MMR response was also reported in children with reading difficulties when processing syllable discrimination. Similar results were also found for the LDN with an attenuated response in dyslexics. These ERPs have been shown to reflect acoustic spectral changes within the spoken syllables in the context of reading difficulties [68,69]. Change detection of the phonological structure investigated MMR and LDN responses using the oddball paradigm with syllable stimuli and was shown to reflect the neural maturational state [70,71]. We analyzed discriminatory ERP responses such as the mismatch response (MMR), commonly labeled in literature as the Mismatch negativity (MMN), and late discriminative negativity (LDN).

1.4. The Discriminatory Brain Responses

The MMR component has been largely investigated in auditory [72] and developmental language processing contexts [73], and in relation to reading development [74]. It reflects pre-attentive discriminatory abilities in a pattern regularity violation context [63,75,76]. The MMR is typically elicited in the oddball paradigm and expressed as a negative peak in adults, or as a positive or negative peak in infants and children between 130 ms and 250 ms [77]. The response is visible in the subtraction of the response to a frequently repeated standard stimulus from the response to a deviant stimulus. Moreover, the MMR component has been studied extensively in relation to reading and reading difficulties [65,78–81] and to foreign language learning [5,20,82].

In addition to the MMR response obtained in the oddball paradigm, several ERP studies have highlighted the presence of a later response at a time frame between 300 ms and

600 ms [83–85], which was called the late mismatch response [86–88] or, more commonly, termed as late discriminative negativity (LDN) [70,71,78,80,83,89,90]. The LDN response seems to be co-occurring in the MMR-P3a-LDN complex [65,71,84,91–94], commonly observed in linguistic stimuli, and has been reported to reflect further auditory discriminative and complex cognitive processes [16,65,78,83]. Studying these discriminatory brain responses may give further insight on native and foreign language processing and how it may be linked to reading difficulties.

1.5. Hypotheses and Objectives

This study investigates brain responses in typically developing children (*CTR*) and children with reading difficulties (*RD*) while processing native and foreign speech sounds. The paradigm used is based on the two-sequence two-deviant oddball paradigm presented in Ylinen's study [5]. Our goal is to further investigate whether discriminatory speech processes (MMR and LDN) differ between *CTR* and *RD* groups in native and foreign speech sounds. The participants of this study are two years older than those in Ylinen and colleagues' study. This age group is expected to have a stronger neural representation of the foreign speech items, so this new data may provide further insights into foreign-language processing. This investigation will also look at the relationship between speech perception in both languages and reading. Assuming a weak quality of the phonetic representations in foreign language compared to the native language phonetic representation in the *RD* group and based on previous studies reporting diminished brain responses in dyslexics when processing native speech sounds [5,65,91,95], we may expect a similar effect on foreign-language processing. Based on previous literature, we may expect both MMR and LDN responses to reflect these weaker neural representations via diminished ERP activations [16,87,92]. Thus, abnormal, reduced, ERP responses are expected in the *RD* group in both languages. These responses are hypothesized to be further diminished in the foreign language processing context compared to the native language processing. However, as we are using the same paradigm and stimuli used in Ylinen et al. [5], we expect to observe possible similarities in the results, although they may be contradictory to previous findings. Ylinen found no group differences between the *CTR* and *RD* groups in processing native words and foreign pseudowords. The amplitude of the MMR response for familiar second-language words correlated with the reading skills in native language [5]. Furthermore, we investigated the time course variation of the response patterns and dynamics occurring at the MMR and LDN time windows in each contrast to investigate the variation of the phonological brain representation within *CTR* and *RD* groups. These were studied to better understand the origin of the group differences and to compare the MMR and LDN responses with previous findings in the literature.

2. Materials and Methods

2.1. Participants

We report the ERP results of 86 typically reading control participants (*CTR*) and 26 participants with reading difficulties (*RD*) whose data remained valid for analysis after excluding those with poor electroencephalogram (EEG) data quality or an insufficient number of artifact-free EEG epochs (for a detailed accepted number of trials, see the summary Table S1 in the Supplement). The mean age for the control children was 12.36 years (standard deviation (SD) = 0.27; range = 11.78–12.84; 43 females and 43 males), and for the children with reading difficulties it was 12.31 years (SD = 0.34; range = 11.84–12.94; 8 females and 18 males). The participants invited for the EEG recordings were a sub-sample of 440 children from eight different schools in the area of Jyväskylä city in central Finland, who initially participated in the eSeek project (Internet and learning difficulties–A multidisciplinary approach for understanding reading in the new media (eSeek), project number (274022)) [96]. All participants were native Finnish-speaking school children with no history of neurological disorders, head injuries, or hearing problems, based on the parental reports. They were all studying English as a foreign language in school and exposed to the English language daily through media, such as TV channels or the Internet. The groups were sorted based on a reading fluency score derived from three reading tasks (described below) and computed for each participant over the whole sample. The reading fluency score threshold was set below the 10th percentile for the *RD* group and was set at equal to or above the 10th percentile for the *CTR* group. Additionally, all participants had to score above 15 points in the shortened Raven's progressive matrices test and below 30 points in the Attention and Executive Function Rating Inventory (ATTEX in English, KESKY in Finnish) on the amount of attention and executive function problems. The detailed descriptions for each test are presented below. All participants and their parents signed informed consent forms prior to their participation. The study was conducted according to the Declaration of Helsinki. Approval for the project was given by the ethical committee of the University of Jyväskylä, Finland.

2.2. Selection Criteria and Tests

2.2.1. Reading Score

A latent score was computed for reading fluency using principal factor analysis with PROMAX rotation in the IBM SPSS Statistics 24 program (IBM SPSS Statistics for Windows, Version 24.0. IBM Corp; Armonk, NY, USA). This score was estimated with the following three tests: the Word Identification Test, a subtest of the standardized Finnish reading test ALLU [97]; the Word Chain Test [98]; and oral pseudoword text reading [99]. These tests were loaded to the fluency factor as follows: Word Identification Test (0.683), Word Chain Test (0.872), and oral pseudoword text reading (0.653).

The word identification test included 80 items, each consisting of a picture and four alternative written words. The task was to identify and connect the correct picture–word pairs. The score was the number of correctly connected pairs within the two minutes. The word chain test consisted of 25 chains of four words, written without spaces between them. The task was to draw a line at the word boundaries. The score was the number of correctly separated words within the 90 s time limit. The oral pseudoword text-reading test consisted of 38 pseudowords (277 letters). These pseudowords were presented in the form of a short passage, which children were instructed to read aloud as quickly and accurately as possible. The score was the number of correctly read pseudowords divided by the time, in seconds, spent on reading (for a detailed description of these tests, see Kanniainen's study [100]). The summary of the reading test results for the *CTR* and *RD* groups is presented in Table 1.

Table 1. Summary of the three reading tests (ALLU, Word Chain reading and Pseudoword reading) and the Raven's Standard Progressive Matrice test for the *CTR* and the *RD* groups.

Group		**ALLU**			**Word Chain**			**PW Reading**			**RAVEN**		
	df	**t-Value**	***p*-Value**	**Cohen's d**	**t-Value**	***p*-Value**	**Cohen's d**	**t-Value**	***p*-Value**	**Cohen's d**	**t-Value**	***p*-Value**	**Cohen's d**
CTR vs. *RD*	111		<0.001	1.824		<0.001	2.017		<0.001	1.39		0.192	0.26
			M	**SD**		**M**	**SD**		**M**	**SD**		**M**	**SD**
CTR		4.36	52.39	8.80	0.94	45.39	12.66	3.23	32.96	3.40	3.14	22.95	3.37
RD		1.00	36.69	7.88	0.99	22.23	5.89	1.25	27.11	6.19	3.95	22.11	2.59

Note: *RD* = the group with reading difficulties; *CTR* = the control group; Cohen's d = the effect size; M = Median, SD = standard deviation of each test in the two groups. The FDR correction alpha value is 0.05.

2.2.2. Cognitive Nonverbal Assessment

Participants with a nonverbal reasoning score below the 10th percentile (a score equal to or below 15) in the classroom testing were excluded. This test included a 30-item version of Raven's progressive matrices test [101]. In this task, partially uncompleted pictures are presented to the child with six different options (six possibilities to complete the pattern), and the child's task is to identify the correct solution. The performance was timed and the children had a maximum of 15 min to accomplish the task.

2.2.3. The Attention and Executive Function Questionnaire

ATTEX is a questionnaire filled out by teachers [102]. It includes 55 items designed to screen and measure students' degree of attentional and executive function problems in the school environment. All participants identified with attention deficit (according to their teacher's rating), and those who scored more than 30 points were excluded from this study, as they exhibited attention problems. The summary of the attention test results for the *CTR* and *RD* groups is presented in Table 1.

2.3. Stimuli and Procedure

2.3.1. Stimuli

The auditory stimuli were presented in a passive oddball paradigm, for a total duration of ~20 min. The paradigm was divided into two blocks; the block with Finnish stimuli was presented first, followed by the English stimuli. The stimuli were recorded by a bilingual male native speaker in both Finnish and English and pronounced in a neutral way. These recordings were then screened by native Finnish and English speakers to check for any language bias in pronunciation. The recordings were equalized and normalized in segmental durations, pitch contours, and amplitude envelopes with Praat 5.1.45 [103] and were shortened and resynthesized using the overlap-add method (for a more detailed description of stimuli preparation, see Ylinen's study [5]. The stimuli consisted of Finnish and English consonant-vowel (CV) syllables that were either words or pseudowords (syllables): *shoe* [ʃʊː], *shy* [ʃaɪ], and *she* [ʃiː] as the English stimuli and *suu* [sʊː] (mouth), *sai* [saɪ] (got), and *sii* [siː] (pseudo-word, also a single syllable) as the Finnish stimuli (The spectrograms of the different stimuli are presented in Figure 1).

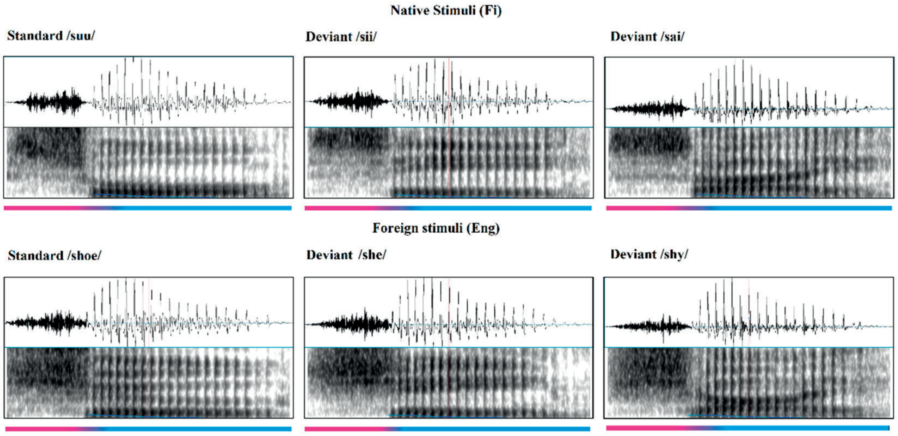

Figure 1. Spectrograms of the stimuli used in the oddball paradigm. At the top are the native (Finnish) stimuli and at the bottom are the foreign (English) stimuli. The color bar below shows the sound change from the fricative (in pink) to vowel(s) (in blue) at around 120 ms.

Finnish phonology does not include the sound [ʃ], so the English items can be easily recognized and identified as a foreign language from the onset of the word [104]. The foreign English stimuli were expected to differ as a function of their frequency of use as words in daily use: *she* is well known and the most frequent of the stimuli, whereas *shoe* and *shy* are known, but less frequent according to the British national corpus [105]. For the Finnish stimuli, *sai* is the most frequent item (the past tense of the verb saada, "to get"), *suu* ("mouth") is less frequent, and *sii* (a syllable without its own meaning) is the most infrequent according to the Finnish language bank [106]. The Finnish items were chosen as the phonetic equivalents to the English items rather than according to their frequency of use. We prioritized the phonology because it is the most important aspect for across languages comparison. The frequency difference was addressed in the previous paper by Ylinen and colleagues. For a more detailed description of the paradigm and stimuli see [5]. The CV syllable type occurs at a rate of 12.7 percent in the Finnish language (for details, see [107] (p. 65)).

The stimuli (standard [ʊː] 800 repetitions, deviant [iː] 100 repetitions, and deviant [aɪ] 100 repetitions) were presented in a pseudorandomized order within each block, with always at least two standard stimuli (and a maximum of five standard stimuli) between the two consecutive deviant stimuli. The inter-stimulus interval between stimuli varied randomly between 850 ms and 1000 ms. The stimuli were presented via a loudspeaker placed on the ceiling approximately 100 cm above the participants' ear positions and were presented at approximately 65 dB(A). The stimulus volume level was tested with an audiometer before each recording. The sound level meter (Type 2235, Brüel & Kjaer system) was used on a pedestal device at the participant position (settings: sound incidence = frontal; time weighting = fast; ext filter = out; frequency weighting = A; range = 40–110 dB; display = max). Summary of the stimuli properties are available in the Supplementary Materials (for details see Table S2A–C).

2.3.2. Euclidean Distance and Center of Gravity

Computation of the Euclidean distance (ED) is commonplace in speech perception and language studies investigating phonological distancing [108–112]. The ED is defined as the scalar sum estimating the difference in phonological/acoustic features between two spoken vowels/items. The ED is applied to a bi-dimensional acoustic space based on tongue position during speech production that correlates with its first (F1) and second (F2) formant frequencies in each item [113]. With the acoustic method, the formant frequencies (F1 and F2) were determined using Praat®software version 6.0.49 [103], and the distance was computed using Excel®2016 software version 16.0.6742.2048 (Microsoft Corporation. (2022)) by applying the following formula:

$$d(p,q) = \sqrt{\sum_{i=1}^{n} (q_i - p_i)^2}.$$

For fricative consonants, computing the center of gravity (COG) is the most common method to calculate the difference in acoustic features between two fricatives. The COG is the phonetic cue in fricative perception consisting of the magnitude weighted average of frequencies present in the fricative spectrum. The COG allows us to distinguish the sibilant fricatives with different places of articulation ([s] vs. [ʃ]) [114]. Importantly, the COG characteristics of a fricative change according to the subsequent vowel (for example, the value for [s] is lower before a rounded vowel, such as [u], than before a non-rounded vowel, such as [i]) [115].

2.4. EEG Recording and Pre-Processing

EEG data were recorded in a sound-attenuated and electrically shielded EEG laboratory room located at the University of Jyväskylä. During the measurement, the child was asked to sit comfortably on a chair while watching a muted cartoon movie playing on a computer screen. The child was instructed to minimize his/her movements as much as possible in order to reduce the artifacts in the EEG recording while listening passively to the auditory stimuli. The behavior of the participant was monitored by the experimenters via a video camera. The data were recorded with 128 Ag-AgCl electrodes net (Electrical Geodesic, Inc., Eugene, OR, USA) with Cz as the online reference with NeurOne®software and using a NeurOne amplifier (MegaElectronics Ltd., new designation: Bittium Corporation). The data were sampled online at 1000 Hz, high pass filtered at 0.16 Hz, and low pass filtered at 250 Hz during the recording. Impedances were aimed to be kept below 50 kΩ, and data quality was checked continuously. All necessary adjustments or corrections were performed during short breaks and between the blocks to ensure the best data quality of the recordings.

Brain Electrical Source Analysis (BESA®) Research 6.0 and BESA Research 6.1 (BESA GmbH, Gräfelfing, Germany) were used for offline data pre-processing and averaging. Bad channels that showed noisy data or movements were identified and corrected via signal reconstruction (interpolation) when possible or discarded from the data (number of excluded bad channels: 5.6 [mean]; range: 1–13). Independent component analysis (Infomax applied on a 60 s segment of the EEG; [116]) was used to correct the blinks from each participant's data. The epochs were set from −100 ms (pre-stimulus baseline) to 850 ms. The artifact detection was set to a maximum threshold of 175 µV for amplitude fluctuations within the total duration of the epoch. A high pass filter of 0.5 Hz, zero phase, was set before the averaging. Bad channels showing noisy data were interpolated using the spherical spline interpolation method [117]. The data were offline re-referenced to the average reference and averaged individually and separately for each stimulus type. Difference waveforms were calculated by subtracting the response to the standard stimulus prior to the deviant stimulus from the deviant response (that is, the deviant minus the standard response). The preprocessing analysis comprised all trials for the deviant stimuli (a total of 100 trials for each deviant stimulus) and the trials before the standard stimulus trials (pre-deviant trials, a total of 200 trials for Finnish standard stimuli and 200 trials for English standard stimuli, 100 for each deviant type). The range, mean number, and SD of the accepted EEG trials in each stimulus type are presented by group and summarized in Table S1, which is available in the Supplementary Materials.

2.5. Statistical Analyses

Two time windows were used in the current analysis: 150–300 ms was used to investigate the MMR response, and 450–850 ms was used for the LDN response. Statistical differences between the two groups' brain responses, between the deviant and standard stimuli within each group, and between languages were estimated using BESA Statistics 2.0, with the nonparametric cluster-based permutation tests (BESA, Germany; for the principles of nonparametric cluster-based permutation tests in M/EEG data; see [118]) The number of permutations was set to 1000 for each contrast, and the channel neighboring distance was set to 4.5 cm (with 129 electrodes). False discovery rate (FDR) correction was applied across the permutation tests [119] to correct the p-value (FDR correction with $p = 0.05$) performed for the between-language comparisons (Finnish vs. English), between-group comparisons (*CTR* vs. *RD*), and within-group comparisons. The obtained values resulting from the permutation statistics should be viewed as rough estimates; they do not reflect the exact range where the processing differs between the stimuli. To investigate whether the *CTR* and *RD* groups process the Finnish and English stimuli differently, we examined the interaction term in an ANOVA model. A two-factor repeated measures ANOVA was performed (2 [Finnish, English] × 2 [*CTR*, *RD*] mixed ANOVA). The mean voltage was calculated over the full different time windows of each ERP component (same time windows as described above) over the selected electrodes. The selection of electrodes was based on scalp distribution voltage maps and on previous literature as the MMR and LDN responses are typically observed in the fronto-central area [70,91,120]. Eight electrodes were selected: E4, E5, E10, E11, E12, E16, E18, and E19. For a montage illustration, see Figure S1 in the Supplement. ANOVA was performed for the difference waves (deviant stimulus–standard stimulus) for both MMR and LDN responses.

3. Results

3.1. Native vs. Foreign Language Processing

3.1.1. Comparisons between Native and Foreign Language Processing in the CTR Group

The difference waves (deviant stimulus–standard stimulus) of the English stimuli and their Finnish counterparts in the *CTR* group are presented in Figure 2A,B. The cluster-based permutation test results showed a clear statistically significant enhancement in discriminative responses in the difference wave comparisons for the MMR (~150–300 ms), but not for the LDN (Table 2). The MMR component was enhanced in the foreign contrasts between the *shy-shoe* (gray curve) compared with the native counterpart *sai-suu* (black curve) and between the *she-shoe* (gray curve) compared with the native counterpart *sii-suu* (black curve). This discriminative difference was clearly present at the mastoids (see Figure 2B).

3.1.2. Comparisons between Native and Foreign Language Processing in the RD Group

The difference wave comparisons (deviant stimulus–standard stimulus) of the English stimuli and their Finnish counterparts in the *RD* group (Figure 2C,D) showed a statistical difference between native and foreign language in the MMR time window (~150–300 ms) for both comparisons *she-shoe* vs. *sii-suu* and *shy-shoe* vs. *sai-suu* (Table 2). The responses to the foreign language were larger than those to the native language. Similarly, for the *CTR* group, no statistical difference was found in the LDN time window.

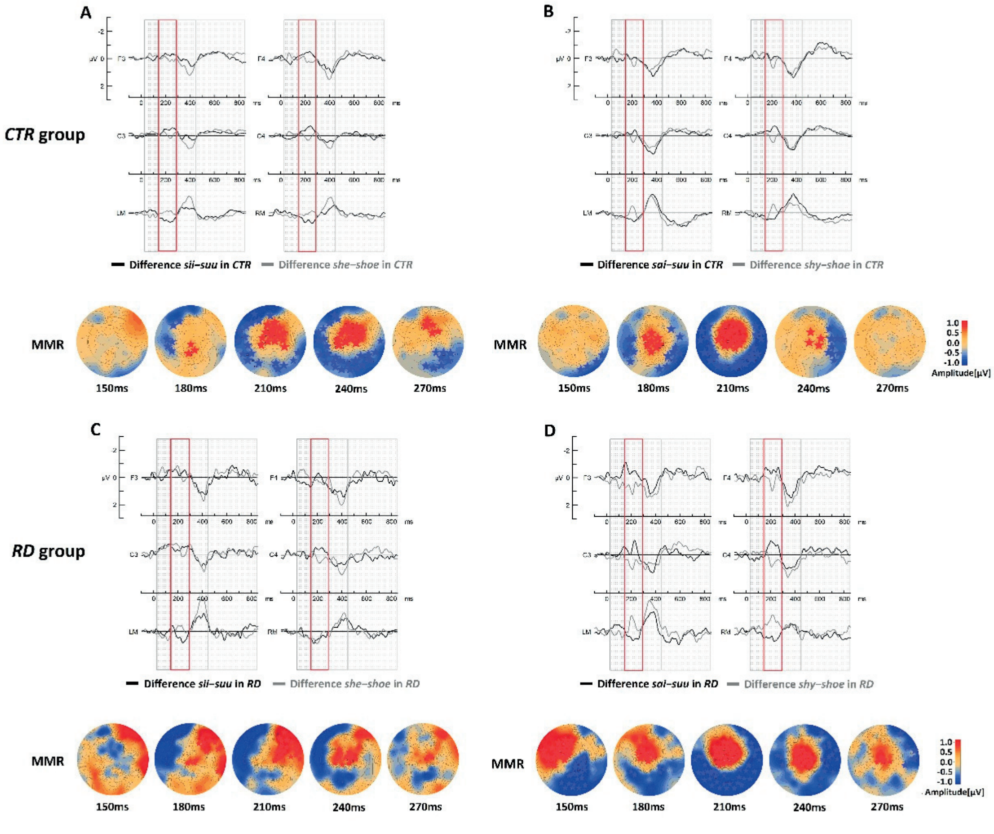

Figure 2. In the top panel, difference waveforms of *CTR* group (**A**) for the contrasts *she-shoe* (in gray) vs. *sii-suu* (in black) and (**B**) for the contrasts *shy-shoe* (in gray) vs. *sai-suu* (in black). The statistically significant difference topographies (English–Finnish) in the cluster-based permutation test results are presented below the corresponding waveforms. In the bottom panel, difference waveforms of the *RD* group (**C**) for the contrasts *she-shoe* (in gray) vs. *sii-suu* (in black) and (**D**) for the contrasts *shy-shoe* (in gray) vs. *sai-suu* (in black). The statistically significant difference topographies (English–Finnish) in the cluster-based permutation test results are presented below the corresponding waveforms. F = Frontal; C = Central; ML = left mastoid; MR = right mastoid.

Table 2. Cluster-based permutation test results of comparison between English and Finnish difference waves for the *CTR* group and for the *RD* group.

	MMR (150–300 ms)	**LDN (450–850 ms)**
	***CTR* group**	
she-shoe **vs.** *sii-suu*	Cluster [171–279 ms], Positive (max. 231 ms), $p < 0.001$ Cluster [170–294 ms], Negative (max. 253 ms), $p < 0.001$	ns
shy-shoe **vs.** *sai-suu*	Cluster [166–252 ms], Positive (max. 208 ms), $p < 0.001$ Cluster [150–254 ms] Negative (max. 206 ms) $p < 0.001$	ns
	***RD* group**	
she-shoe **vs.** *sii-suu*	Cluster [152–276 ms], Positive (max. 195 ms), $p < 0.005$	ns
shy-shoe **vs.** *sai-suu*	Cluster [150–277 ms], Positive (max. 205 ms), $p < 0.001$ Cluster [150–281 ms], Negative (max. 239 ms), $p < 0.002$	ns

Note. The statistical information in each column represents the cluster range, polarity, time point of maximum amplitude, and *p*-value, respectively. ns = non-significant. All the results were FDR-corrected and only results that survived the FDR corrections were included in the table.

3.2. Group Comparison

The group comparisons of the difference waves (deviant–standard) between the *CTR* vs. *RD* groups in each contrast *sii-suu*, *sai-suu*, *she-shoe*, and *shy-shoe* did not show any statistically significant differences between the groups in any of the contrasts (see Figure S2 in Supplement).

3.3. Within-Group Analyses

3.3.1. Within-CTR Group Comparisons for Native Stimuli

The ERP waveforms, amplitude topographies, and cluster-based permutation tests for the control group in both native language conditions, with the deviant stimuli *sii* and *sai*, are illustrated in Figure 3A,B. In the [150–300 ms] time window, the MMR response was observed as enhanced negativity for the deviant stimulus (red curve), with a fronto-central maximum effect between 200–300 ms (~80–180 ms from the CV transition; that is, the onset of the difference between the stimuli), with a slight right-hemispheric preponderance. The MMR response was clearly present at the mastoids with a reversal of the polarity, and less pronounced for the *sai* deviant stimuli than for the *sii* deviant stimuli.

In the statistical cluster-based permutation analyses, the difference between the responses to the deviant stimuli and those to the standard stimuli was statistically significant for both contrasts *sii-suu* and *sai-suu*, with larger responses to the deviant stimuli than those to the standard stimuli. The largest statistical differences appeared between ~180 ms and 240 ms (~60–120 ms from the CV transition) in both native contrasts. The permutation tests showed two clusters: one with a more negative response to the deviant than the standard stimuli at the central area and another with a corresponding more positive response to the deviant at the temporal areas, reflecting the reversal of polarity between the fronto-central and temporal brain areas across the Sylvian fissure. In the late time window [450–850 ms], a slow and late negative fronto-central response (LDN) emerged. The difference was mostly flat, almost null, for the *sii-suu* contrast and more pronounced, with a right-hemispheric preponderance, for the *sai-suu* contrast. In this time window, the difference reached significance after ~550 ms (~430 ms from the CV transition) for *sii-suu*, with only one positive cluster emerging at the occipital area. This effect was somewhat earlier and clearer for the *sai-suu* contrast, emerging at ~500 ms (~380 ms from the CV transition) with two widespread clusters on the frontal and occipital areas. The responses to the deviant stimuli were smaller than those to the standard stimuli. The LDN component was clearly present on the frontal right hemisphere between ~600 ms and 750 ms (~480–630 ms from the CV transition) in the contrast *sai-suu*. This effect was very weak and not clear in the first contrast *sii-suu*.

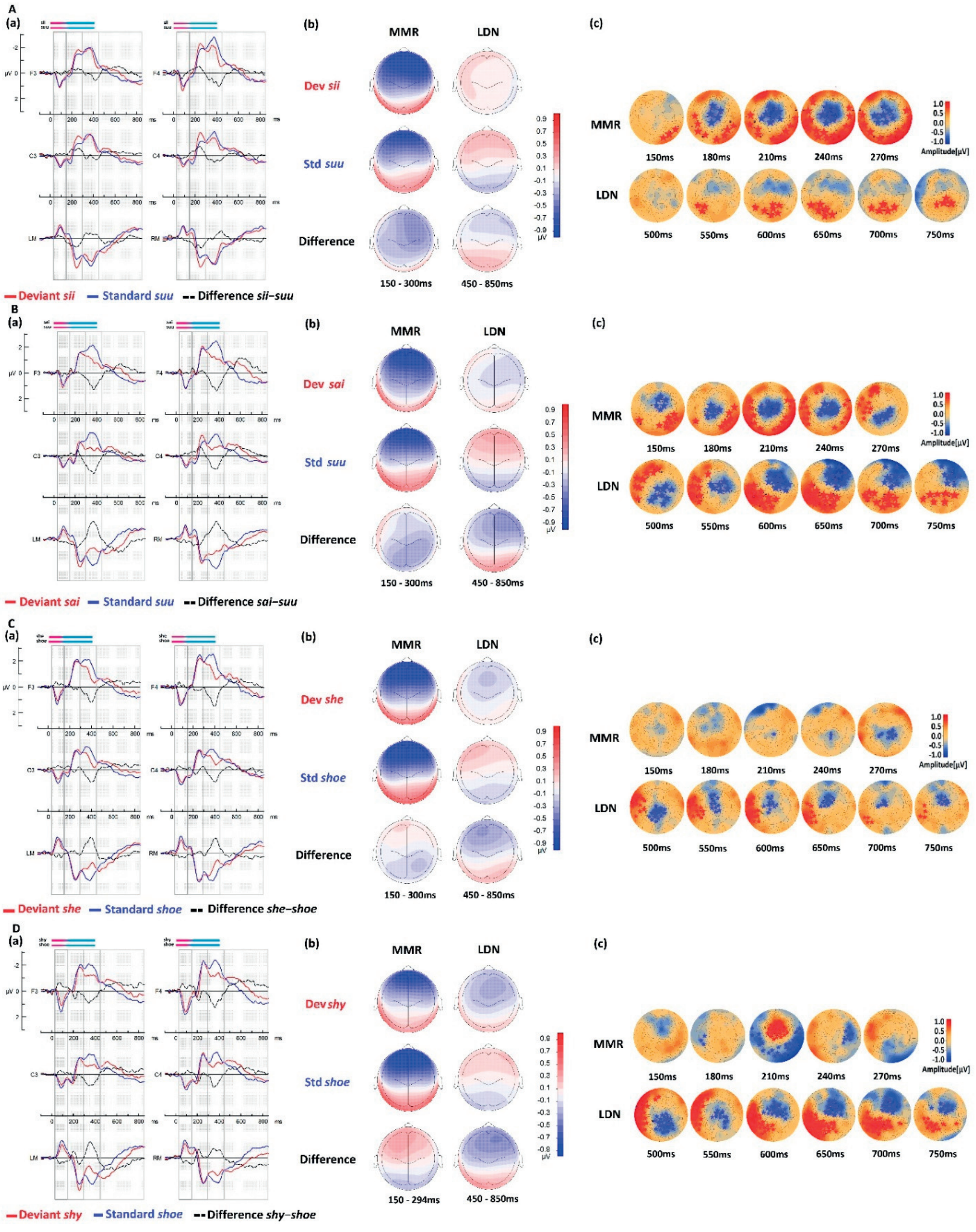

Figure 3. Average brain responses of the control group (N = 86) to the native conditions (**A**) *sii-suu* and (**B**) *sai-suu* and to the foreign conditions (**C**) *she-shoe* and (**D**) *shy-shoe*. (**a**) ERP waveforms of the native language deviant in red, the standard in blue, and their difference wave deviant-standard in black. The windows of interest showing the MMR and the LDN components are highlighted in black boxes. (**b**) Corresponding means topographic maps over the MMR and LDN time windows. (**c**) The statistical cluster-based permutation test results showing significant differences between the responses to deviant and standard stimuli are indicated with stars. Blue and red colors indicate negative and positive amplitude values, respectively. The measuring unit is μV.

3.3.2. Within-CTR Group Comparisons for Foreign Stimuli

The ERP waveforms, amplitude topographies, and cluster-based permutation tests for the control group for both deviant stimuli she and *shy* are illustrated in Figure 3C,D, respectively. At the MMR time window, the mismatch effect seemed weaker with a diminished amplitude than that in the native phonologically equivalent conditions. The MMR polarity for the *she-shoe* contrast (Figure 3C) was negative only at the parietal scalp area. The polarity for the *shy-shoe* contrast was clearly positive in the typical MMR fronto-central areas (see difference wave at 150–300 ms, Figure 3D). Cluster-based permutation tests showed a very small negative cluster between ~210 ms and 270 ms in the contrast *she-shoe* and a brief but more robust, larger, and focal frontal cluster at ~210 ms (~90 ms from the CV transition) in the contrast *shy-shoe*. The response to the deviant stimulus *shy* was larger than the standard stimulus response in this time window, in which the effect was almost absent for the stimulus *she*.

The ERP responses in the late time window were similar to those described in the native conditions (see Figure 3A,B for comparison) with the emergence of a typical LDN. In the LDN window, the difference was significant in both foreign contrasts producing two clusters: one negative in the fronto-central area and one positive in the left temporal area. The response was clearer in these foreign contrasts than in the native ones, and it was more pronounced for the second foreign contrast *shy-shoe* than for *she-shoe*, as it was for its phonologically equivalent native contrast *sai-suu* compared to *sii-suu*. The right hemispheric preponderance of the frontal negative cluster was also found for the *shy-shoe* contrast. The cluster-based permutation test results for the *CTR* group are presented in Table 3.

Table 3. Summary of the within *CTR* group statistics using cluster-based permutation tests for the native (Finnish) and foreign (English) conditions.

	Condition (Deviant–Standard)	
	MMR (150–300 ms)	**LDN (450–850 ms)**
sii-suu	Cluster [154–300 ms], Negative (max. 246 ms), $p < 0.001$ Cluster [150–300 ms], Positive (max. 258 ms), $p < 0.001$	Cluster [532–800 ms], Positive (max. 661 ms), $p < 0.02$
sai-suu	Cluster [150–300 ms], Negative (max. 203 ms), $p < 0.001$ Cluster [150–300 ms], Positive (max. 217 ms), $p < 0.001$	Cluster [450–849 ms], Negative (max. 586 ms), $p < 0.001$ Cluster [450–850 ms], Positive (max. 640 ms), $p < 0.001$
she-shoe	Cluster [207–295 ms], Negative (max. 294 ms), $p <0.02$	Cluster [450–849 ms], Negative (max. 503 ms), $p < 0.005$
shy-shoe	Cluster [183–234 ms], Negative (max. 209 ms), $p < 0.001$ Cluster [175–275 ms], Positive (max. 214 ms), $p < 0.001$ Cluster [231–295 ms], Positive (max. 257 ms), $p < 0.03$ Cluster [263–297 ms], Negative (max. 290 ms), $p < 0.03$	Cluster [450–850 ms], Positive (max. 575 ms), $p < 0.001$ Cluster [450–849 ms], Negative (max. 671 ms), $p < 0.001$

Note. The statistical information in each column represents the cluster range, polarity, time point of maximum amplitude, and *p*-value, respectively. ns = non-significant. All the results were FDR-corrected and only results that survived the FDR corrections were included in the table. The polarity of each cluster indicates the direction of the comparison whether negative (if the second ERP response is bigger than the first) or positive (if the first ERP response is bigger than the second).

3.3.3. Within-RD Group Comparisons for Native Stimuli

The ERP waveforms, amplitude topographies, and cluster-based permutation tests for the *RD* group in both native language conditions with the deviant stimuli *sii* and *sai* are illustrated in Figure 4A,B, respectively. The *RD* group showed similar ERP patterns to those of the *CTR* group. The ERP pattern of the MMR showed a clear effect on the mastoids in both contrasts. However, the statistical cluster-based permutations did not show significance for the contrast *sii-suu* in the MMR time window, unlike the *CTR* group's response to the same first condition. The difference remained statistically significant with two clusters for the *sai-suu* contrast, as it was in the *CTR* group. This central negativity emerged between ~180 ms and 270 ms for this contrast (~60–150 ms from the CV transition). Interestingly, the LDN response did not reveal any statistical differences for the native contrasts in the *RD* group.

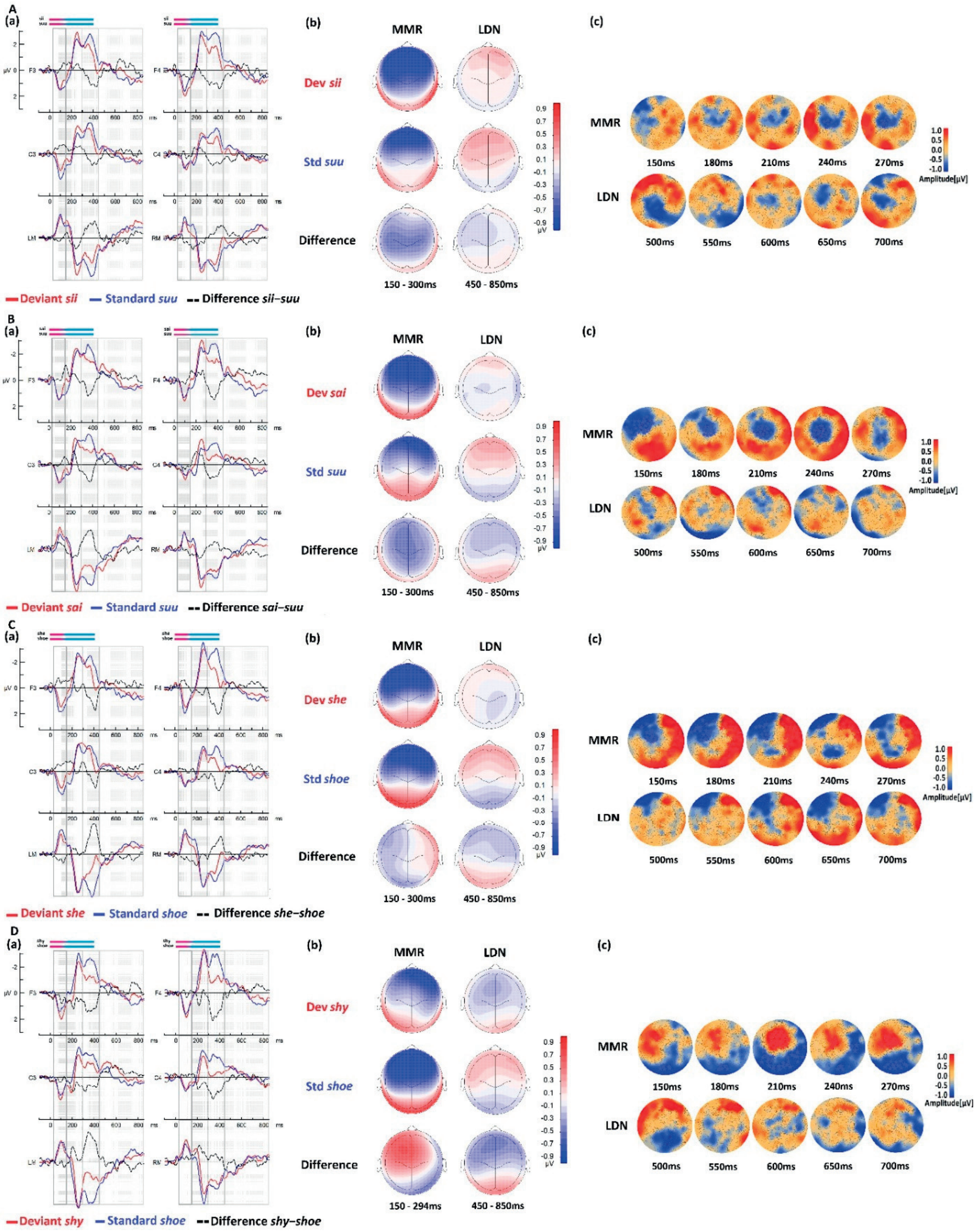

Figure 4. Average brain responses of the reading difficulties group ($N = 26$) to the native conditions (**A**) *sii-suu* and (**B**) *sai-suu* and to the foreign conditions (**C**) *she-shoe* and (**D**) *shy-shoe*. (**a**) ERP waveforms of the native language deviant are shown in red, the standard in blue, and their difference wave deviant-standard in black. The windows of interest showing the MMR and the LDN components are highlighted in black boxes. (**b**) Corresponding means topographic maps over the MMR and LDN time windows. (**c**) The statistical cluster-based permutation test results showing significant differences between the responses to deviant and standard stimuli are indicated with stars. Blue and red colors indicate negative and positive amplitude values, respectively. The measuring unit is µV.

3.3.4. Within-RD Group Comparisons for Foreign Stimuli

The ERP waveforms, amplitude topographies, and cluster-based permutation tests for the *RD* group in both foreign language conditions with deviant stimuli *she* and *shy* are illustrated in Figure 4C,D, respectively. The *RD* group showed similar ERP patterns to the *CTR* group, with enhanced amplitude in the foreign language responses. The cluster-based permutation test rendered two clusters for the *she-shoe* contrast, with a clear negative cluster on the left frontal area and a widespread positive cluster at the right temporal and occipital areas. In the MMR time window (150–300 ms), significant differences were also found for both contrasts, in which the responses to the standard were larger than those to the deviants. For the second foreign contrast *shy-shoe*, a positive cluster emerged at an early time point, ~120 ms, on the frontal left hemisphere, merging gradually to the central area and becoming similar to the *CTR* group cluster pattern observed at this latency (~210 ms). Interestingly, the LDN was not significant for either foreign condition in this group. The cluster-based permutation test results for the *RD* group are presented in Table 4.

Table 4. Summary of the within *RD* group statistics using cluster-based permutation tests for the native (Finnish) and foreign (English) conditions.

	Condition (Deviant–Standard)	
	MMR (150−300 ms)	**LDN (450−850 ms)**
sii-suu	ns	ns
sai-suu	Cluster [150–300 ms], Negative (max. 232 ms), $p < 0.001$ Cluster [150–289 ms], Positive (max. 156 ms), $p < 0.003$	ns
she-shoe	Cluster [150–300 ms], Positive(max 177 ms), $p < 0.001$ Cluster [150–259 ms], Negative(max. 199 m), $p < 0.005$	ns
shy-shoe	Cluster [150–295 ms], Negative (max. 209 ms), $p < 0.001$ Cluster [182–294 ms], Positive (max.294 ms), $p < 0.002$	ns

Note. The statistical information in each column represents the cluster range, polarity, time point of maximum amplitude, and *p*-value, respectively. ns = non-significant. All the results were FDR-corrected and only results that survived the FDR corrections were included in the table.

The polarity of each cluster indicates the direction of the comparison whether negative (if the second ERP response is bigger than the first) or positive (if the first ERP response is bigger than the second).

3.4. ANOVA Results

To test the language × group interaction effect, we conducted 2 × 2 ANOVA separately for the two time windows. The ANOVA results did not show group × language interaction in any of the time windows. Only a language main effect was found, confirming the earlier findings in the between-language cluster-based permutation tests. The ANOVA at the MMR time window yielded a significance for the difference wave comparison, showing a language main effect in the difference between *sai-suu* vs. *shy-shoe*. The ANOVA at the LDN time window also showed a significant effect for the difference *sii-suu* vs. *she-shoe*. In both these difference contrasts, the effect was caused by the larger ERP responses to the foreign stimuli (see the ANOVA results in Table S3 in the Supplement).

4. Discussion

We examined the differences of discriminatory ERP brain responses to native and foreign speech sounds in typically developed children (*CTR* group) and in children with reading difficulties (*RD* group). To this end, we used an auditory oddball paradigm and contrasted the discriminatory brain responses between and within languages (Finnish and English) and groups (*CTR* vs. *RD*). The results showed that only MMR, but not LDN, differed between Finnish and English stimuli within both groups. Neither MMR nor LDN showed significant differences when comparing the contrasts between groups. In the within-group analysis, both groups showed a negative MMR with a lower amplitude to native stimuli and a positive MMR to foreign stimuli. The *CTR* group showed significant MMR and LDN responses for all contrasts; however, the MMR response was diminished in foreign language processing and the LDN was somehow weaker in the *sii-suu* and *she-shoe* conditions than in *sai-suu* and *shy-shoe*. On the other hand, the *RD* group did not show a significant LDN response in any of the contrasts. The topo maps of the LDN response between 450 and 850 ms showed a reversal of the hemispheric polarity in the frontal area for all the conditions compared to the *CTR* group (see Figures 3 and 4). Overall, the results show a clear MMR difference in language processing in both groups. They also hint at differences in discriminatory brain mechanisms in both typical and poor readers in processing native and foreign speech stimuli. There was also evidence on brain activation variability within language processing, most probably due to the within-stimulus features and semantics.

4.1. Native vs. Foreign Language Processing

To study the role of long-term representations of the native and foreign languages in school-age children, we compared the discriminatory processing of each speech contrast of both languages within the *CTR* and *RD* groups (see Figure 2). The enhanced brain responses in foreign language processing were observed for the foreign-language difference waveforms within the MMR time window in both groups. These waveforms showed that the brain treated the native contrasts in a typical way, as this discriminatory component is typically a negative response. On the other hand, the foreign contrast showed positive polarity over fronto-central electrodes and overall larger amplitude, reflecting enhanced activity. Interestingly, the late processing reflected in the LDN response did not differ between the two languages.

These results showed that the brain responses to foreign language items were different than the native ones within both groups as indicated by the MMR findings. This difference may reflect the instability of the cortical representations in foreign (English) language speech sounds processing, which remain relatively novel items compared with the native sounds even after a long exposure.

Earlier, we hypothesized that less exposure to foreign sounds may lead to weaker representations caused by unstable networks to reflect unfinished or unestablished neural language representation [20,121]. These unstable networks may require more neural resources (either larger cortical area activation or multiple sources) to process the sounds, leading to large, positive responses. For example, processing a foreign sound may recruit additional brain processes, such as a higher activation of the early auditory arousal-attentional mechanism during the early 100 ms post stimulus (P1/N1 response; [122,123]), which may overlap with the first discriminatory response, the MMR. Another possible interpretation of this result is that the enhancement observed in foreign-language processing could be due a specific neural response to differences in the physical features within the stimuli, notably the effect of the early foreign sound [ʃ]. It is also possible that a number of these explanations may co-occur.

In the language comparison, a significant difference was observed in the MMR but not for the LDN response within *CTR* and *RD* groups. This result was supported by the ANOVA findings as it indicated a language effect.

4.2. Group Comparison CTR vs. RD

Our results did not show any statistically significant differences between the groups in any of the components. In native language context, a similar result was previously reported by Ylinen and colleagues, as no significant group difference was found in native language word form processing [5]. However, the authors reported a significantly weaker MMR in the *RD* group when processing a second language familiar word (the word *she*). This difference between our results and the previous study's results in this contrast could be explained by a possible attenuation of this response in our group sample due to a longer exposure to the foreign language and to the age difference of the participants between the two studies. As Ylinen et al. originally reported "a weak MMR", this response may have further diminished with age until it disappeared. Thus, foreign-language processing, and particularly this contrast, may have reached a mature native-like language processing after some years of exposure. Ylinen et al. did not investigate the LDN response; the authors only focused on the mismatch response. Our results did not show group differences in this component despite the absence of the LDN significance within all conditions in the *RD* group (see Table 4). As an example of a previous study investigating both MMR and LDN responses to speech sounds (vowels discrimination task), Froyen and colleagues reported no discrimination problem of the speech stimuli in the dyslexic group who showed similar brain responses to the *CTR* group [124]. Our results show a similar result, as we did not find any statistically significant differences in any of the components in the group comparison. Some previous studies reported group differences in the MMR responses between *CTR* and *RD* groups, but those studies used different stimuli and paradigms as they investigated nonlinguistic stimuli such as tones [90,125] or synthetic speech [126], which make it difficult to compare with our findings.

When it comes to the foreign-language processing, our study is the first of its kind to investigate both discriminatory brain responses MMR and LDN, in foreign-language processing in the context of good and poor reading. To our best knowledge, only one study has investigated the MMR in dyslexics versus controls in foreign language context [5]. On the other hand, there is no previous evidence in the literature about the LDN response in dyslexics when processing a foreign language. When comparing the two groups, we were able to observe an overall tendency to larger responses in the *RD* group compared to the *CTR* group responses (see Figure S2 in Supplement). This enhancement may indicate extra neuronal activations in the *RD* group when processing the different stimuli. Enhanced ERP responses have also been described in other studies to reflect the less efficient linguistic performance in discriminatory processes [73,80,127]. This is explained as a greater processing effort [73], which may lead to the activation of a compensatory mechanism when processing speech stimuli [80]. In the literature, neuronal networks have been described as remaining open to relevant and irrelevant speech sounds in case of dyslexia as described by the allophonic theory [22]. This higher sensitivity may play a role in compensating for the phonological deficit, expressed in our results as larger amplitude and reflected in higher neuronal activity.

In native and in foreign language processing, neither MMR nor LDN showed a statistically significant difference between the *CTR* and *RD* groups, despite a hint on possible processing deficits in the *RD* group as indicated by the larger brain response.

4.3. Within Group Results

4.3.1. Native and Foreign Language Processes in Typical Readers

Brain responses to standard native (Finnish) speech stimuli in the *CTR* group revealed overall typical brain dynamics like those reported earlier in the literature [128,129]. The statistical comparison revealed a difference in processing the deviant and standard stimuli showing the presence of a typical MMR and LDN responses, except for the first contrast *sii-suu* showing a less clear response with only a positive cluster over the occipital area.

In the foreign contrasts, the statistical comparison revealed a difference in processing the deviant and standard stimuli, showing the presence of an MMR and LDN responses equally. However, the MMR was very weak and atypical compared to that obtained with the native language stimuli. It showed a very small negative cluster over the central area for the condition *she-shoe*, and a positive and very brief cluster for the *shy-shoe* condition (see Figure 3C,D). This result may indicate an early effect related to the presence of the foreign onset sound [ʃ] (pronounced *sh*) at the beginning of the English stimuli.

In addition, atypical responses could be attributed to the coarticulation effect. This sound may produce a different transition cut between the consonant and vowel compared to the initial [s] natively present in the language producing a different brain activation pattern. Formant transitions are important perceptual cues in speech processing. Their shapes vary according to the neighbor consonant affecting the identification of the following vowel [130]. This foreign sound may generate extra attentional processes that may overlap with the MMR response in the foreign language context. Moreover, the response to the fricative [ʃ] could partially encode information coming from the vowel and diphthong that represents a combined information fricative-vowel simultaneously. Generally, in the case of a strong vowel, the information could be present on the prior consonant [131,132] or, in our case, the pre-vowel fricative, producing a specific and distinctive articulatory configuration for each of the initial consonants ([s] and [ʃ]) in each of the stimuli [133,134].

The Mismatch Response within the CTR Group

We observed larger negativity in response to the deviant stimuli than in response to the standard stimuli in native language processing, suggesting that typical MMR was generated as a marker of change detection [72,135,136]. The MMR in our study clearly diminished for both foreign language contrasts and created a topographic pattern tending toward positivity. The positive MMR is thought to reflect a mismatch response, which is usually reported in infants and less frequently in older children [67,85]. A clear difference in MMR response between native and foreign stimuli could be seen in our results. However, Ylinen and colleagues reported a negative mismatch response to the same foreign stimuli in younger children (around nine years old) [5]. Thus, it is more likely that the positive MMR observed in our results came from the larger overlapping of an attentional response to the foreign contrasts, an early P3a overlapping with the MMR. The different analysis and filtering settings used in our study compared with those in Ylinen's work may also be the origin of different results.

Although these remain valid possibilities, our results clearly show that foreign and native stimuli generated different brain responses, with a clear MMR response to the native stimuli, that was less typical in foreign stimuli context reflecting different brain responses in discriminatory processes between native and foreign languages.

These MMR results may also hold the acoustic distance effect between speech items and between different languages, as the MMR has been previously shown to be sensitive to acoustic distance [137]. Based on previous findings, the perceptual stimulus dissimilarity could be quantified via the Euclidian distance, where the ED between standard and deviant stimuli may partially explain the size of the discriminative responses. The ED analysis (see Table S2B,C in the Supplement) showed that English and Finnish vowels were acoustically distinct and that the *ii* ([iː]) deviant was acoustically further in ED from the standard *uu* ([ʊː]) than the deviant *ai* ([aɪ]). In the *CTR* group, the responses to the Finnish language may be explained by the ED. The larger the ED between the standard and deviant stimuli, the more pronounced the MMR. However, this effect was not reproduced with the foreign stimuli. Hypothesizing that the brain representations are weaker for the foreign language, we would assume that the brain would rely more on the acoustic features; however, our results suggest that the ED did not play the major role in the ERP responses to foreign stimuli. We think that the early identification of a foreign sound [ʃ] may initiate a different process, indicating clearly that the brain did not rely only on the acoustic properties but other processes may have contributed to the response. Similar conclusions have been reported earlier in Ylinen's study [5]. Previous studies in control participants exploring sub-phonemic vowel contrast perceptions (the difference between equivalent speech items) showed the sensitivity of the MMR component to the phonetic distance between the stimuli [137]. This highlights the specificity of the brain processes recruited for each language processing.

The Late Discriminative Response within the CTR Group

The late discriminative processing (LDN, 450–850 ms) for all native and foreign stimuli was more negative for the deviant than for the standard stimuli; however, the LDN response was not significant in any of the contrasts. Our results showed a frontal negativity with a preponderance to the right hemisphere in response to *sii-suu* and *sai-suu* contrasts, more left centrally oriented in the *she-shoe* contrast and right centrally oriented in the *shy-shoe* contrast. The LDN response to the native *sai-suu* contrast was more prominent than that to the *sii-suu* contrast in the native language processing. The response to the *shy-shoe* contrast was also larger than that to the *she-shoe* contrast.

Different interpretations of the LDN role have been proposed in the literature, but the functional significance of this component remains speculative because no clear evidence is available in the literature about its exact role [138,139]. This late negativity over the fronto-central area is known to have been generated in response to complex auditory stimuli, such as linguistic stimuli [83]. A recent study showed that LDN is a marker for phonological complexity [70]. The LDN response was previously studied as an index of foreign phonological contrast discrimination [93] and as an indicator of speech perception development [127]. The LDN response may also indicate a coarticulation effect contributing to the late response by generating a stronger response for deviant stimuli carrying the diphthong *ai* (in *sai* and *shy*) compared with the vowel *ii*. This may explain the stronger response obtained with both native and foreign stimuli carrying the diphthong *ai*, which possibly needed an additional neural activation.

Previous studies of the LDN response have shown that this response is not only linked to the complexity of the stimuli [140], but also comprises high-order cognitive processes [89]. We think that, in addition to the coarticulation present in the features (vowel vs. diphthong), additional processes may be involved in the late response, and they are linked to the functions and semantics of the words [84]; *sii* as a pseudoword would produce smaller activation than *sai*, which comprises a function and a meaning (verb = got, past tense). *She* as a word would also produce a smaller activation as a familiar English pronoun than *shy*, which is less familiar and has a complex function (adjective). The difference in processing words vs. pseudowords was earlier highlighted in the early discriminatory response MMR, where distinct responses were reported [141]. The enhancement was interpreted as an indicator of the long-term memory traces for spoken words, which make it one the most plausible explanations. The modulatory effect of the lexical meaning on the brain discriminatory response was earlier shown to offer a processing advantage for the meaningful items [142]. However, all these interpretations remain hypothetically possible.

4.3.2. Native and Foreign Language Processes in Poor Readers

The Mismatch Response within the RD Group

The *RD* group showed statistically significant difference for the *sai-suu*, *she-shoe*, and *shy-shoe* contrasts between 150 and 300 ms, but not for the *sii-suu* contrast. Interestingly, this same contrast showed a very weak MMR response in the *CTR* group. The more asymmetric activation in this contrast may indicate atypical brain responses in the *RD* group. The weaker and atypical MMR activation in this contrast compared to responses to the other contrasts, maybe due to the nature of the deviant stimulus as a non-word engaging a different encoding strategy compared to real words. Our results also suggested that the response in the *RD* group was different than that to the *CTR* group, which may reflect a different processes in encoding strategy of the same non-word. The positive MMR that was reported earlier in typical readers when processing a foreign language was reproduced in the *RD* group in the same contrasts. The electrical distribution maps within this group showed atypical activations, mostly in foreign language processing. Atypical brain activity in response to speech sound contrasts is supportive evidence of the phonological system deficit that has been previously described in the literature [64]. Smaller MMR amplitude responses to syllables were earlier reported in the *RD* group compared with the *CTR* group [88], and later investigation showed that this effect was speech-specific [143].

The nativeness of the stimuli did not seem to play a major role in the early processing phase in the *RD* group, suggesting weaker and less sensitivity to the initial sound. This effect could be explained by a memory encoding deficit in the *RD* group, as previously reported [144,145]. Phonological deficit and memory impairment were shown to share neuronal mechanisms in dyslexic children between 10 and 14 years old [146]. Thus, a deficit in memory construction with a phonological deficit may be a valid explanation for the results found in the MMR time window within the *RD* group.

The Late Discriminative Response within the RD Group

The late discriminative component (LDN) between ~450 ms and 850 ms did not show significant differences between the deviant and standard stimuli responses in any of the contrasts within the *RD* group. Commonly, in the auditory paradigms investigating discriminative processes, the later negative response was reported as part of the complex MMR-P3a-LDN [65,91,93]. The functionality of this response remains largely debated. It is thought to be related primarily to discriminative processing, but further complex processes are also considered to take part in the LDN response [83], such as sound structure processing [70], and attentional processes [94,147].

The absence of any LDN significant effect may suggest reduced abilities of auditory discriminative processing in this group compared to the *CTR* group [16,83], as has also been pointed out in the MMR findings. Weaker LDN responses in dyslexics are expected because they have been reported in the literature [92]. The LDN response was also suggested to reflect neuronal phonological representations [127] and was shown to be modulated by the phonological complexity present in linguistic stimuli [70].

Earlier, we hypothesized weaker neuronal representations in the *RD* group, and our results may indicate such an effect. Weaker representations may produce lower amplitude responses. The complexity (in the case of a diphthong), the coarticulation effect, and the nativeness of the stimuli (Finnish vs. English), as discussed above, did not seem to affect this response because the LDN effect was absent in all the contrasts.

4.4. Strengths and Limitations

The complexity of the stimuli maybe considered as limitation since it makes it harder to interpret the results. It is however also a strength of this study because we used natural speech with two deviants in two different languages. Natural speech stimuli in this type of design were rarely investigated in previous studies of dyslexia.

Furthermore, the larger amplitude variation is typically found at the end of the ERP epoch. The lower number of participants in the *RD* group may have increased the signal-to-noise ratio compared with the *CTR* group, which may have caused the results to not reach significance during this time window. Moreover, weak responses combined with the high variability within the group and noisier responses among the participants may induce the suppression of the LDN effect. This smaller *RD* group size compared to the *CTR* group size maybe considered as a limitation in the current study as is causes lower statistical power for some ERP effects.

Another possible limitation in the current analysis is the frequency of use of some speech items, which may have had some effects on the discriminatory responses. However, it is unlikely that this was the case based on the previous study by Jacobsen and colleagues who showed no effect of word frequency/familiarity on the MMR response [142].

Although the current study does not directly investigate the relationship between reading scores and the brain responses via a direct correlation analysis, the group definition and the analysis were based on those reading scores. The direct correlation analyses between the brain responses to speech items and the reading scores were previously conducted using the same group's data and results showing the direct link between reading scores and speech processing are available in our previously published research [148].

5. Conclusions

Our results showed that both *CTR* and *RD* groups discriminatory process, as indexed with the MMR response, were different for the native compared to foreign language. They provide new evidence on foreign speech processing, both in typical readers and in children with reading difficulties. Furthermore, our results showed effects of the within-stimulus features and semantics as they seem to affect the ERP responses in both groups. Further investigation is needed to examine in depth the origins of these differences between typical readers and children with reading problems. Our study is, to our best knowledge, the first brain-based evidence on the late discriminative processing in foreign language context and in the context of reading difficulties.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/brainsci13010076/s1; Figure S1: The electrodes selection (highlighted in yellow) and the region of interest for the ANOVA computations; Figure S2: Group difference waveforms of the *RD* group (in red) vs. the group difference waveforms of the *CTR* group (in green). (A) The difference waveforms in native *sii-suu* and (B) native *sai-suu*, (C) The difference waveforms in the foreign *she-shoe* and (D) in foreign *shy-shoe*; Table S1: Number of accepted trials for each stimulus by group; Table S2A: Summary of the stimuli used in the oddball paradigm presented in two blocks (Finnish and English) with the detailed trial numbers used in the experiment, the total duration of each stimulus (ms), and the frequencies (Hz) before and after the transition point from the consonant to the vowel; Table S2B: Euclidean distance within language stimuli vowels; Table S2C: Center of Gravity (COG) of the English [s] and Finnish [ʃ] fricatives within each stimulus; Table S3: Summary of the ANOVA results.

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Data Availability Statement: The data presented in this study are available in Figures 2–4 and in the Supplementary Material, Figure S2. Original data can be made available by the authors upon reasonable request.

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BRAIN SOURCE CORRELATES OF SPEECH PERCEPTION AND READING PROCESSES IN CHILDREN WITH AND WITHOUT READING DIFFICULTIES

by

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Brain Source Correlates of Speech Perception and Reading Processes in Children With and Without Reading Difficulties

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Neural correlates in reading and speech processing have been addressed extensively in the literature. While reading skills and speech perception have been shown to be associated with each other, their relationship remains debatable. In this study, we investigated reading skills, speech perception, reading, and their correlates with brain source activity in auditory and visual modalities. We used high-density event-related potentials (ERPs), fixation-related potentials (FRPs), and the source reconstruction method. The analysis was conducted on 12–13-year-old schoolchildren who had different reading levels. Brain ERP source indices were computed from frequently repeated Finnish speech stimuli presented in an auditory oddball paradigm. Brain FRP source indices were also computed for words within sentences presented in a reading task. The results showed significant correlations between speech ERP sources and reading scores at the P100 (P1) time range in the left hemisphere and the N250 time range in both hemispheres, and a weaker correlation for visual word processing N170 FRP source(s) in the posterior occipital areas, in the vicinity of the visual word form areas (VWFA). Furthermore, significant brain-to-brain correlations were found between the two modalities, where the speech brain sources of the P1 and N250 responses correlated with the reading N170 response. The results suggest that speech processes are linked to reading fluency and that brain activations to speech are linked to visual brain processes of reading. These results indicate that a relationship between language and reading systems is present even after several years of exposure to print.

Keywords: reading, ERPs, FRPs, auditory P1, auditory N250, visual N170, source reconstruction, brain correlates

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INTRODUCTION

Learning to read is a complex multi-step process that requires both visual and auditory processes (Kavale and Forness, 2000; Norton et al., 2015; Vernon, 2016; LaBerge and Samuels, 2017). The question of whether speech processing and visual processing deficits are linked to reading disorders has been extensively addressed in the literature (Breznitz and Meyler, 2003; Breznitz, 2006; Wright and Conlon, 2009; Georgiou et al., 2012; Kronschnabel et al., 2014; Francisco et al., 2017; Karipidis et al., 2017; Ye et al., 2017). However, the nature of the link between the two modalities remains unclear (Gibson et al., 2006; Wright and Conlon, 2009; Blau et al., 2010; Georgiou et al., 2012; Ye et al., 2017; Rüsseler et al., 2018; Stein, 2018). Several studies have investigated this relationship using simultaneous auditory and visual stimuli in dyslexic vs. typical readers using behavioral and brain measures (Aravena et al., 2018; Karipidis et al., 2018; Fraga-González et al., 2021). In the present study, we investigated the extent to which speech processing at the brain level is associated with reading fluency and brain activity during reading. We examined these associations in a group of children with different levels of reading skills, ranging from poor to good.

Reading difficulty (RD), or dyslexia, is a frequent neurodevelopmental impairment that is commonly reported among school-age children. It involves a failure to acquire a satisfactory level of reading and spelling performance, despite normal intelligence and typical linguistic performance, in the absence of any organic, psychiatric, or neurological disorders, and despite adequate pedagogical opportunities (Démonet et al., 2004; Peterson and Pennington, 2015; Snowling et al., 2020). Dyslexia has been commonly linked to deficits in speech processing (Schulte-Körne et al., 1998; Kujala et al., 2000; Bishop, 2007; Abrams et al., 2009; Hämäläinen et al., 2013; Christmann et al., 2015; Lizarazu et al., 2015; Gu and Bi, 2020) and phonological processing (Snowling, 1998; Richardson et al., 2004; Vellutino et al., 2004; Christmann et al., 2015; Smith-Spark et al., 2017; Goswami, 2019).

A frequently reported problem in dyslexia is word decoding, which is mainly described as a deficit in reading speed, accuracy, or spelling difficulties (Snowling, 2001; Vellutino et al., 2004; Siegel, 2006; Hulme and Snowling, 2014). According to phonological theory, RD is caused by alterations in brain functions, such as a deficit in phonological representations, an information storing dysfunction, or information inaccessibility (Ramus and Szenkovits, 2008; Hoeft et al., 2011; Boets et al., 2013; Hornickel and Kraus, 2013; Prestes and Feitosa, 2017). Based on this theory, one of the main hypotheses underlying the mechanism of reading disability is the creation of phoneme-grapheme neural connections or inadequate representations when processing speech signals. This deficit could result from an alteration of the process of decoding grapheme-phoneme correspondences when decoding single letters, letter clusters, or words while reading (Goswami, 2000; Prestes and Feitosa, 2017). Weakness in building a stable network by binding letters and sounds eventually leads to reading problems (Goswami, 2002; Noordenbos et al., 2012; Vogel et al., 2013). Several studies of brain responses in children with reading difficulties have reported deficits in speech and phonological processing (Snowling, 1998; Castles and Friedmann, 2014; Ramus, 2014; Catts et al., 2017), with atypical phonological or phonetic representations of speech sounds shown to alter normal phoneme and word identification. Alternatively, an impairment in letter-speech sound mapping has also been suggested to be the origin of reading problems (Ehri, 2005; Maurer et al., 2010; Žarić et al., 2014; Fraga-González et al., 2015). Several studies have shown that speech processing is tightly linked to reading processes and reading skills (Pennington and Bishop, 2009; Zhang and McBride-Chang, 2010; Price, 2012; Duncan, 2018). The early ERP response, P1/N1-P2/N2 complex, is known to reflect basic phonological processes such as sound detection and identification and complexity processing (Maurer et al., 2002; Alain and Tremblay, 2007; Durante et al., 2014; Hämäläinen et al., 2015). Another response, the N2/N250, which is also part of the early complex, has been described in the context of syllable processing and interpreted to reflect the building of neural representation with repeated auditory stimuli (Karhu et al., 1997; Ceponiene et al., 2005; Vidal et al., 2005; Hommet et al., 2009; Hämäläinen et al., 2018; Wass et al., 2019). Studies have shown that basic speech processing was a strong predictor of infants' and young children's reading skills development as early as 6 months of age (Leppänen et al., 2002; Meng et al., 2005; Boets et al., 2011; Hayiou-Thomas et al., 2017; Lohvansuu et al., 2018).

Using the electroencephalography (EEG) technique, letter-sound mapping was investigated in typical (CTR) and dyslexic readers, and the quality of letter-speech sound processing was shown to be related to reading fluency, with evidence of a relationship between the auditory and visual modalities (González et al., 2016; Moll et al., 2016; Karipidis et al., 2018). This grapheme-phoneme bind created during cross modalities network coactivation, has been described as a key step for developing fluent reading (Chyl et al., 2018; He et al., 2021) by enhancing the specialized visual areas related to print when presented with the corresponding letter-speech sound. This process typically occurs in the early learning stages of reading (Ehri, 2005; Fraga-González et al., 2021). As an example of this effect in EEG studies, it has been shown that ERP amplitudes (for the mismatch responses MMN and LDN, for example) were enhanced when speech sounds were presented to typical readers with letters—an effect that was absent in dyslexic readers (Froyen et al., 2009)—suggesting that in atypical reading development, this letter-speech bind is absent or very weak. Similar results were reported in adults. Blau et al. (2009) investigated whether phonological deficits impaired the mapping of speech sounds into equivalent letters. The authors showed reduced audiovisual integration among dyslexics compared to controls, which was linked to reduced activation of the superior temporal cortex, reflecting a deficit in auditory speech processing. The importance of the auditory cortex in the integration of letter-speech sounds has also been addressed in functional magnetic resonance imaging (fMRI) studies, both in adults (Van Atteveldt et al., 2004; Holloway et al., 2015; Yang et al., 2020) and in children. Yang et al. (2020) studied the neural basis of audiovisual integration deficits in dyslexic children *via* fMRI. Based on brain activation analysis, the authors reported a less developed correspondence of orthographic and phonological information matching in dyslexic children. They also reported reduced functional connectivity of important brain structures involved in integration processes, such as the left angular gyrus and the left lingual gyrus. This difference in the left superior temporal gyrus (STG) between the two groups of children was supported by previous findings in literature, whereas the angular gyrus (AG) activity was mainly related to task demand and attentional processes.

Visual processing deficits in reading have also been reported for dyslexia and reading problems (Eden et al., 1996; Lobier et al., 2012, 2014; Giofrè et al., 2019; Archer et al., 2020). Visual deficits related to reading have previously been reported at different levels, such as in the sensory, temporal, attentional, and memory processes (Farmer and Klein, 1995; Snowling, 2001; Facoetti et al., 2006; Boets et al., 2008; Wright and Conlon, 2009; Conlon et al., 2011; Goswami, 2015). For example, low-level visual processing in letter-speech sound integration was addressed using a mismatched paradigm to investigate the influence of speech sounds on letter processing. Despite previous evidence of the systematic modulation effect of speech sound processing on letter processing, the reverse effect was not found (Froyen et al., 2010). The emergence of letter-speech sound correspondence has been studied in children *via* different neuroimaging techniques. Brem et al. (2010) studied the establishment of a reading network *via* speech processing in beginning readers *via* ERP and fMRI. That study focused on the left occipitotemporal cortex underlying the VWFA. The authors showed that print sensitivity in this area emerged in the early phases of reading acquisition, highlighting the critical role of VWFA in sound-print mapping. The results of Brem et al.'s investigation of fMRI and EEG data clearly indicated brain activity enhancement in the occipitotemporal area after the establishment of speech-print mapping through training. The authors reported that the auditory network involved was not the only one, but that a visual network was clearly co-activated during the coding-decoding phases, which highlighted the importance of the VWFA in this learning process. Brem et al. also associated the activation of this brain area with the visual N1 response of the ERP component sensitive to print, more commonly named N170. Pleisch et al. (2019) studied differences in reading processes between typical and dyslexic first-grade children by measuring the neural activation of the N1 response to print *via* combined EEG–fMRI methods. A differential modulation reflecting sensitivity to print was found only in typical readers in the ventral occipitotemporal cortex. The authors concluded that functional brain alterations in the language network play a role in dysfluent reading development.

The role of speech and language as the basis for reading is well established, where most dyslexics show difficulties in phonological processing (Siegel, 2006; Navas et al., 2014; Giofrè et al., 2019). Sensory or orthographic visual processing deficits have only been observed in a subgroup of the dyslexics (Wright and Conlon, 2009; Giofrè et al., 2019). Visual processing in RD remains an important processing aspect to study in reading research, which has already been a focus of investigation in the literature (Salmelin et al., 1996; Lobier et al., 2014; Archer et al., 2020). However, the ties between visual and auditory information processes in the context of reading vs. speech processing remain unclear. The processing of several letters in a short timeframe is an important skill for developing fluent reading. It has been shown that RD is characterized by slow word recognition and a higher error rate compared to typical reading (Ozeri-Rotstain et al., 2020). Efficient word processing depends on parallel visual processing of multiple letters (Lobier et al., 2012), where a problem in letter pattern perception leads to a problem in orthographic processing, inducing reading problems (Georgiou et al., 2012).

Monzalvo et al. (2012) used fMRI to investigate cortical networks for vision and language by comparing cortical activity in minimally demanding visual tasks and speech-processing tasks. In the visual paradigm, objects, faces, words, and a checkboard were used as stimuli presented in different blocks, and short sentences in native and foreign (unfamiliar) languages were used in the speech processing paradigm. Both visual and spoken language systems have been reported to be impaired in dyslexics. Monzalvo et al. found that dyslexics had reduced activation of words in the VWFA in the visual task and reduced responses in different brain areas, including the posterior temporal cortex, left insula, planum temporal, and left basal language area, extending to the VWFA, in the speech tasks, and the authors concluded that there was hypoactivation in the VWFA for written words and speech listening. These results highlight the role of the VWFA as an associative area in the processing of both types of stimuli: visual information in reading and auditory information in speech processing. A more recent fMRI study by Malins et al. (2018) used a task of matching printed and spoken words to pictures and found a significant correlation between the neural activity of both print and speech and reading skills in children. The authors studied trial-by-trial neural activation of different brain areas and their relationship to reading. They showed that the variability of the neural activation to print was positively correlated with the activation variability of the inferior frontal gyrus providing an additional evidence on the relationship between reading skills and sound processing. The authors discussed the common neural activations for print and speech and highlighted individual differences.

When studying visual processing, the eye-tracking technique is frequently used to examine visual processes and eye movements to investigate reading and reading disorders (Jainta and Kapoula, 2011; Tiffin-Richards and Schroeder, 2015; Kim and Lombardino, 2016; Nilsson Benfatto et al., 2016; Jarodzka and Brand-Gruwel, 2017; Breadmore and Carroll, 2018; Robertson and Gallant, 2019; Christoforou et al., 2021). FRPs are a specific type of ERP that rely on eye fixations and their corresponding brain activity (Baccino, 2011). This combined technique is commonly used to investigate reading (Baccino, 2011; Wenzel et al., 2016; Loberg et al., 2019; Degno and Liversedge, 2020). The FRP is based on EEG measurements of brain activity in response to visual fixations obtained by extracting the signal-averaged time-locked to the onset of eye fixations (Baccino, 2011). Fixations in reading are known to reflect the online cognitive process of several factors, such as the duration and location of a word, word frequency, and predictability. This process occurs in a series of events, starting with the transmission of the visual signal of the printed word from the retina to the visual cortex, visual encoding, initiation of word identification, and programming the next eye movement (Degno and Liversedge, 2020). A commonly used measure for studying individual differences in reading is first-pass fixation duration. This measure reflects the cognitive components of early visual processing, word identification, attention shifts, and oculomotor control (Zhang et al., 2021a). Jainta and Kapoula's (2011) study of eye fixations in reading showed a large fixation disparity that caused unstable fixations in dyslexic children when reading sentences. The authors concluded that visual perturbation may cause letter/word recognition and processing difficulties that lead to reading disorders. Zhang et al. (2021a) used first-pass fixation in sentence reading to investigate the brain network in natural reading. They showed that seed regions in the early visual cortex, VWFA, and eye-movement control network were associated with individual reading performance and brain connectivity in a resting state.

Interestingly, this visual dysfunction was not found systematically, since some studies did not report any differences between RD and typical readers and not all children with RD show a visual deficit.

In the context of RD, both speech and visual processes have only rarely been investigated *via* the ERP method. For example, Bonte and Blomert (2004a) investigated dyslexic readers' phonological processing in spoken word recognition using a priming paradigm. The authors examined the general ERP response and reading skills of beginning readers and reported deficits in N1 and N2 speech processes in dyslexics compared to controls. They interpreted these results as a phonological processing deficit reflecting the recruitment of different neural sources (Bonte and Blomert, 2004a). The N250 response, which is known to be part of the obligatory response (P1-N250), was also investigated in dyslexia, and previous studies showed a different response in this component in the RD group compared to the control group (Lachmann et al., 2005; Lohvansuu et al., 2014). The N250 is thought to represent low-level auditory processing, such as sound detection or feature extraction, but it is also part of a critical processing stage, which is the formation of the neuronal representation of sound/speech stimuli (Karhu et al., 1997; Hämäläinen et al., 2015). As reading involves the ability to convert print into sound, it is critical to further investigate the N250 response and its relationship to reading, as previous evidence has shown differences in this component between good readers and dyslexics. However, the relationship between N250 and reading remains unclear. In addition to the N1-N2 findings, later ERP responses were also found deficient among RD participants, such as the P3a, the N400, and the LDN (Hämäläinen et al., 2008, 2013; Jednoróg et al., 2010; Desroches et al., 2013; Leppänen et al., 2019). These findings provide evidence that speech processing may be altered in dyslexics at different stages of processing and at different latencies.

The brain potential of interest in reading is the N170, an ERP component that peaks between 150 and 200 ms, with a peak around 170 ms and a temporo-occipital negative topography (Rossion et al., 2002; Maurer et al., 2005b; Sánchez-Vincitore et al., 2018). The N170 has been identified as reflecting facial recognition and being sensitive to facial expressions (Blau et al., 2009; Hinojosa et al., 2015; Wang et al., 2019). This component is known to be sensitive to orthographic processing (Rossion et al., 2003) and to letters strings/words in reading. When left lateralized, the N170 has been shown to be a reliable physiological marker of reading and reading skills (Maurer et al., 2005b, 2008; Lin et al., 2011; Hasko et al., 2013; Zhao et al., 2014; Lochy et al., 2016). For example, it was studied in dyslexic children compared to controls, where the N170 was shown to have a larger response in the dyslexic group compared to controls (Fraga González et al., 2014; González et al., 2016). Time-locked to the visual response, this ERP response becomes a strong indicator for studying the dynamics of the visual cognitive processes (labeled FRP N170) of reading and reading disorders (Dimigen et al., 2011, 2012; Kornrumpf et al., 2016; Loberg et al., 2019; Dimigen and Ehinger, 2021).

In the present study, we investigated how the basic speech ERP responses—the P1-N250—are related to reading process, and how the visual FRP response in reading—the N170, which is known as a reliable marker of reading processes (Maurer et al., 2005b; Hasko et al., 2013)—are associated with reading skills in the same children. Previous evidence has shown a link between speech perception and reading, with speech processing being a predictor of reading development at an early age, but the temporal-brain dynamics remain unclear. Moreover, the question of whether this relationship remains present after the development of reading skills has scarcely been investigated. Here, we aim to investigate whether the basic processes of speech remain associated with basic processing of reading in school-aged children who have established a reading network, and how their reading skills may reflect their neuronal activity. This study represents a new approach to investigate how visual reading and auditory speech processes may be interlinked and linked to reading skills by combining different methods (ERP, FRP, and CLARA) for high temporo-spatial analysis.

Both auditory and visual modalities were tested in two separate tasks: a speech perception task and a sentence-reading task. We used source reconstruction with correlation analyses to identify the link(s) among reading skills and auditory processes, reading skills and visual processes, and the neuronal activity of the two modalities. This enabled us to study the brain dynamics of these processes by examining the neuronal origin of brain activity at the source level and to explore its relationship to reading skills. Based on previous evidence, we hypothesized that speech perception basic responses (P1-N250) would show correlations with reading skills (Bonte and Blomert, 2004a; Lohvansuu et al., 2018) and that the visual N170 response would also correlate with reading skills (Maurer et al., 2008; Mahé et al., 2013; Fraga González et al., 2014). Furthermore, we expect to observe a relationship between the speech processes P1 and N250, and the visual reading processes over the VWFA within the same subjects in these two independent tasks.

MATERIALS AND METHODS

Participants

A total of 440 children from eight schools in the area of Jyväskylä, Finland, participated in three test cohorts. The study included a subsample of 112 children, all Finnish native speakers aged between 11 and 13. These children were invited to participate in the eSeek project (Internet and Learning Difficulties: A Multidisciplinary Approach for Understanding Reading in New Media). The participants were grouped based on their reading fluency scores derived from three different reading tasks. The latent score was computed for reading fluency using principal factor analysis (PAF) with PROMAX rotation in the IBM SPSS 24 statistical program (IBM Inc.). This score was based on the following three tests: The Word Identification Test, a subtest of standardized Finnish reading test ALLU (Lindeman, 1998) (factor loading 0.683); the Word Chain Test (Nevala and Lyytinen, 2000) (factor loading 0.683); and the Oral Pseudoword Text reading (Eklund et al., 2015) (factor loading 0.653).

The word identification test included 80 items, each consisting of a picture and four alternative written words. The task was to identify and connect correct picture–word pairs. The score was the number of correctly connected pairs within the 2 min. The word chain test consisted of 25 chains of four words written without spaces between them. The task was to draw a line at the word boundaries. The score was the number of correctly separated words within the 90 s time limit. The oral pseudoword text-reading test consisted of 38 pseudowords (277 letters). These pseudowords were presented in the form of a short passage, which children were instructed to read aloud as quickly and accurately as possible. The score was the number of correctly read pseudowords divided by the time, in seconds, spent on reading (for details, Kanniainen et al., 2019).

This reading score was computed for the whole sample for each subject. Children who scored below the 10th percentile were identified as poor readers (RD) and those who scored above the 10th percentile were identified as good readers (CTR).

All participants scoring equal to or below 15 points (10th percentile) in the cognitive non-verbal assessment testing were excluded. This assessment included a 30-item version of Raven's progressive matrices test (Raven and Court, 1998). Attentional problems were screened *via* the ATTention and EXecutive function rating teacher inventory (ATTEX in English and KESKY in Finnish) (Klenberg et al., 2010). To be included in the analyses, the participants had to score below 30 points on this test. Children with clear attentional problems were excluded from the study.

The brain response analyses were conducted on 112 participants: auditory data: 86 CTR participants (43 females and 43 males; age range = 11.78–12.84 years; mean age 12.36 years, SD: 0.27) and 26 RD participants (eight females and 18 males; age range = 11.84–12.94; mean age 12.31 years, SD: 0.34). Preprocessing and source modeling were performed on 92 participants' reading data: 65 CTR participants and 27 RD participants.

The correlation analysis only included participants with valid auditory and visual data. Sixty of these participants comprised the final CTR group (30 females and 30 males; age range = 11.88–12.84 years; mean age 12.37 years, SD: 0.28) and 20 participants were in the RD group (six females and 14 males; age range = 11.84–12.94 years; mean age 12.34 years, SD: 0.36). The final group, which included both samples from CTR and RD (labeled CTRD), comprised 80 subjects and was tested for normality and skewness. The tests showed a normal distribution and no skewness. For details, see the **Supplementary Material**.

None of the participants declared any auditory problems, and they all had normal or corrected vision with no history of neurological problems or head injuries. The current study was conducted in compliance with the Declaration of Helsinki, and the study protocols were approved by the Ethics Committee of the University of Jyväskylä, Finland. All of the methods used were performed in accordance with university guidelines and regulations. The participants and their parents provided signed informed consent prior to the study.

Materials and Procedures

Auditory Materials and Stimulus Presentation

The auditory stimulus used for this study was originally presented in a passive oddball paradigm designed for another study, comprising a standard stimulus and two deviant stimuli presented over a duration of 10 min. The target stimulus (standard) was presented 800 times in the paradigm, but only 200 trials, which were the pre-deviant standard stimulus responses, were used for the analysis. These trials are believed to have the strongest representations of stimuli due to repetition. The stimulus consisted of a Finnish monosyllabic word *suu* (which means "mouth" in English), a basic, frequent, short, and easy word that is commonly used by itself in the Finnish language but could also be part of other words like [o**suu**s ("a portion or contribution") or a**suu** ("lives")]. This is also one of the first words learned by Finnish children at a very early age and is therefore expected to have a strong neural representation among Finnish participants. The stimuli were recorded by a male native speaker and were pronounced in a neutral manner. The recording was equalized and normalized in segmental durations, pitch contours, and amplitude envelopes using Praat software (Boersma and Weenink, 2010) for a more detailed description of stimulus preparation (Ylinen et al., 2019). The stimuli were presented *via* a loudspeaker placed on the ceiling ∼100 cm above the participants' ear position and were presented at ∼65 dB. The stimulus volume level was calibrated before each recording with a sound level meter (Brüel and Kjaer) placed on a pedestal device at the participant's head position (with the following settings: sound incidence = frontal; time weighting = fast; ext filter = out; frequency weighting = A, range = 40–110 dB; display = max).

Reading Materials

Two hundred sentences, each with between five and nine words, and a median length of six words, were used as visual stimuli. The sentences were presented in 20-point Times New Roman font on the screen in a free-reading task. Each letter was subtended at an average visual angle of 0.4 degrees on the screen, where the distance of the participants was ∼60 cm from the monitor. A total of 912 words, with lengths varying from 5 to 13 letters, were included in the FRP analysis. The materials for this paradigm were part of a previous study. For a detailed description, see Loberg et al. (2019).

Data Measurements

EEG recordings were performed in a sound-attenuated and electrically shielded EEG laboratory room located at the University of Jyväskylä facilities. There was no task for the auditory paradigm. Each child was instructed to minimize movement while listening passively to auditory stimuli. To maintain the child's interest in the experiment, he/she watched a muted cartoon movie playing on a computer screen. In the reading paradigm, the measurement was performed in the same room using a dim light. The child was instructed to freely read different sentences that appeared on the screen. During the recordings, the experimenters observed the participant *via* live video camera streaming and monitoring from a separate control room to ensure the wellbeing of the participant and that the experiment proceeded as expected.

Both EEG datasets were recorded with 128 Ag-AgCl electrode nets (Electrical Geodesic, Inc.) with Cz as the online reference, using NeurOne software and a NeurOne amplifier (MegaElectronics Ltd., new designation Bittium). The data were sampled online at 1,000 Hz, high-pass filtered at 0.16 Hz, and low-pass filtered at 250 Hz during the recording. The experimenter aimed to keep impedances below 50 kΩ and the data quality was checked continuously. All necessary adjustments or corrections were performed during short breaks and between the experiments' blocks to maintain good quality throughout the measurements.

The Eyelink 1,000 with 2,000 Hz upgrade (SR research) version was used for the eye-movement data acquisition of the reading task using a 1,000 Hz sampling rate. The sentences were presented on a Dell Precision T5500 workstation with an Asus VG-236 monitor (1,920 × 1,080, 120 Hz, 52 × 29 cm). At the beginning and the end of each trial, the synchrony between the two measures was ensured with a mixture of transistor-to-transistor logic pulses (to EEG) and Ethernet messages [to eye tracking (ET)]. The participants held their heads in a chinrest during the measurements. The calibration routine consisted of a 13-point run of fixation dots performed before each block and before each trial. This reading task was divided into four blocks. If the fixation diverged from the calibration by more than one degree, the calibration was redone. The experiment's trial started only upon the experimenter's approval of the calibration. Once the task started, the participants were instructed to press a button to move to the next trial (for details, see Loberg et al., 2019). The participants were instructed to read as quickly as possible. The quality of the EEG and the ET was maintained throughout the experiment, and corrections and recalibrations were performed as required. Short breaks were taken when needed or upon the participant's request.

In both experiments, the participants were informed that they were allowed to terminate the experiment at any time in the case of discomfort.

Auditory Data Preprocessing

BESA Research 6.0 and 6.1 were used for offline data processing. Bad channels were identified from the data (number of bad channels: mean: 5.6, range: 1–13). Independent component analysis (Infomax applied to a 60-s segment of the EEG) (Bell and Sejnowski, 1995) was used to correct the blinks from each subject's data. Epoch length was set from −100 ms (pre-stimulus baseline) to 850 ms. The artifact detection criterion was set to a maximum of 175 μV for amplitude fluctuations within the total duration of the epoch. A high-pass filter of 0.5 Hz was set before averaging. Bad channels showing noisy data were interpolated using the spherical spline interpolation method (Ferree, 2006). The data were re-referenced offline to average the reference and averaged individually and separately for the standard stimulus.

Reading Data Preprocessing

The co-registered EEG-ET data were processed in MATLAB using EEGLAB (v14.1.2) with an EYE-EEG (0.85) add-on. A high-pass filter at 0.5 Hz and a low-pass filter at 30 Hz were applied. Synchronization between the raw gaze position data and the EEG data was performed using shared messages in both data streams at the beginning and the end of each trial. Gaze positions outside the screen were automatically discarded. Discarded trials included all zero gaze positions resulting from blinks and between trial gaps in the recordings. All fixations corresponding to all the words within the sentences, except for the last word, during a first-pass reading were used to compute the FRP estimate. The responses were locked to the first fixation of each word, mean word length of 8, and saccade amplitude of 1,8798'. A time window of 100 ms was also considered bad data before and after these values. A binocular median velocity algorithm for detecting fixations (and saccades) was applied to the remaining gaze positions.

Deconvolution Modeling of FRPs

The UNFOLD toolbox (Ehinger and Dimigen, 2019) was used for the FRPs estimation. The FRPs were estimated *via* a generalized linear model that was used for response estimation and the correction of overlaps between the responses with a generalized additive model for non-linear predictors (Loberg et al., 2019). The modeled response ranged from −700 to 500 ms from fixation onset. All blink time points, eye movements outside the screen, and segments with large fluctuations were removed from the response estimates. Fixations on the target word during re-readings were excluded from the FRP estimation.

Source Reconstruction and Spatial Filtering

Source analyses were conducted using BESA Research 6.1 and 7.0 to estimate the active sources in the speech processing and reading tasks. The neuronal sources were estimated *via* an inverse approach with a distributed source model in the brain volume: classical LORETA analysis recursively applied (CLARA) restricted to the cortex. For accurate forward head modeling, an appropriate FEM head model for 12-year-olds was implemented. Model solutions were created based on the group ERP brain source reconstructions for each brain component for the CTRD group combined in a unique model. For the auditory data, source locations were calculated for P1, P1-$_2$, N250, and N250-$_2$ (see an illustration of the ERP auditory responses in **Figure 1**). Model solutions were similarly computed for the reading data based on the group FRP estimates, where the target component was N170. The source analysis was performed ∼10 ms before the peak for all components. This time point was chosen after inspection and after searching for the best solutions for the different responses. This time showed the best modeling solution for the source activity, with the clearest sources and the best residual variance. These group-based solutions were used to create a standard model to filter cortical sources, and only sources that were found to be activated in the common group (CTRD) were included in the final model. For each CLARA source identified, a regional dipole was fixed to combine the power sum of the three

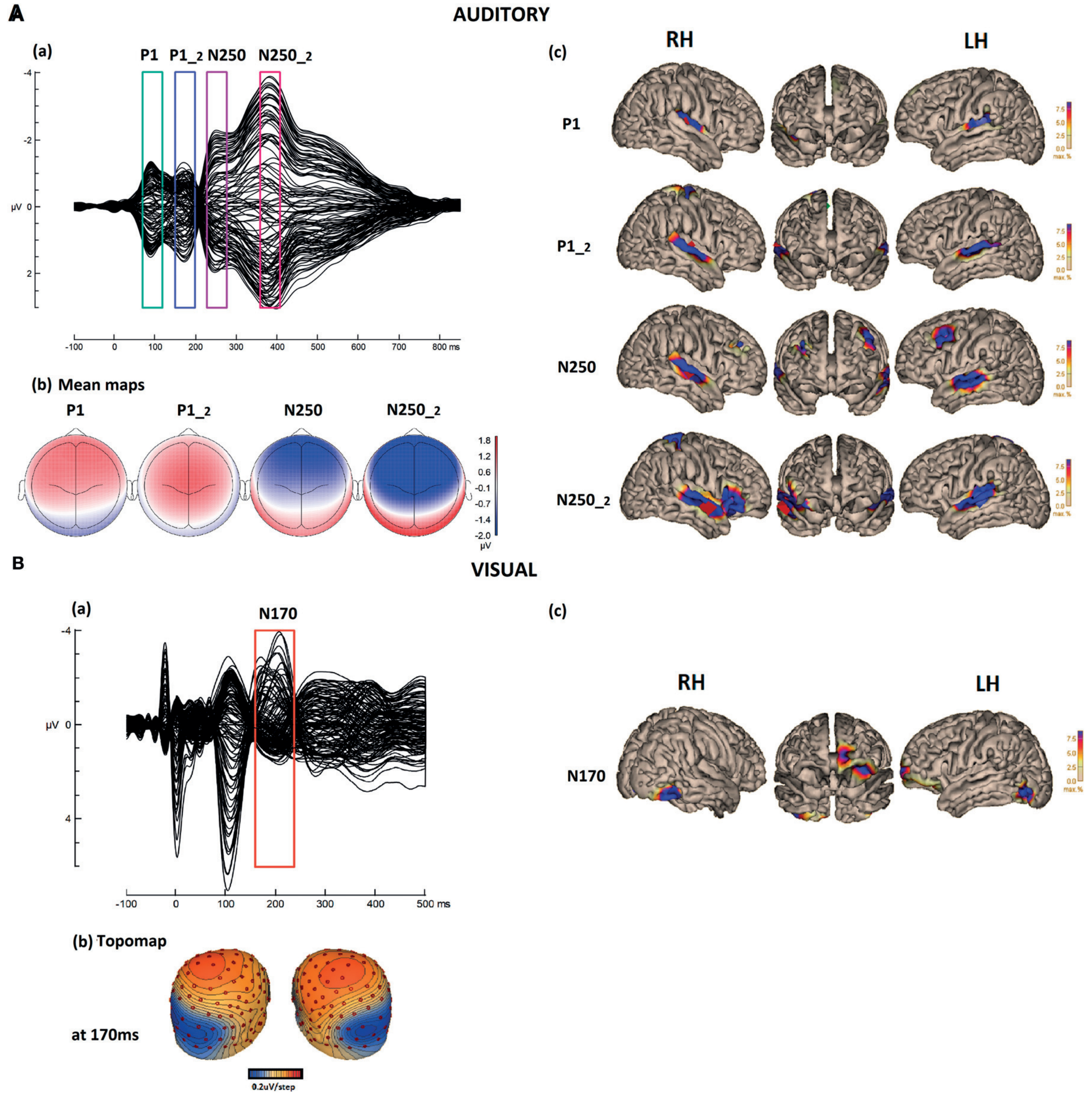

FIGURE 1 | (A) (a) Auditory/speech ERPs in the CTRD group ($N = 80$) grand average. Butterfly plots for the responses to the standard stimulus "suu" over 129 electrodes. The boxes around the peaks indicate P1, P1-2, N250, and N250-2 responses. (b) The corresponding mean topographic maps for the time windows of 70–120 ms (P1), 150–200 ms (P1-2), 230–280 ms (N250), and 360–410 ms (N250-2), respectively. (c) Cortical CLARA reconstruction for each component. **(B)** (a) Visual/reading FRPs in the CTRD group ($N = 80$) grand average. Butterfly plots for the responses to word stimuli over 129 electrodes. (b) The topographic map of N170 at 170 ms and (c) its cortical source CLARA reconstruction.

orthogonal orientations of the regional sources. The regional sources were computed for each component. They were then used as spatial source filters and applied to individual data. The source filter generated individual solution waveforms for each participant. A mean scalar value for each subject was computed as the sum of the source activity measures at all time points over a time window between ∼20 and 30 ms around the peak, specified for each component (a detailed description of the time windows is provided below).

Correlations

Correlations between source activations were converted into scalar values for each modality, and the reading scores (PAF) were examined across the CTRD group using Pearson's correlation coefficients. For each source activity, the mean value was calculated around the peak using MATLAB R2019b (Mathworks®), as described above. For the auditory data, the time windows for the averages were 80–110 ms for P1, 150–180 ms for P1-₂, 230–250 ms for N250, and 360–390 ms for N250-₂. For the visual data, the time window 180–210 ms was used for N170. These time windows were chosen based on visual inspection of the group ERP and FRP grand averages. The time windows were fixed so that the peak was always located in the middle of the window.

Pearson's correlation coefficients were calculated between the average source activity and the reading score of the participants using IBM SPSS statistics 26 (IBM corp), version 26.0.0.1, and applying a false discovery rates (FDR) correction of q = 0.05 (Benjamini and Hochberg, 1995) for the brain-to-behavior correlations and the brain-to-brain correlations. Correlations within brain activity between auditory and visual source activities were computed. A partial correlation (controlling for reading skills/PAF) between the source activity in the reading and speech processes was also performed.

RESULTS

Brain Responses and Source Reconstructions

Brain Responses to Auditory ERP and Visual FRP Data

The auditory grand average ERP and the different auditory components are illustrated in **Figure 1A**. The ERP waveform (**Figure 1A**a) shows four components that emerged in response to the auditory stimulus. The first component peaked at around 90 ms, with a clear fronto-central positive polarity, and reflected the P1 response to the stimulus onset. This was followed by a second positive component peaking at around 170 ms, reflecting a second P1 response (P1-₂) in response to the onset of the vowel or to the consonant-vowel transition. This response had a somewhat more central topography. The third component peaked at around 250 ms and reflected the N250 response to the stimulus onset, followed by a fourth component peaking at around 370 ms, most likely reflecting a second 250 (N250-₂) response to the consonant-vowel transition or the onset of the vowel in the stimulus. Both responses showed clear negativity in the fronto-central area, with a larger amplitude for the second N250 response (**Figure 1A**b).

The grand average of the FRPs during reading is illustrated in **Figure 1B**. The component peaking around 200 ms reflects the visual N170 response, with topography (**Figure 1B**b) showing a typical N170 response. The polarity was positive over the central area and negativity in the occipital areas, with a preponderance toward the left occipital hemisphere.

Cortical Sources in Speech Processing

The group-based cortical source reconstruction (applying CLARA) of the auditory responses is illustrated in **Figure 1A**c. For auditory P1, the source reconstruction at 80 ms, shows a bilateral focal activation of the primary auditory cortices (A1) [with a total residual variance (RV) of 1.78%]. The source reconstruction of the second component P1-₂ performed at 160 ms shows the activation of similar bilateral sources over the auditory cortices. This second response shows slightly larger activity covering a larger area than the first P1, with an additional small activation over the central region (total RV = 5.12%). The third source reconstruction performed at 230 ms for the first N250 response revealed four sources. Two sources were active bilaterally in the left and right temporal lobes at the level of the superior temporal area (STA). In addition, the inferior frontal area (IFA) in the left hemisphere and the middle frontal area in the right hemisphere were activated (total RV = 2.83%). The fourth reconstruction was performed for the N250-₂ response at 370 ms. The source reconstruction showed four sources: bilateral activation of the left and right STA, the third source in the right IFA, and the fourth in the center-right area of the cortex (total RV = 2.19%). Only the bilateral auditory sources across the different components were used to run the correlation analysis to investigate the relationship between the auditory speech perception processes and the reading processes at both the behavioral and neuronal levels. The other sources were discarded because they are believed to reflect additional processes that are related to attentional or semantic processes.

Cortical Sources in Reading Processing

The group-based cortical source reconstruction of the visual response is illustrated in **Figure 1B**c. For reading N170, the reconstruction was performed at 190 ms and showed five main sources (with an RV of 6.07%). Two sources were located in the left and right occipital areas: one over the middle temporal area and one over the right visual cortex. Two additional activations were also found over the left frontal area: one source located in the left orbitofrontal area and the second in the left prefrontal area. Only the visual reading sources of the occipital areas were kept for the correlation analysis to investigate the reading processes, as the frontal sources are believed to reflect other processes that are mainly related to attentional processes.

Correlations

Cortical Source Correlations With Reading Scores

Table 1 presents the correlations between the scalar values of the cortical source activity in the speech paradigm and reading scores, and in the cortical source activity in the reading paradigm and reading scores.

A significant negative correlation was found between the P1 source activity of the left auditory cortex (A1) and the reading score (PAF). The correlation analysis with the right source activity did not reveal any significant results. Neither the right nor the left brain activity of the P1-₂ or N250 sources correlated with PAF. At the time window of the N250-₂ response, source activities in both the left and right temporal areas (STA) correlated negatively with PAF. The correlations indicated that the larger the response, the poorer the reading score. The correlations between the scalar values of the visual sources and the PAF are illustrated in **Table 1**. Only the left occipital source activity located over the left occipital area (L VWFA) correlated negatively with the PAF score. However, this correlation became non-significant after multiple comparison corrections.

TABLE 1 | Brain-to-behavior correlation analysis between reading fluency and brain source activity in auditory and visual sources.

	Components									
	Auditory P1		**Auditory P1_2**		**Auditory N250**		**Auditory N250_2**		**Visual N170**	
Sources	**R AC**	**L AC**	**R STA**	**L STA**	**R STA**	**L STA**	**R STA**	**L STA**	**R VWFA**	**L VWFA**
Correlation	−0.141	**−0.337**	−0.034	−0.192	−0.204	−0.096	**−0.304**	**−0.273**	−0.210	**−0.224**
Significance	0.212	**0.002**[a]	0.762	0.880	0.690	0.396	**0.006**[a]	**0.014**[a]	0.062	**0.046**

AC, auditory cortex; STA, superior temporal area; VWFA, visual word form area; R, right hemisphere; L, left hemisphere.
The correlations significant before the FDR correlation are shown in bold.
[a] *indicates that the correlations remained significant after the FDR multiple comparison corrections.*

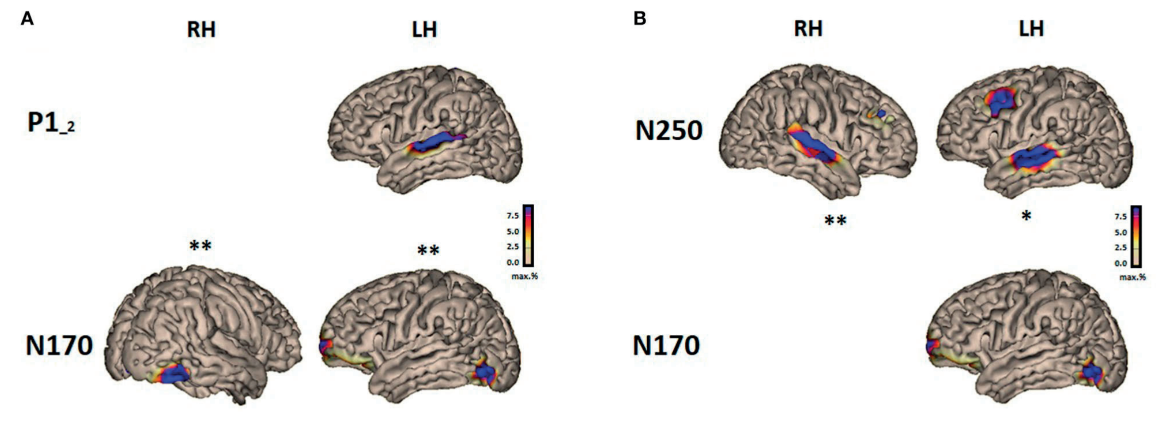

FIGURE 2 | Summary results showing significant correlations between the source activity in speech processing and reading in the brain-to-brain analysis for the P1-2 vs. N170 **(A)** and N250 vs. N170 **(B)**.

TABLE 2 | Brain-to-brain correlation analysis between auditory and visual source activity.

			Auditory components							
			Auditory P1		**Auditory P1_2**		**Auditory N250**		**Auditory N250_2**	
	Sources		**R AC**	**L AC**	**R STA**	**L STA**	**R STA**	**L STA**	**R STA**	**L STA**
Visual N170	L VWFA	Correlation	0.146	0.196	0.121	**0.335**	**0.294**	**0.286**	**0.222**	**0.231**
		Significance	0.197	0.081	0.284	**0.002**[a]	**0.008**[a]	**0.010**[a]	**0.047**	**0.039**
	R VWFA	Correlation	−0.004	0.118	0.180	**0.316**	0.209	0.154	0.122	**0.225**
		Significance	0.972	0.299	0.109	**0.004**[a]	0.063	0.172	0.279	**0.045**

AC, auditory cortex; STA, superior temporal area; VWFA, visual word form area; R, right hemisphere; L, left hemisphere.
The correlations significant before the FDR correlation are shown in bold.
[a]*indicates that the correlations remained significant after the FDR multiple comparison corrections.*

Correlations Between Visual and Auditory Sources

Figure 2 shows the correlations between the scalar value of the visual N170 source and the auditory source activities.

The activity of the auditory P1-2 source (for consonant-vowel transition/vowel onset in "suu") located in the left hemisphere over the temporal area (L STA) correlated significantly with both active sources of the N170 over the left and right hemispheres (L VWFA and R VWFA). The higher the auditory source activity, the higher the activity of the visual sources. The activity of the auditory N250 sources (for the stimulus "suu" onset) located in the left and right hemispheres (L STA and R STA) correlated significantly only with the left source activity of the N170 response (L VWFA). The larger the response to the auditory stimulus, the larger the response to the visual stimulus; see **Table 2** for details.

Partial correlations controlling for reading scores were conducted to investigate whether the brain-to-brain correlation was mainly driven by reading skill level. As shown in

TABLE 3 | Partial correlation (controlling for reading scores) between the auditory and visual source activities conducted for the brain-to-brain correlations (after FDR correction).

	Components correlated							
	Auditory P1_$_2$ * Visual N170				**Auditory N250 * Visual N170**			
Sources correlated	**Auditory L STA**	**Visual L VWFA**	**Auditory L STA**	**Visual R VWFA**	**Auditory R STA**	**Visual L VWFA**	**Auditory L STA**	**Visual L VWFA**
Correlation	0.306		0.288		0.260		0.273	
Significance	0.006		0.010		0.021		0.015	
df	77		77		77		77	

STA, superior temporal area; VWFA, visual word form area; R, right hemisphere; L, left hemisphere; df, degree of freedom.

Table 3, controlling for the reading score did not change the correlations noticeably.

DISCUSSION

This study had two main aims. The first was to investigate the relationship between speech processes and reading fluency, indicated by the PAF score, and visual brain activity in reading, as reflected by the VWFA activation, with the reading score. The second aim was to investigate the brain-to-brain responses for speech and reading processes among a group of children with different reading skills, ranging from good to poor. The study was conducted using brain ERPs for speech stimuli, FRPs for words in sentence stimuli, and source reconstruction for both processes to conduct the correlation analysis. To reveal the link between brain activity and reading skills, we first investigated the correlation between the brain activity of each modality (auditory and visual separately) and reading skills, as indicated by PAF, a reading fluency score derived from three different reading tasks. Our results showed that brain activity correlated with reading scores over the P1 and N250-$_2$ components. The brain activity in reading, as reflected in N170 over the left hemisphere occipital area (L VWFA), correlated significantly with the reading fluency score. However, this correlation did not survive the statistical correction. The brain-to-brain analysis revealed the presence of significant correlations between speech-generated brain responses and reading source activity. The strength of the speech processing sources in the P1-$_2$ and the early N250 showed a correlation with the VWFA source strength for N170. The current results are in line with the trends found in the literature, where the early speech components, P1 and N250, showed correlations with reading. However, our results showed that specific components correlate with behavioral reading skills, whereas other components correlate with brain reading processes. Our findings provide new evidence that there is still reliance on the auditory system and basic speech processes, even after long exposure to print, suggesting that the visual reading system continues to be linked to the auditory system at this developmental age.

In the first part of the study, we investigated the different brain components emerging in speech processing and reading tasks and their cortical sources. In the speech processing task, we examined brain responses to the standard "suu". We chose this stimulus because it was the most repeated speech sound in the oddball paradigm. The literature has shown that stimulus repetition forms a strong memory trace (Jaramillo et al., 2000; Näätänen and Rinne, 2002; Haenschel et al., 2005) and generates a strong neural phonemic/phonetic representation. This phonetic representation was suggested to be linked to the print N170 response (Hsu et al., 2009; Zhang et al., 2021b).

The speech processing ERP results showed two main responses, P1 and N250, both of which have a two-peaked structure reflecting the nature of the syllable-word stimulus "suu". Two similar positive peaks appeared in the early part of the response, one at 80 ms and the second at 170 ms, both of which showed similar scalp topographies with a fronto-central distributed positivity. The first peak seems to be a classic P1 peak emerging in response to the first sound of the syllable /s/, labeled here as P1. The second peak seems to emerge as a response to the second sound of the stimulus, /uu/, labeled as P1-$_2$. This double-peak structure was also found for the second part of the response in the time range of the N250 component. Two similar peaks with similar fronto-central negative topographies appeared at 250 and 370 ms. The first N250 response is likely to reflect the further processing phase of the first sound /s/ (of /suu/), labeled as the early N250, and the second response to reflect the second processing phase of the second sound /uu/ and labeled as N250-$_2$. N250 and N250-$_2$ differed in amplitude, where the second component showed a very high negative amplitude compared to the first. This may be interpreted by a cumulative effect, where the N250-$_2$ compromised the coarticulation processing in addition to the stimulus second sound /uu/ processing. This higher amplitude could also reflect the repetition effect, as both N250 and N250-$_2$ showed higher amplitudes compared to the P1 responses. Another possible interpretation is that this enhanced response is due to the nature of the word stimulus, its strong familiarity, and its well-established neural representation. Early lexical/semantic access in this early phase is also possible. Early semantic access at this time range has been proposed in the literature (Zhao et al., 2016).

Previous studies have identified the early complex P1/N1-P2/N2 as the auditory change complex, reflecting the consonant-vowel transition in naturally produced syllables by children (Boothroyd, 2004). The P1-N250 complex response has been described in the literature as part of the basic auditory processing response (Ceponiene et al., 2005; Gansonre et al., 2018). The

P1 is known to be an obligatory response reflecting sound detection and phoneme identification (Durante et al., 2014; Hämäläinen et al., 2015; Kuuluvainen et al., 2016), whereas the N250 was suggested to reflect phonological processing (Eddy et al., 2016), but also seemed to play a role in memory trace formation (Karhu et al., 1997; Ceponiene et al., 2005; Khan et al., 2011; Hämäläinen et al., 2013). These auditory speech responses have previously been shown to be linked to reading skills and have been studied in the context of typical reading and reading problems (Parviainen et al., 2011; Hämäläinen et al., 2015; Kuuluvainen et al., 2016). Differences between typical and dyslexic readers in these obligatory brain responses were found to emerge between 100 and 250 ms (Bonte and Blomert, 2004b; Hämäläinen et al., 2007, 2015; Khan et al., 2011).

In the reading task, the FRP results showed a typical N170 response. The N170 component has previously been described as reflecting objects and face recognition processes (Rossion et al., 2002; Collin et al., 2012; Hinojosa et al., 2015). It is also known to reflect print and word reading processes. This response was investigated in typical reading and RD and has been shown to have left-lateralized brain activity in reading (Maurer et al., 2005a, 2008; Mahé et al., 2013; Sacchi and Laszlo, 2016; Loberg et al., 2019).

In source reconstructions, the P1 component showed bilateral activation over the primary auditory cortices. In P1-$_2$, the source reconstruction also shows bilateral brain activity in the auditory areas extending to the lateral surface of the STAs in this later response. The sources seem to be similar in both P1 responses, as both reflect similar processes occurring at different time points, where each component reflects the processing of a specific sound of the stimulus. Similar brain areas have been identified for P1 sources when processing auditory stimuli in adults and children (Godey et al., 2001; Shahin et al., 2004; Ruhnau et al., 2011). Our source reconstruction of the N250 component showed more inferior bilateral sources over the auditory areas (superior temporal and middle temporal areas), but an activation of frontal sources was also observed. In the N250-$_2$, bilateral activation was also found in the auditory areas, with slightly more anterior location and with activation of frontal areas. Similar brain areas have previously been defined as the source origins of the N250 component to auditory stimuli (Parviainen et al., 2011; Hämäläinen et al., 2015) and speech processing (Ortiz-Mantilla et al., 2012). The STAs has been said to play a role in phonological (Hickok and Poeppel, 2007) and language processing (Trébuchon et al., 2013). The encoding of speech sounds in the STG was summarized in the review by Yi et al. (2019).

The source reconstruction of the P1-N250 complex showed the basic speech processing temporal and spatial dynamics of the stimulus, suggesting that these responses are more anteriorly located through time. Furthermore, our results suggest that the generators of the P1 and N250 components are different, although very closely located, with our source analysis suggesting more anterior and ventral sources for the N250 responses. The difference in source generators and topographies between the P1 and N250 responses clearly indicates two different processes. We argue that the P1 components seem to reflect the sound detection, phonetic processing, and feature extractions of each stimulus unit, whereas the N250 seems to reflect more complex processes, such as articulation processing and memory trace formation, as introduced above. The differences between the double peaks in P1 (P1 and P1-$_2$) and N250 (N250 and N250-$_2$) probably reflect the transitional state from one processing to the next, notably observed in the second components (P1-$_2$ and N250-$_2$) with slightly different auditory source locations in addition to the emergence of frontal sources. These frontal activations may reflect additional processes. These findings confirm our interpretations of the ERP responses.

The source reconstruction of the N170 shows bilateral activation of the occipital areas over the VWFA and activation of the left frontal area. The activation of VWFA as the source generator of N170 confirms previous findings. The N170 is known as the marker of visual specialization for print processing, and its relationship to the VWFA is well established in the literature (Maurer et al., 2005a; Maurer and McCandliss, 2007; Mahé et al., 2013). The left frontal activation is also in line with previous findings (Maurer et al., 2011). However, previous evidence showed a left lateralization of the N170/VWFA to be characteristic of the visual expertise of reading (Maurer et al., 2008). Interestingly, we observed bilateral activation over the occipital areas. N170 bilateral activation was previously reported in young children, indicating immature development of their reading systems (Uno et al., 2021). Our group sample of children comprise sixth-graders, who were exposed longer to print, but this group comprised both good and poor readers. Given that dyslexic readers have been shown to lack hemispheric lateralization of the N170/VWFA (Maurer et al., 2005a), the atypical activation observed in the right hemisphere in the source analysis most likely comes from the poor reader subsample. This atypical activation may also indicate an immature reading system in the RD subgroup.

The correlation analysis excluded frontal sources found in both speech ERP and reading FRP source reconstructions because they are known to be part of the attention network and the frontal eye field (Ptak, 2012).

In the reading process, N170 correlated with the reading scores, but it did not survive the statistical correction. The relationship between the N170 and reading was expected based on strong evidence in the literature showing the role of this visual component in reading and print processing (Maurer et al., 2005a; Hasko et al., 2013). In line with previous findings, correlation results between the N170 response and reading scores were found over the left occipital area. This left lateralization has also been described in the literature as the neural biomarker of the brain's sensitivity to print and word processing (Simon et al., 2007; Maurer et al., 2008; Zhao et al., 2012). However, it seems that the correlation we found was weak, as it did not survive the statistical corrections. One reason for this result is the methodological approach used in this study. As we have been computing FRPs for a group average containing 80 subjects and for multiple words, the effect may have been weakened through this averaging procedure.

The correlation analysis between cortical brain activity and reading scores in the auditory P1 response showed a significant correlation between left (primary) auditory cortex activity and reading score. Previous studies have shown that time cues and temporal acoustic information are typically processed by the left auditory cortex (Ladeira et al., 2011; Heimrath et al., 2016). Our results also suggest a left lateralization effect of the auditory P1 in response to speech stimuli, which is in line with previous findings. Interestingly, we found a negative correlation with reading skills, showing that the more active this brain area was, the lower the reading skills; this result contradicts previous findings (Shaywitz et al., 2002; Meyler et al., 2007). The smaller response observed in good readers may reflect the maturity of the neural network. Furthermore, correlations were not found in the right hemisphere for this component, which may suggest that brain activity in the right hemisphere may not be linked to reading skills.

N250-$_2$ showed significant correlations between the reading scores and the STAs in both hemispheres. These brain areas were also shown to be part of the N250 component in typical auditory and language processing (Albrecht et al., 2000; Mody et al., 2008; Proverbio et al., 2011). This temporal activation was studied previously, and the role of the temporal areas was discussed in speech sound processing as reflecting low-level speech encoding (Hullett et al., 2016; Berezutskaya et al., 2017; Yi et al., 2019). The literature includes strong evidence of the role of the superior temporal area in reading and demonstrates the function of this brain area in relation to phonological processing in reading (Simos et al., 2000; Mesgarani et al., 2014).

All the correlations found between the auditory/speech brain activity and the reading scores or the visual/reading brain activity and the reading scores were negative. These results show that the more active the brain was, the lower the reading skills were. One possible interpretation is the recruitment of additional neuronal resources to compensate during atypical processing. Recruiting additional resources could be an adaptation to rebalance processing, as previously suggested in the literature (Lohvansuu et al., 2014). Another possible explanation for this result is the developmental phase of this age group. It has been suggested that visual reading skills follow an inverted U-shaped developmental trajectory (González et al., 2016). It is possible that in this age group, reading skills follow the inverted U-shaped curve of expertise in both the visual and auditory domains, which may explain the negative correlation.

We found correlations between brain activity to the visual stimuli and the auditory stimuli. The auditory source activity (in the STA) of the P1-$_2$ response correlated significantly with both N170 sources in the left and right hemispheres (VWFA). The N250 sources (L STA and R STA) correlated only with the left N170 source (L VWFA). The N250-$_2$ sources also showed correlations with the N170 sources over both hemispheres, but these correlations were weak and did not survive the statistical correction. Overall, these brain-to-brain correlation results suggest a strong relationship between the left occipital source in the reading processes and the auditory processes in both hemispheres. This result confirms our hypothesis, assuming that auditory and reading processes are interlinked and is grounded in the literature (Lin et al., 2011). Furthermore, the left lateralization found in the N250 correlation with the N170 is in line with the phonological mapping hypothesis. As this theory proposed that the left lateralization of the VWFA, the source origin of the N170 results from recruiting the left auditory language regions to link the orthography and phonology (Sacchi and Laszlo, 2016). Our correlation analysis suggests that the auditory region recruited for this purpose could be the STA as this area correlated with the VWFA. In addition, the positive correlation results suggest that both modalities behave in the same direction, so when brain activity is higher in one modality, it is also higher in the other modality. This may be interpreted by the presence of a compensatory or a complementary system that seems to act consistently across the two modalities.

Interestingly, the partial correlation analysis did not reveal a significant difference after controlling for reading. This result may indicate that the two modalities may be linked independently of the reading variable, suggesting the presence of possible common mechanism or network between the two modalities. This claim requires further investigation.

In line with our hypothesis, we found correlations between brain activity in speech processing and reading. Correlations between auditory and visual perception and reading have previously been shown on the behavioral level *via* meta-analysis (Kavale and Forness, 2000), and several studies have investigated both processes using simultaneous audiovisual stimuli. No such correlation was investigated *via* neuroimaging, as our findings showed the presence of correlation, even in independent tasks. With this method, we were able to investigate spatio-temporal processing in both processes and reveal, with high temporal accuracy, the different events, which allowed audiovisual sequential partial mapping in relation to reading. Our results confirmed earlier findings of auditory cortex responses to speech stimuli linked to reading skills, suggesting either the activation of the phonological route or the effect of learning to read through phonology still active at sixth grade when reading skills are fluent in most children. Similarly, the fusiform cortex or (STA) activity in response to print and correlation to reading skills confirms earlier findings and suggests this area is sensitive to environmental regularities, which seems to be linked to reading skills. From our results we were able to show the relation between the two routes, suggesting a link between the VWFA and STA.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, upon reasonable request.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Ethical Committee of the University of Jyväskylä. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

NA, OL, JH, and PL: conceptualization, writing, revising, and editing. OL: programming. NA: data collection, writing the main manuscript, and created the figures. NA and OL: data preprocessing and analysis. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnins.2022.921977/full#supplementary-material

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III

AUDITORY P3A RESPONSE TO NATIVE AND FOREIGN SPEECH IN CHILDREN WITH OR WITHOUT ATTENTIONAL DEFICIT

by

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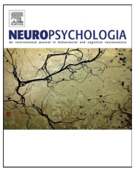

Auditory P3a response to native and foreign speech in children with or without attentional deficit

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ABSTRACT

The aim of this study was to investigate the attentional mechanism in speech processing of native and foreign language in children with and without attentional deficit. For this purpose, the P3a component, cognitive neuromarker of the attentional processes, was investigated in a two-sequence two-deviant oddball paradigm using Finnish and English speech items via event-related potentials (ERP) technique. The difference waves reflected the temporal brain dynamics of the P3a response in native and foreign language contexts. Cluster-based permutation tests evaluated the group differences over the P3a time window. A correlation analysis was conducted between the P3a response and the attention score (ATTEX) to evaluate whether the behavioral assessment reflected the neural activity. The source reconstruction method (CLARA) was used to investigate the neural origins of the attentional differences between groups and conditions. The ERP results showed a larger P3a response in the group of children with attentional problems (*AP*) compared to controls (*CTR*). The P3a response differed statistically between the two groups in the native language processing, but not in the foreign language. The ATTEX score correlated with the P3a amplitude in the native language contrasts. The correlation analyses hint at some hemispheric brain activity difference in the frontal area. The group-level CLARA reconstruction showed activation in the speech perception and attention networks over the frontal, parietal, and temporal areas. Differences in activations of these networks were found between the groups and conditions, with the *AP* group showing higher activity in the source level, being the origin of the ERP enhancement observed on the scalp level.

1. Introduction

1.1. Attention deficit disorder – general context and definition

Attention is the ability to direct and maintain the focus on a selected stimulus (Kałdonek-Crnjaković, 2018). The related disorder to this ability is attention-deficit/hyperactivity disorder (AD/HD), a neurodevelopmental disorder commonly detected in early childhood and tending to persist for the lifespan (Biederman and Faraone, 2005; Bush, 2010). Its worldwide prevalence is approximately 5–10 percent, with a higher occurrence in males (Polanczyk et al., 2007; Bush, 2010; Willcutt, 2012; Polanczyk et al., 2014; American Psychiatric Association, 2015). Attentional problems (AP) commonly describe the developmental disorders of attention, including the different AD/HD profiles exhibiting attentional impairments (Sohlberg and Mateer, 2001; Günther et al., 2011). AP and AD/HD share similar symptoms (Gopalan et al., 2020) where AP more generally describes the attentional deficits observed in most of the AD/HD cases and explains them (e.g., Zentall, 2005; Lin et al., 2017). AD/HD in children has been shown to be highly comorbid with a variety of other disorders (Pliszka, 1998; Gillberg et al., 2004) such as learning difficulties (Leons et al., 2009; Sparks et al., 2003; Doyle, 2020), language impairment, and reading disorder (for example, dyslexia) (Germanò et al., 2010; Hawkins et al., 2016; Kałdonek-Crnjaković, 2018). Symptoms generally include difficulties maintaining attention (Kałdonek-Crnjaković, 2018), impulsive behavior, and poor performance in cognitive tasks (Söderlund and Jobs, 2016), which lead to difficulties in the academic and social life of children with this disorder (Bush, 2010; Yang et al., 2015; McCoach et al., 2020). Despite the important impact of this disorder on these children's wellbeing, there is a clear lack of brain-level information related to the language processes of speech in children with attentional problems. Although several studies reported an overlap between attentional

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deficits and language processing problems (Blomberg et al., 2019), with early studies showing a 45 percent rate of language deficit among 6–11-year-old AD/HD children (Tirosh and Cohen, 1998), neural mechanisms of attention in auditory processing remain poorly investigated. In this study, we examined the electrical brain processes of speech via event-related-potentials (ERPs), their correlations to the behavioral assessment, and their neuronal sources associated with these processes in the context of attentional problems. For this purpose, we used a two-deviant passive auditory oddball paradigm with native and foreign language sequences.

Specific tools have been developed to screen for attention deficit disorder, such as questionnaires directed to parents or teachers, to screen and detect attentional problems (e.g., Attention and Executive Functions (ATTEX) questionnaire for teachers; for details, see Klenberg et al., 2010; Klenberg et al., 2017). Both rating scales and clinical history were identified as strong and recommended tools to diagnose AD/HD (for a review, see Gualtieri and Johnson, 2005). Teacher rating scales to assess AD/HD symptoms in the classroom were recently contrasted to clinical assessments and showed its efficacy and validity (for a systematic review and meta-analysis, see Staff et al., 2021). The ATTEX questionnaire was used in the present study as the screening tool to identify school children with AP who did not have any formal diagnosis of attention deficit disorder.

1.2. *Attention and attentional problems (AP) in language and speech perception*

In auditory research, impairment in central auditory processing has been previously reported in AD/HD (Gomez and Condon, 1999; Lanzetta-Valdo et al., 2017; Blomberg et al., 2019). It is common to observe co-occurrence of auditory or language/speech impairment with AD/HD in clinical evaluations (Cohen et al., 2000; Bruce et al., 2006; Wassenberg et al., 2010). Although this overlap is frequently reported (Kim and Kaiser, 2000; Weiss et al., 2003; Mueller and Tomblin, 2012; Michalek et al., 2014; Hawkins et al., 2016; Söderlund and Jobs, 2016; Redmond, 2020), many questions related to speech processing remain unanswered. The early studies mainly used neuropsychological assessments to investigate language processing in attention deficit disorder. For example, one of the earliest assessments showed that children with AP represented greater difficulties compared to controls when performing language tasks (Carte et al., 1996). Early findings also showed lower performance in AD/HD children compared to age-matched typically developed participants in speech and language tests (Kim and Kaiser, 2000). Furthermore, it is common to report pragmatic language problems in AD/HD children (Camarata and Gibson, 1999; Bruce et al., 2006; Hawkins et al., 2016), which was interpreted as reflecting possible deficits in executive functions, whereas problems found with the language structure were thought to reflect difficulties in phonological processing (Hawkins et al., 2016). Recently, Blomberg et al. (2019) addressed cognitive speech processes in adolescents with AD/HD in a natural speech context. The authors reported that speech perception skill in AD/HD adolescent participants was different than the age-matched control group. They required a higher signal-to-noise ratio to understand speech signals. Due to the repeated pattern showing children with language problems in the attention deficit context (see review by Cantwell and Baker (1992), some researchers suggested that the attention deficit mechanisms play an important role in the language and speech impairment, but due to a lack of brain data, they were not able to make certain conclusions.

Later, the effect of attention on phonetic sound processing was investigated in language processing via CV-syllables in dichotic listening tasks. The role of attention on phonological processing was reported to have a facilitating or inhibiting effect, depending on the attention directed to the stimuli as instructed during the task (Asbjornsen and Hugdahl, 1995). As another example, Hugdahl et al. (2003) contrasted functional magnetic resonance imaging (fMRI) scans of the brain activations in speech attention tasks. They were able to show the modulatory role of attention in passive and active speech processing via a directed attention task. The investigation of the subcortical brain activity in AD/HD and typical eight to 12-year-old children of speech and non-speech stimuli processing showed a deficit in temporal neural encoding in AD/HD children (Jafari et al., 2015). Some researchers have sought to find the link between language problems and auditory/speech processing deficits in AD/HD (Weiss et al., 2003; Michalek et al., 2014; Jafari et al., 2015; Hawkins et al., 2016). However, the nature of this association remains a standing question as the neuronal temporal dynamics are still unclear and the neural origin of the impairment remains subject of investigation, especially in developmental research, where these studies are rare.

1.3. *Foreign speech perception and attentional problems*

Another question raised in language research was foreign language learning, as some findings suggest learning difficulties of foreign languages in participants with attentional deficits. Previous reports have been contradictory, which has made it difficult to construct any clear conclusions. Some studies have reported foreign language learning difficulties among students with attentional problems (Ferrari and Palladino, 2007; Leons et al., 2009; Liontou, 2019), whereas others have reported average learning performance of the *AP* participants when compared to control participants based on academic evaluations and achievements (for a review, see Weyandt and DuPaul, 2006; Sparks et al., 2003). For example, Sparks et al. (2003) compared college students' performance in foreign language learning based on their school grades and cognitive assessments. Some statistical differences were found between the AD/HD students and those with other learning disabilities (Sparks et al., 2005). More recently, Kałdonek-Crnjaković (2018) discussed the same topic and highlighted working memory deficit in the phonological component (Kormos, 2016) as the possible origin of foreign language learning deficit among AD/HD participants. Given the sparse research on the topic and the minimal evidence, the individual profile differences, the common co-occurrence of other learning disorders that goes sometimes undetected and missing standardized methods for group sampling (for a review, see Green and Rabiner, 2012), no conclusions could be derived from the available literature on the foreign language processing in attention-deficit context. Moreover, to our best knowledge, no brain data on foreign language processing in *AP* children are available in the literature, where most of the available studies were based only on behavioral assessments, classroom evaluation, or academic scores (Sparks et al., 2005; Leons et al., 2009; Kałdonek-Crnjaković, 2018; Doyle, 2020). Thus, there is a clear need to conduct this type of brain-data-based investigation to identify the neuronal dynamics behind the processes that may explain these observed behavioral deficits in language processing, which is a topic we address in this study. We investigated the correlation of the brain responses with the behavioral scores, both in native and foreign language processes.

1.4. *ERPs of auditory and speech processing in the attention-deficit context*

One of the most commonly used techniques for studying the brain dynamics of attention is brain ERPs. This is a useful tool with which to investigate attentional processing and possible brain impairments in AD/HD children (Barry et al., 2003). In ERP research, the early studies conducted on the auditory processing in children with AD/HD focused mostly on simple stimuli processing, such as tones (Oades et al., 1996; Rothenberger et al., 2000; Yamamuro et al., 2016), whereas very few used natural speech stimuli such as syllables (Breier et al., 2002; Jafari et al., 2015). The main component, commonly used in ERP measure of attention, is the P3a response, which is typically observed in adults between ≈250 and 400 ms depending on the nature of the stimuli, with a maximum activity over the fronto-central area (Alho et al., 1998; Law et al., 2013; Sams et al., 1985; Yang et al., 2015). This component was observed earlier in young children ≈200–350 ms with a maximum activity over the central area (Ceponiene et al., 2004). The P3a is considered a reliable developmental neuropsychological marker of attention switching or attention orienting and is observed in response to novel or infrequent target stimuli presented in an oddball paradigm, reported both in visual and auditory modalities (Escera et al., 1998; Gumenyuk et al., 2001; Polich and Criado, 2006; Stige et al., 2007; Sussman et al., 2003). The P3a is believed to reflect the involuntary attention switch or orienting, in the presence of change detection. In Barry et al. (2003), the most robust ERP finding across literature was a reduced P3a in AD/HD compared to controls, in auditory oddball tasks. Several ERP studies investigated the P3a response in attention deficit disorder and mainly reported a lower P3a amplitude and a longer latency in AD/HD participants compared to controls (Oades et al., 1996; Barry et al., 2003, Gumenyuk et al., 2004; Tsai et al., 2012). Alexander et al. (2008) studied the P3 response in typical children and children with attention-deficit. The authors reported a smaller P3 amplitude for both visual and auditory oddball targets with a deficit in low-frequency wave activity. These lower frequencies were proposed to partially explain the smaller P3 amplitude (Alexander et al., 2008). Furthermore, ERPs with reaction time (RT) measures showed an attenuated P3 amplitude in the AD/HD group, which was found to be associated with longer RT and interpreted as a neurophysiological impairment of the attention allocation (Cheung et al., 2017). Longer latency and lower amplitude of the P3 component were also reported in six to 13-year-old AD/HD participants in this study. The smaller P3 response was interpreted as reflecting dysfunction of the inhibitory control in AD/HD. However, not only was a lower P3 amplitude in AD/HD compared to *CTR* found in the literature, but contradictory results were also reported. For example, Van Mourik et al. (2007) tested 8 to 12-year-old children, in a passive auditory oddball paradigm and reported a larger P3a component in AD/HD compared to controls in response to novel sounds. Gumenyuk et al. (2005) also reported a larger "late" P3a response in AD/HD compared to controls in novel sound detection, although reporting a smaller response in the "early" P3a response. Oja et al. (2016) also reported larger late P3a amplitude and longer latency in AD/HD participants compared to controls. This larger P3a response was linked to the higher distractibility in AD/HD. This inconsistency across studies is believed to be due to various factors, such as different experimental designs, different target age groups, different analysis settings, and different diagnostic classification systems (Oades et al., 1996; Rothenberger et al., 2000). These contradictions in the literature (Barry et al., 2003), besides the small number of published research conducted in this specific context, makes it difficult to conclude the neural origins of these processing deficits in the context of language processing in AD/HD. Thus, the present study focused on the P3(a) response, the neurophysiological marker of attention, as the most studied ERP component in this context.

1.5. *fMRI and source reconstruction studies in ADHD*

Bush (2010) summarized the attention network in the AD/HD context based on neuroimaging data. In that review, the AD/HD attention network included the dorsal anterior midcingulate cortex, the dorsolateral prefrontal cortex, the ventrolateral prefrontal cortex, parietal cortex, striatum, and the cerebellum. All these structures were also reported to show functional abnormalities in AD/HD. The fMRI technique was used to investigate the origins of the atypical brain activity by identifying the abnormalities in brain networks and connectomics among AD/HD participants (Stevens et al., 2007; Salmi et al., 2018) (also see reviews by (Konrad and Eickhoff, 2010); Bush, 2011; Cao et al., 2014). fMRI brain activity deficits in attentional response to infrequent stimuli (tones) were reported in the brain regions associated with orienting and working memory (Stevens et al., 2007). The regions identified in these processes were the frontal, temporal, and parietal lobes. On the other hand, enhanced brain activity during an attention auditory task was reported in some brain areas with the activation of brain regions that belongs modalities irrelevant to the task in AD/HD participants (Salmi et al., 2018). The authors showed the activation of the dorsal attention network and the cerebellum to attention-capturing stimuli. The study by Opitz et al. (1999) used ERP and fMRI to investigate the auditory processing of novelty. The authors tested the same paradigm with pure tones in both techniques and on the same participants. The ERP results showed a P3 response, whereas the fMRI scans revealed a bilateral activation of the STG. The attended condition activated the right prefrontal cortex (rPFC). Using speech attention tasks, Hugdahl et al. (2003) contrasted brain activations (fMRI) scans. The authors found bilateral activation of the superior temporal gyrus (STG) in passive listening while the activation increased anteriorly in the middle temporal lobes (MTL) in instructed attention to pseudowords. The activation also increased in the superior/medial temporal lobe when instructed to attend to a vowel, while a word generated a leftward asymmetric brain activation, showing the modulatory role of attention in passive and active speech processing via a directed attention task. The structural and functional connectivity reviews conducted by Konrad and Eickhoff (2010) and, more recently, by Cao et al. (2014), found abnormal connectivity and brain network dysfunction in AD/HD compared to controls.

The neuronal generators of the P3a and the P3b were also investigated via deep recordings. The attention orientation system related to the P3a was found to be located in the paralimbic and attentional frontoparietal cingulate cortex (Halgren et al., 1998). The source reconstruction method was also used to study brain abnormalities in AD/HD. Brain generators of the P3 component (P3a and P3b) in the auditory modality were studied in an oddball paradigm using tone stimuli via LORETA (Low-resolution brain electromagnetic tomography) reconstruction method applied on typically developed adult participants (Volpe et al., 2007). The authors reported sources in the cingulate, frontal and right parietal area for the P3a component. They also found the bilateral frontal, parietal, limbic, cingulate, and temporo-occipital sources for the P3b component in processing task-relevant events (Volpe et al., 2007). The effect of auditory attention modulation on P3a (along with the mismatch response and the late response) in adults was investigated via the source reconstruction method, and the findings revealed key regions in temporal and frontal areas contributing to this response (Chennu et al., 2013). An ERP source reconstruction study using an auditory oddball task testing control and AD/HD children (aged seven to 14) showed differences in the frontopolar and the temporoparietal regions of the left hemisphere. These results were interpreted to reflect altered top-down and bottom-up attentional processes in the AD/HD group (Janssen et al., 2016). The contribution of the frontal, temporal and paralimbic regions could be highlighted as possible main contributors to the P3a response.

Cross-comparing the literature findings when using both techniques (EEG/ERPs source reconstructions and fMRI) suggests activations in similar brain areas for the P3 response, namely the temporo-parietal and the frontal areas, since early studies (Linden et al., 1999). The joint independent component analysis conducted by Mangalathu-Arumana et al. (2012) in a combined EEG-fMRI experiment investigating the P3 component also revealed similar brain networks and common sources in both neuroimaging modalities. Janssen et al. (2015) and Janssen et al. (2018) also reported similar results by comparing fMRI and the Local autoregressive average source imaging results obtained with AD/HD participants.

1.6. *Goals of the study and research questions*

In the current study, we investigated ERP brain responses in typically developed children (*CTR*) and in children with attentional problems (*AP*) in response to speech sounds presented in native and foreign languages. By investigating these ERP responses in these two groups, we aim to better understand the temporal brain dynamics underlying the attention-deficit mechanisms that interfere with speech processing in the context of attention deficit and to investigate how altered attentional processes in children with *AP* symptoms may affect the speech processes, both in native and in foreign languages and how they manifest on the neuronal level. For this purpose, a correlation analysis was used to investigate how behavioral assessments reflect the electrical brain responses. We also used a source reconstruction method to investigate the neural origins of the speech attentional processes in both groups of children.

Based on previous evidence in the literature, we expect to observe differences in the brain responses between *AP* and *CTR* groups when processing speech sounds at the latency range of the P3a response, the neurophysiological marker of attention switching (Escera et al., 1998; Gumenyuk et al., 2001; Sussman et al., 2003; Yang et al., 2015). A second question addressed in this study is how different the brain responses are in second language processing between the two groups. This remains an exploratory question since we did not find any clear evidence in the literature. However, we did expect to find differences in the brain responses between *CTR* and *AP* children if we based our hypothesis on earlier observations in AD/HD behavioral studies reporting learning problems of a foreign language in AD/HD students (Ferrari and Palladino, 2007; Leons et al., 2009; Liontou, 2019). As the P3a component reflects attentional processes, we hypothesized that if the mechanism of attention allocation is altered in speech processing of one language, it will be equally altered in the other language. We also used a behavioral tool in this study to identify children with attentional problems. We explored the association of the attention score with the brain activity by conducting a correlation analysis between the attention score (ATTEX) and the ERP (P3a) amplitude. Our aim was to investigate whether the neural responses correlate with the behavioral scores and whether they reflect what teachers observe in the classroom. Altered or abnormal attentional brain networks as concluded by some previous connectivity reviews (Konrad and Eickhoff, 2010; Cao et al., 2014) may be the origin of electrical brain activity differences when expressed on the scalp level. Based on this evidence, differences in the ERP responses between typical children and AD/HD children are expected. To investigate the neural origins of these attentional processes in *CTR* and *AP* groups, we compared the source reconstructions in both groups. These neural sources were described and discussed in reference to earlier findings in the literature, as part of the auditory -attention network and in the attention deficit context.

2. Methods

2.1. Participants and procedures

2.1.1. Participants

Initially, 466 voluntary sixth-graders took part in the eSeek project (Internet and Learning Difficulties: A Multidisciplinary Approach for Understanding Reading in the New Media Project, project number (274 022)). Participants were recruited from eight different schools in the area of Jyväskylä city, Central Finland (for a detailed description, see Kiili et al., 2018a;b). A total of 448 participants completed the ILA tests (Kiili et al., 2018a, 2018b; Kanniainen et al., 2019), which consisted of a simulated closed Internet environment with four tasks that measured individual abilities to locate information, evaluate information, synthesize information, and communicate information (Leu et al., 2013; Kiili et al., 2018a, 2018b). Only 153 participants were invited for the individual EEG measurements, upon completion of the ILA test and Raven test results (Raven and Court., 1998). The details of the grouping criteria are presented below.

The data set of this study consists of EEG recordings collected on 118 participants, all of whom were Finnish-speaking school children aged between 11 and 13. They were divided according to the following criteria. All participants had to score above 15 points in the shortened Raven's progressive matrices test. For the attentional problems (*AP*) group (N = 20; with 12 boys and eight girls; mean age = 12.31, SD = 0.34; range =11.95–12.74), participants had to score above 30 in the attention and executive function questionnaire (ATTEX) (Klenberg et al., 2010) and above the 10th percentile in the reading score. (This second score is a composite score of three reading tasks computed using principal factoring (PAF); for details, see full description below.) For the control (*CTR*) group (N = 98; with 48 boys, 50 girls) (mean age = 12.35; SD = 0.28; range = 11.78–12.84), participants had to score below 30 in the ATTEX and above the 10th percentile in the reading score. EEG data of 86 *CTR* participants and 17 *AP* participants (103 participants EEG, mean age = 12.36; SD = 0.27; range = 11.78–12.84) remained valid for analysis after excluding participants with an insufficient number of trials (12 *CTR* and 3 *AP* data were rejected).

Based on parental reports, none of the participants had any hearing problems, a history of neurological disorders, or head injuries. They were all studying English as a second language in school, listening and using the English language frequently through media such as on TV and the Internet. All participants and their parents signed an informed consent form prior to their participation. This study was conducted according to the Declaration of Helsinki. The ethical committee of the University of Jyväskylä, Finland gave its approval for the protocol used in this project.

2.2. Selection criteria and tests

2.2.1. The cognitive nonverbal assessment

We used a 30-item version of Raven's progressive matrix test (Raven and Court., 1998). In this task, partially uncompleted pictures are presented to the child with six different options to complete the picture and the correct solution has to be identified. The total duration of this task is 15 min. All participants with nonverbal reasoning scoring equal or below 15 points (10th percentile) in the classroom testing were excluded.

2.2.2. The reading score

A latent score was computed for the reading fluency using principal factor analysis with PROMAX rotation in IBM SPSS 24 statistical program (IBM Inc.). The factor analysis was forced into one factor. This score was estimated based on the three following tests: the Word Identification Test – a subtest of standardized Finnish reading test ALLU (Lindeman, 1998) (factor load 0.683), the Word Chain Test (Nevala and Lyytinen, 2000) (factor load 0.872), and the Oral Pseudoword Text reading (Eklund et al., 2015) (factor load 0.653). The word identification test and word chain test were conducted as a group session. The oral pseudoword text-reading test was conducted as an individual session. For a full detailed description of these tests, see Kanniainen et al. (2019).

2.2.3. The attention and executive functions questionnaire

The ATTention and EXecutive function rating inventory (ATTEX in English, KESKY in Finnish) is an attention deficit disorder scaling tool used to measure executive functions in the school environment. It is based on a questionnaire performed by teachers and includes 55 items to measure difficulties of inhibition, attention, and executive function. These items were grouped into 10 clinical subscales: distractibility (four items on the scale), impulsivity (nine items), motor hyperactivity (seven), directing attention (five), sustaining attention (six), shifting attention (four), initiative (five), planning (four), execution of action (eight), and evaluation (three). The teachers were instructed to rate the child's behavior on a three-point scale ("not a problem," "sometimes a problem," and "often a problem"). The internal consistency reliability of ATTEX and its scales varies between 0.67 and 0.98 and criterion validity varies between 0.68 and 0.95. This test is designed specifically to be used as a screening tool in the school environment to detect students with attentional problems (AD/HD) (Klenberg et al., 2010). All participants identified with attention deficits (based on their teachers' rating) and scored more than 30 points were included in this study under the *AP* group. All participants who scored below 30 points in this test and did not show any reading deficits and representing typical cognitive non-verbal skills were included in the control group (see Table 1).

2.3. Stimuli and experimental procedure

In this EEG experiment, we used a modified version of the two-sequences, two-deviant passive auditory oddball paradigm designed by Ylinen et al. (2019) to measure the auditory attentional processes (for illustration see Fig. 1). In this experiment, the stimuli were presented in a 20 min passive oddball paradigm divided into two blocks: (Finnish) native stimuli were presented in the first block, and (English) foreign stimuli were presented in the second block. This presentation order was kept standard, always starting with the native language (not counterbalanced as in the original paradigm) to avoid any possible interference of the foreign language processing on the native language after a possible repetition effect if the foreign language block was presented first. The stimuli were pronounced by a Finnish-English bilingual male in a neutral way and checked for any language bias in the pronunciation by native Finnish and English speakers. The recordings were equalized and normalized in segmental durations, pitch contours, and amplitude envelopes with Praat (Boersma and Weenink, 2010); for a more detailed description of stimuli preparation, see Ylinen et al., 2019).

The stimuli were all CVV-syllables, being either words or syllable (only one) in Finnish and English languages: *shoe* [ʃʊː], *shy* [ʃaɪ] and *she* [ʃiː] as the English stimuli, and *suu* [sʊː] (mouth), *sai* [saɪ] (got) and *sii* [siː] (single syllable) as the Finnish stimuli (see Fig. 2). The Finnish items were chosen as the phonetic equivalents to the English items and not according to their frequency of use as for the English ones; thus, they were selected after the English stimuli. This explains why there is a syllable in the native oddball sequence instead of a word as no phonological equivalent word was found for the third English item. The original paradigm comprised a third condition to counterbalance words and syllables with and English item shoy [ʃɔɪ] (syllable/pseudoword with no meaning) and Finnish word soi [soi] (with its own meaning plays/rings/allowed). However, this last condition was not included in our study as the experiment was very long and we had to drop the last condition to reduce the experimental total time. We faced more dropping rates from our participants who chose to not complete the experiment in the piloting phase when using the full version of the paradigm. We should note here that this dropping rate was quite high because our EEG data recording was performed in a series with three other EEG experiments on the same participants in a total session of 3.5–4 h.

The Finnish phonology does not include the sound/ʃ/, so the English items can be easily recognized and identified as a foreign language from the onset of the word (Lennes, 2010). The English stimuli were expected to differ as a function of their frequency as words in daily use, according to the British national corpus (Leech et al., 2016): *shoe* and *shy* are known but less frequent than *she*, which is well known as the most frequent of the stimuli. For the Finnish stimuli, *sai* is the most frequent item (the past tense of the Finnish verb saada, 'to get'), the word *suu* ('mouth') is less frequent and *sii* (without its own meaning but commonly used syllable) the most infrequent compared to the other two syllables according to the Finnish language bank (Huovilainen, 2018). For details, see the full description in Ylinen et al. (2019).

The stimuli within each block were presented in a pseudorandomized order, with a minimum of two standards and a maximum of five standards between two consecutive deviants. The inter-stimulus interval between stimuli varied randomly between 850 and 1000 ms. The total number of presented stimuli was 2000. The stimuli were presented in the Finnish block as follows: 80 percent of the stimuli *suu* being standard stimulus (800 trials), 10 percent as deviant stimulus *sii* (100 trials), and 10 percent as deviant stimulus *sai* (100 trials). The stimuli in the English block were presented as follows: 80 percent of the stimuli *shoe* being standard stimulus (800 trials), 10 percent as deviant stimulus *she* (100 trials) and 10 percent as deviant stimulus *shy* (100 trials). The duration of all the stimuli was fixed to 401 ms. The stimuli were presented to the participants via a loudspeaker placed on the ceiling of the experimental room, above the participant's heads, and presented at approximately 65 dB. The loudness was tested with an audiometer for each stimulus prior to recording. The sound level meter (Brüel & Kjaer) was used on a pedestal device with settings as following: Pol Voltage = 0v; Sound incidence = Frontal; Time weighting = fast; Ext filter = Out; Frequency weighting = A, Range = 40–110 dB; Display = Max.

2.4. Euclidean distance and center of gravity

The measure of the distance between two factors in a multidimensional space is called Euclidean distance (ED). In the current study, distance was measured between the different vowels of the standard and the deviants ([ʊː], [iː] and [ʊː], [aɪ]). The distance between two phonemes can be presented as coordinates on a two-dimensional space. This distance between items was computed by identifying each formant frequency value ($F1_x$ and $F2_x$) for each item via Praat ® software. The difference was then calculated in Excel ® software using the following formula:

$$d(p,q) = \sqrt{\sum_{i=1}^{n} (q_i - p_i)^2}.$$

For the fricatives, it is more common to measure the center of gravity (COG) to evaluate the distance between two fricatives. The COG is the phonetic cue in fricative perception consisting of the magnitude weighted average of frequencies present in the fricative spectrum. The COG makes it possible to distinguish the sibilant fricatives with different places of articulation (e.g./s/vs/ʃ/) (Chodroff and Wilson, 2020). Importantly, the COG characteristics of a fricative vary according to the preceding vowel (for example, the value for/s/is lower before a rounded vowel such as/u/than before an unrounded vowel such as/i/) (Alan, 2019). As the fricative carries the energy of the following vowel(s), the listener is able to discriminate the phonetic changes in the stimuli's fricative as early as the onset time due to a detectable variation in the spectral cues.

In the supplement tables the ED between the vowels and COG between the fricatives within each language. This information will be used as a support for the discussion.

Table 1

Summary of the Attention and Executive function inventory (ATTEX) and the Raven's Standard Progressive Matrice test between the two groups.

Group		ATTEX			RAVEN		
	df	p-value		Cohen's d	p-value		Cohen's d
CTR* vs *AP	102	0.000		−4.313	0.482		0.193
		t-value	M	SD	t-value	M	SD
CTR		−7.358	6.081	7.990	0.323	22.953	3.398
AP		32 673	41.352	9.13	−1590	22.294	3.495

Note: t-values denote test statistics with degree of freedom (df). *AP* denotes the attentional problems group and *CTR* denotes the control group. Cohen's d denotes the effect size between the two groups. The *M* denotes the mean and *SD* the standard deviation of each test in the two groups. The FDR correction alpha value is 0.05.

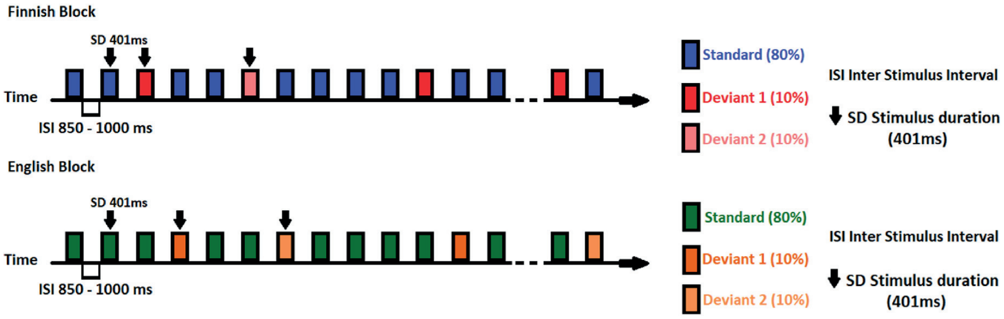

Fig. 1. Schematic illustration of a two-deviant auditory oddball paradigm showing the two sequences: Finnish and English. Each of the sequences contained a standard and two deviants (Deviant 1 and Deviant 2) presented in randomized order.

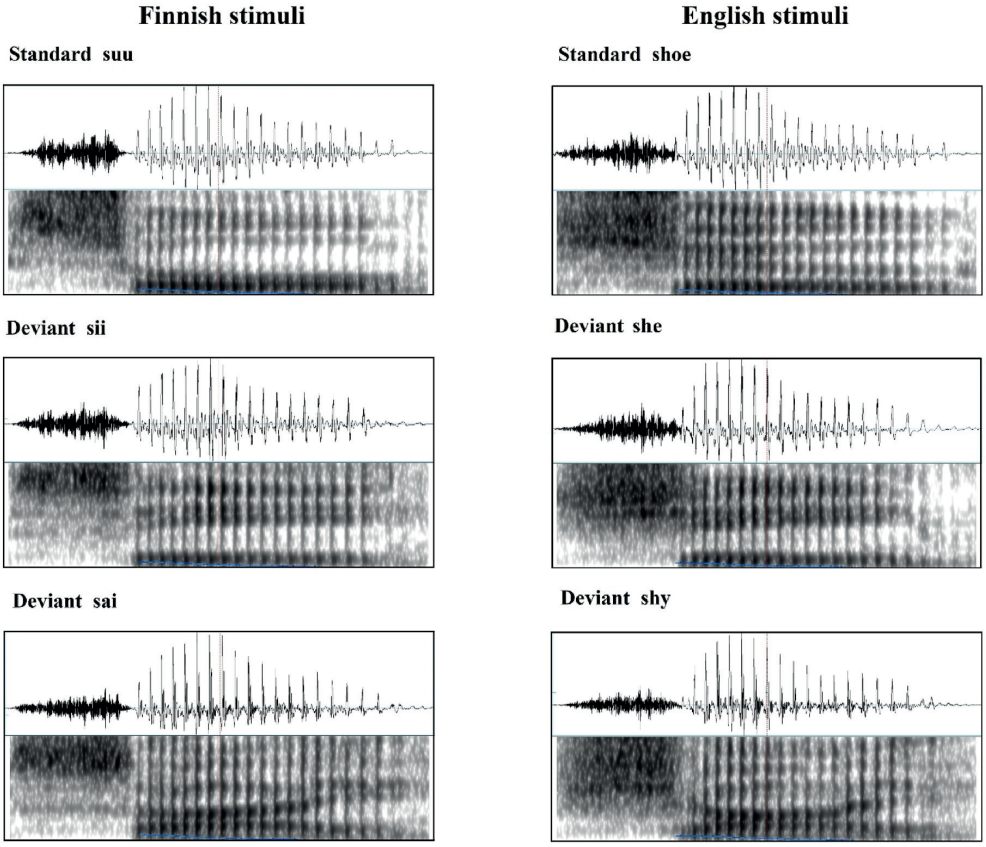

Fig. 2. Spectrograms of the Finnish and English stimuli used in the auditory oddball paradigm. The stimuli fricatives (/s/and/sh/) duration last from the onset of the stimuli at 0 ms until 120 ms where the transition starts with the emergence of the vowels ([ʊː], [iː] and [aɪ]) that last until the end of the stimuli at 401 ms. The vowel formants in *suu*, *sii*, *shoe* and *she* remain stable during the second part of the stimuli, whereas the formants change again between the vowels/a/and/i/in *sai* (at 291 ms) and in *shy* (at 276 ms).

2.5. EEG recording and pre-processing

2.5.1. EEG recording

The EEG data were recorded in an electrically shielded and sound-attenuated EEG-laboratory room located on the second floor of the University of Jyväskylä facilities. During the recording, the child was instructed to sit calmly on a chair while watching a cartoon movie that he/she picked from a movie selection, to be played on the computer screen in mute mode. He/She was asked to minimize as possible his/her body movements in order to reduce the motion artifacts in the EEG recording while listening passively to the auditory stimuli. The behavior of the participant was monitored via a live-stream video camera and a short break was taken every time the participant expressed his/her need for rest, to report any discomfort, or when the experimenters needed to correct noisy electrodes drying over time.

The electroencephalography data were recorded using a high-density array EEG system with 128 Ag–AgCl electrodes using HydroCel Geodesic sensor nets (GSN; Electrical Geodesics). The electrode positions in the GSN-128 channels correspond to the international 10–10 system. The electrode numbers 24, 124, 36, 104, 57, and 100 correspond respectively to the standard placements F3, F4, C3, C4, (left mastoid) LM, and (right mastoid) RM of the 10–10 system (Luu and Ferree, 2005). The data were recorded using the Cz electrode (electrode 129) as the online reference electrode. The EEG recording was performed by the NeurOne software and using a NeurOne amplifier (MegaElectronics Ltd, new designation Bittium). The recordings were sampled online at 1000 Hz with a high-pass filter at 0.16 Hz and a low-pass filtered at 250 Hz. Electrode Impedances were kept below 50 kΩ and the data quality was monitored and corrected continuously to ensure high-quality recordings.

2.5.2. EEG preprocessing

For the offline data pre-processing and averaging both BESA Research 6.0 and BESA Research 6.1 were used. Bad channels with highly noisy data were first identified and marked one by one manually as noisy channels after visual inspection of the data. Channels showing noisy or missing data were interpolated using the spherical spline interpolation method (Ferree, 2006). Independent component analysis (ICA; Infomax applied on a 60-sec segment of the EEG, Bell and Sejnowski, 1995) was used to model and correct the blinks based on individualized models created with the participant's own data. Data were segmented into epochs of 950 ms long for all the stimuli, comprising 100 ms pre-stimulus baseline and 850 ms post-stimulus window. The artifact detection was set to a maximum threshold of 175 μV for amplitude fluctuations within the total duration of the epoch. All fluctuations above the threshold were automatically rejected. A high-pass filter of 0.5 Hz, zero phases, was applied to the raw data. All remaining bad channels were marked as bad and rejected. The bad channels were then interpolated before averaging. A low-pass filter of 30 Hz, zero phases, was applied to the highly-pass filtered and segmented data. The baseline was set to −100 ms and 0 ms to the filtered and segmented data. The data were re-referenced offline to the average reference and accepted trials for each stimulus were averaged for each participant. The average percentage of rejected trials for all the conditions in *CTR* and *AP* groups is given in the supplementary materials (Table A). In the *CTR* group, each condition had a minimum of 43 trials in the Finnish stimuli and 50 trials in the English stimuli for averaging. In the *AP group*, each condition had a minimum of 63 trials in the Finnish stimuli and 75 trials in the English stimuli for averaging (for a full description, see Table A in the supplement). The difference waveforms were also calculated as an extraction of the deviant response from the standard response for each condition (deviant response minus standard response).

2.5.3. Time windows

The averaged epochs were divided into four-time windows based on visual inspection of the stimuli ERPs and the difference waveforms. The peaks of the ERP components were targeted to be around the middle of the time window. The target window in this study was set from 300 ms to 450 ms for the P3a response. This window was used to calculate the statistical differences between groups and between conditions. This same window was used to perform the correlation analysis between the ERP responses and the attention score and to run the source reconstruction analysis.

2.6. Source reconstruction analysis

BESA research 7.1 software was used in an inverse approach with a distributed source model in the brain volume: classical LORETA analysis recursively applied or CLARA. This method allows to produce more focal localization compared to other EEG reconstruction methods and is able to separate close neighbor sources (for reference, see Iordanov et al., 2018; Beniczky et al., 2016). This technique was described as a "good" method used for clinical application such as the ictal EEG (epileptic foci localization) in presurgical evaluation performed in patients with focal epilepsy (for details, see Beniczky et al., 2016). However, as with all of the reconstruction methods, this technique still faces the limitations of the reverse solution. In the current study, this approach was performed for source reconstruction over the group average difference waves to estimate the source areas in the brain related to the attentional process in passive speech perception. For this analysis, the high cut-off filter was set at 20 Hz, and the analysis was conducted over the same time window used earlier for the correlation analysis. The window duration was set to 150 ms showing the strongest correlation results and stable topographic maps (same significance electrodes over the longest time window). The CLARA solution was obtained with 1 percent regularization and 0.005 percent SDV cutoff for iterations, applying a 7 mm voxel size in the Talairach space and unweighted image. An age-appropriate template (age 12 y 0 mo) with a 3-D brain template model (an average MRI) provided by the BESA ® software was used to compute estimations of the cortical sources. The source reconstructions were performed in a descriptive comparative manner to investigate the possible differences in cortical brain activations between the two groups over the statistically significant conditions only.

2.7. Statistics

2.7.1. Cluster-based permutation tests

BESA statistics 2.0 was used to estimate the statistical differences between the two groups between conditions by computing the nonparametric cluster-based permutation tests on the target time window (ref Brain Electrical Source Analysis (BESA), Germany: for the principles of nonparametric cluster-based permutation tests in M/EEG data, see, e.g., (Maris and Oostenveld, 2007). The number of permutations was set to 1000 for each contrast and the channel neighboring distance was set to 4.5 cm (with 129 electrodes). False discovery rate (FDR) correction was applied across the permutation tests (Benjamini and Hochberg, 1995) to correct the p-value (FDR correction with $p = 0.05$) performed for the different comparisons.

2.8. Correlations

BESA Statistics 2.0 was used to estimate the correlations between the ATTEX score and the brain responses over the target time window (300–450 ms) as defined above. The correlations were conducted for each difference (contrast: deviant – standard stimuli) with channel neighboring distance set to 4.5 cm, α set at 0.05, and 1000 permutations for each computation. MATLAB R2019b (Mathworks ®) and the IBM SPSS statistics version.26 software were used in a second step to determine the r-value of each significant correlation obtained in the BESA statistics. The correlation results in the permutation statistics showing the highest correlation values over a 20 ms time window (340–360 ms for the *sii-suu* condition and 380–400 ms for the *sai-suu* condition), and their corresponding significant clusters, are illustrated in Figs. 6 and 7 below. A MATLAB script was used to compute average amplitude over a specific time window and specific electrodes based on the BESA statistics software findings. The corresponding Pearson and Spearman's rho correlation results were reported. A short description of the specific parameters used to compute each r-value is reported in the result section.

3. Results

3.1. ERP group comparison between CTR and AP groups

3.1.1. ERP difference waves in first language (Finnish)

Fig. 3, middle panel, illustrates ERP difference waves of the *AP* group (red curve) and the *CTR* group (green curve) in the Finnish language contrasts over the electrodes F3, F4, C3, C4, LM, and RM. The ERP difference between the deviant stimulus and standard stimuli, over the P3a window (300–450 ms) in the conditions *sii-suu* and *sai-suu* are illustrated in Figures C and D, respectively.

The statistical cluster-based permutation test comparing the two groups over the P3a time window shows a statistically significant difference in the condition *sai-suu* (cluster range: 300–439 ms), with one positive cluster and with a maximum difference at 344 ms and p-value<0.005. The distribution map of this cluster (see Fig. 3F) shows a clear

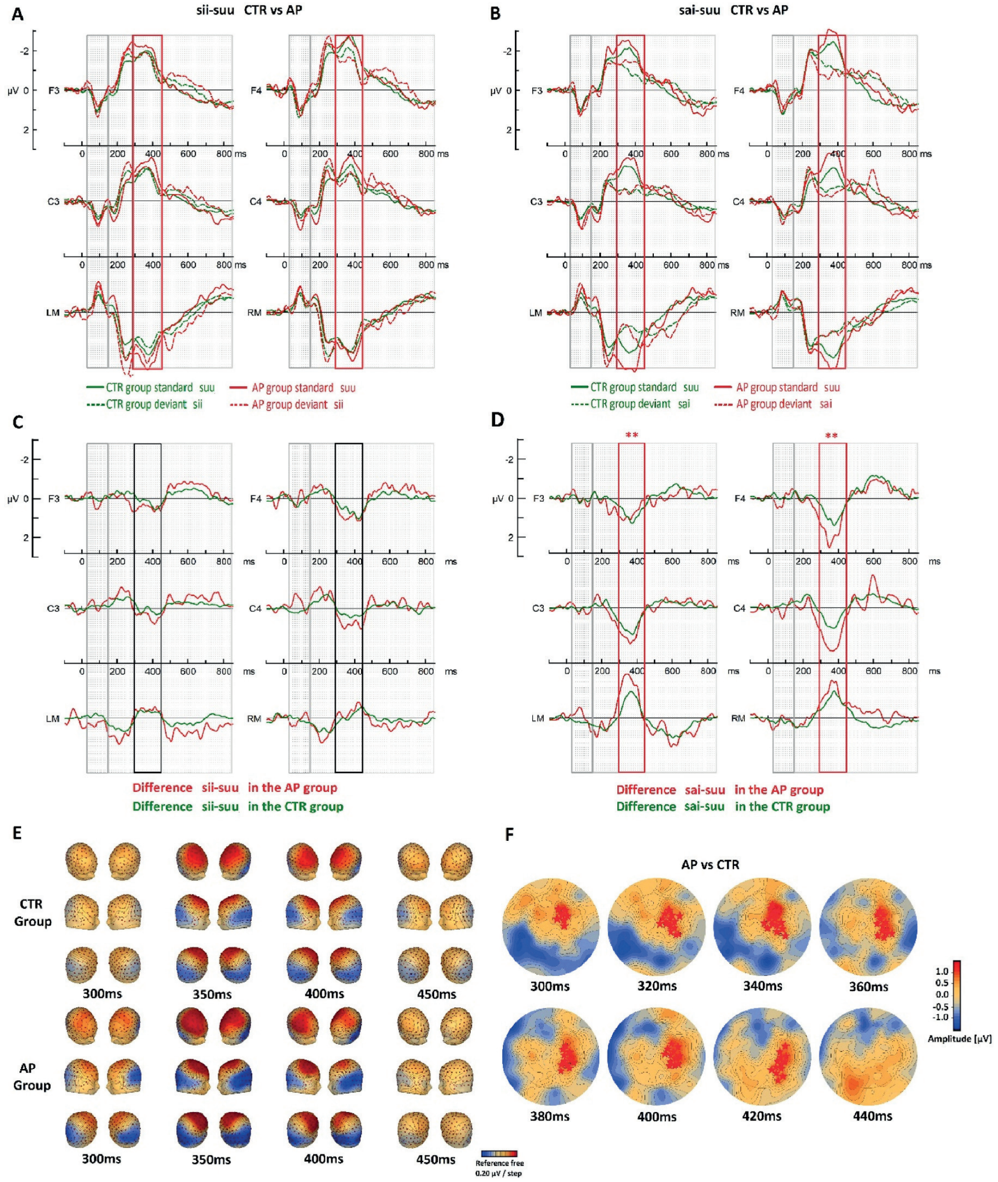

Fig. 3. The ERP waveforms of the standard (pre-deviant) stimuli (solid line) and the deviant stimuli (dashed line) in Control (in green) and in *AP* (in red) groups are presented in the top panel. The native conditions are presented in (A) pre-deviant suu and deviant sii, on the left panel (B) pre-deviant suu, and deviant sai on the right panel. (C) Difference waveforms of the *CTR* group (in green) and the *AP* group (in red) for the sii-suu contrast, and (D) *sai-suu* contrast. No significant difference was found in *sii-suu* contrast. (E) The P3a topographical maps of the *CTR* and *AP* groups in the time window (300–450 ms) for the difference *sai-suu* (statistically significant). (F) Cluster-based permutation test maps of the between-group comparison (*AP* vs *CTR* groups) for the *sai-suu* difference wave at the P3a time window. The significant clusters are highlighted with red stars. The measuring unit is µV.

group difference over the frontal area in the right hemisphere, with the *AP* group showing a more positive P3a response than the *CTR* group. No statistically significant differences were found in the *sii-suu* contrast.

The topographic maps showing the evolution of the electric distribution for the difference *sai-suu* over the whole head for the *AP* group and *CTR* group between 300 and 450 ms are illustrated in Fig. 3E. In the *CTR* group, the maps show the emergence of a positive difference activity between the deviant *sai* and the standard *suu* at around ≈300 ms in the central area, with a shift toward the right hemisphere. In parallel, a negative activity started to appear at the same time over the left temporo-occipital area. This distribution evolves into a clear fronto-central positivity and occipito-central negativity at ≈350 ms. This distribution remained stable until ≈400 ms, where it diminished rapidly. In the *AP* group, the electrical brain activity was higher in amplitude compared to the *CTR* group. The *AP* group showed a strong fronto-central positivity and centro-occipital negativity, remaining stable between ≈300 ms and 400 ms.

3.1.2. ERP difference waves in foreign language (English)

The comparison between the ERP difference waves of the *AP* group (red curve) and the *CTR* group (green curve) in English language contrasts over the electrodes F3, F4, C3, C4, LM, and RM are illustrated in Fig. 4. The ERP difference between the deviant stimulus and standard stimuli over the P3a window (300–450 ms) for the conditions *she-shoe* and *shy-shoe* are presented in Figures C and D, respectively. The cluster-based permutation test of the group difference did not reveal any statistically significant result showing a group difference in any of the foreign contrasts *she-shoe* and *shy-shoe*.

3.2. ERP responses within AP group

3.2.1. Native language processing

The ERP responses to standard and deviant stimuli (red waveforms) of the *AP* group in both first-language conditions *sii* vs *suu* and *sai* vs *suu* are illustrated in Fig. 3 A and B, respectively. The *AP* group ERP responses are overplotted on the ERP responses of the *CTR* group (green waveforms) for the same conditions. Overall, the *AP* group responses to standard showed higher amplitudes in both native conditions compared to the *CTR* group responses, whereas it showed an opposite pattern for the response to deviant stimuli *sii* and *sai*, with lower amplitudes in both native conditions for the *AP* group compared to the *CTR* group. This effect can be clearly observed in the *sai-suu* contrast over the frontal electrodes, with almost no difference over the mastoids. In the P3a time window, clear peaks were observed in both groups, with clear enhanced responses (in this case more negative) of the standard compared to the deviant stimuli (less negative). The amplitude of the difference between

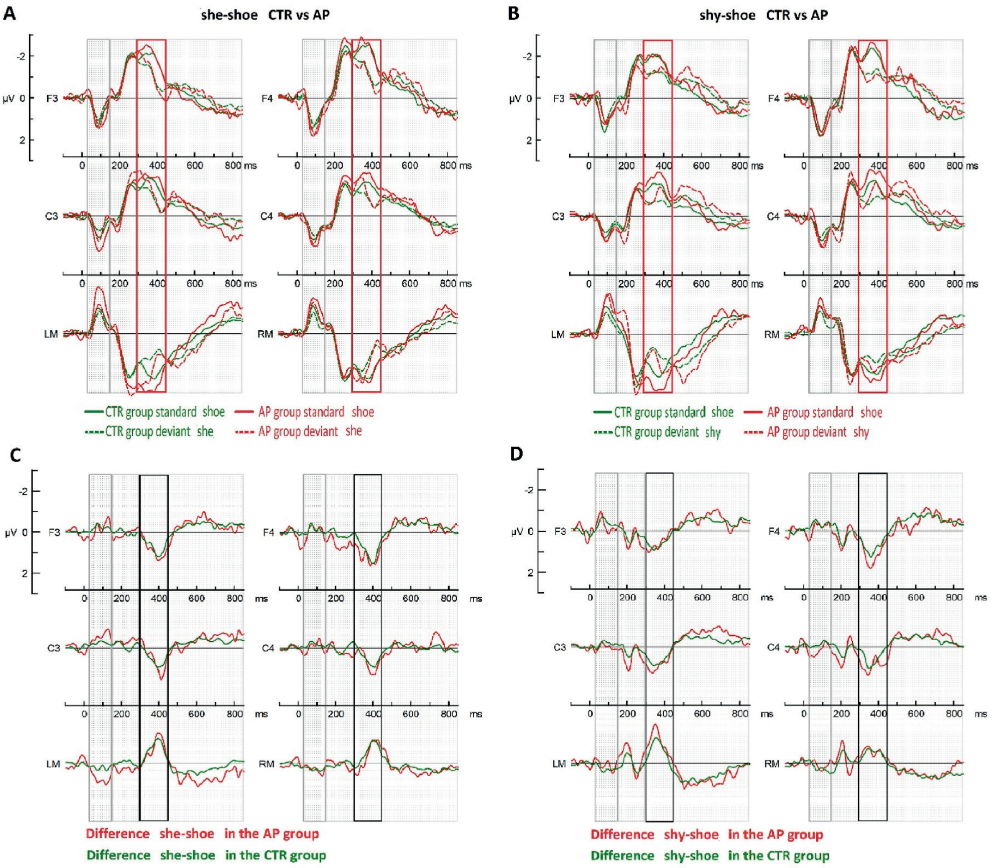

Fig. 4. The ERP waveforms of the standard (pre-deviant) stimuli (solid line) and the deviant stimuli (dashed line) in Control (in green) and in *AP* (in red) groups are presented in the top panel. The foreign conditions are presented in (A) pre-deviant *shoe* and deviant *she* on the left panel, (B) pre deviant *shoe*, and deviant *shy* on the right panel. Difference waveforms of the *CTR* group (in green) and the *AP* group (in red) for the (C) *she-shoe* contrast, and (D) *shy-shoe* contrast. No significant differences were found in the P3a window.

the deviant and standard stimuli was larger in the condition *sai-suu* than in the condition *sii-suu* between ≈300 and 450 ms, an effect that was found in both *AP* and *CTR* groups.

The cluster-based permutation test results of the P3a response within the *CTR* and *AP* groups to native language are illustrated in Fig. 5 A and B. The permutation tests in both native conditions over the P3a time window (300–450 ms) showed a statistical difference reflecting a strong P3a effect in both groups that was more pronounced in the *AP* group. For the *AP* group, and in the *sii-suu* difference, the cluster-based permutation test renders a strong positive cluster emerging at around ≈330 ms in the frontal area, and a negative cluster at the occipital–inferior temporal left areas. The positive cluster becomes more robust ($p < 0.013$) with a preponderance to the right hemisphere until the end of the window. In the second condition *sai-suu*, the positive cluster emerged earlier at ≈ 300 ms with a central positive cluster and a negative cluster on the occipital area. These clusters remained stable and reached a maximum effect at ≈ 360 ms ($p < 0.001$) then started to fade at the end of the time window.

3.2.2. Foreign language processing

The ERP responses to standard and deviant stimuli (red waveforms) of the *AP* group in both foreign language conditions *she* vs *shoe* and *shy* vs *shoe* are illustrated in Fig. 4 A and B, respectively. The *AP* group ERP responses are overplotted on the *CTR* group ERP responses (green waveforms) to the same conditions. For the foreign standard stimulus processing, the observed responses were similar to those in the native language, with the *AP* group responses showing higher amplitudes to standard stimulus in both native conditions compared to the *CTR* group responses. However, the difference between the group's responses is less pronounced in the foreign language. The difference between the deviant stimuli responses is also lower, with the responses to deviants in the *AP* group showing higher amplitude compared to *CTR* group, visibly clear, over the mastoids.

The cluster-based permutation test results of the P3a response for both *CTR* and *AP* groups to foreign language are illustrated in Fig. 5 (C and D). The permutation tests in both native conditions between 300 and 450 ms showed a statistically significant difference, reflecting a strong P3a effect in both groups. In the AP group, over the P3a time window, a clear statistical difference was found in both contrasts *she-shoe* and *shy-shoe* with a $p < 0.001$. In both cases, the difference renders two clusters a positive in the fronto-central area and a negative in the occipital-inferior temporal areas. Similarly, to the native language processing, the *she-shoe* difference shows a similar distribution pattern with the positive cluster emerging at ≈ 330 ms having a preponderance toward the right hemisphere, whereas the positive cluster in the difference *shy-shoe* emerged earlier at ≈ 300 ms in the fronto-central left area, becoming more centrally located between ≈330 and 360 ms. However, the significant clusters faded quicker than the ones described in the native language contrast *sai-suu*, which started to disappear at ≈ 390 ms.

3.3. Correlations between attention score and ERP amplitude

3.3.1. Correlations for the native language (Finnish)

The correlation analysis between the attention score and the amplitude over the whole head including all electrodes (129 electrodes) shows statistically positive correlations in the P3a time window in the conditions *sii-suu* (Fig. 6A) and *sai-suu* (Fig. 7A).

The correlation in *sii-suu* is found over the right hemisphere with a maximum effect at 346 ms (range of the significance: 300–450 ms) and with a p-value<0.02. A positive linear correlation explaining ≈12 percent of the observed brain activity is found between ≈340 and 360 ms (see Fig. 6B). The enhancements observed in the waveform comparisons are also visible in the box plot (see Fig. 6C), showing a higher mean amplitude in the *AP* group compared to the *CTR* group. The result was significant in the Pearson and Spearman's rho correlations with a p-value<0.001 and p-value<0.02 respectively (for details, see Table 2).

The correlation in *sai-suu* is found over the right hemisphere, with a maximum effect at 390 ms (range of significance: 300–439 ms) and with a p-value<0.03. A positive linear correlation explaining ≈17 percent of the observed variability of the brain activity is found between ≈380 and 400 ms (Fig. 7B). Similarly to the *sii-suu* condition, the enhancements observed earlier in the waveform comparisons are also visible in the box plot (Fig. 7C) over this time window, showing a higher positive mean amplitude in the *AP* group than the *CTR* group. The result was significant in the Pearson and Spearman's rho correlations with a p-value<0.001 and p-value<0.002 respectively (for details, see Table 3).

3.3.2. Correlations in the foreign language (English) processing

The correlation analysis between the attention score and the amplitude over the whole head including all electrodes (129 electrodes) in the P3a time window (300–450 ms) in both foreign condition *she-shoe* and *shy-shoe* did not reveal any statistically significant results. No

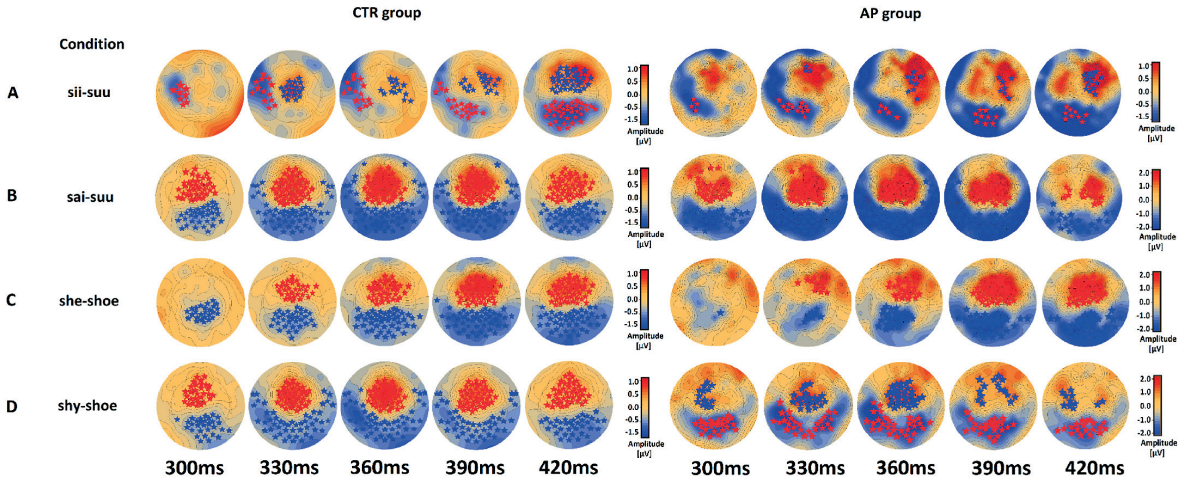

Fig. 5. Cluster-based permutation tests of the P3a component within the *CTR* group (left panel) and the *AP* group (right panel) in the four conditions (A) *sii-suu*, (B) *sai-suu*, (C) *she-shoe* and (D) *shy-shoe* over the P3a time window (300–420 ms). The significant clusters are indicated with stars. Blue and red colors indicate negative and positive amplitude values respectively. The measuring unit is µV.

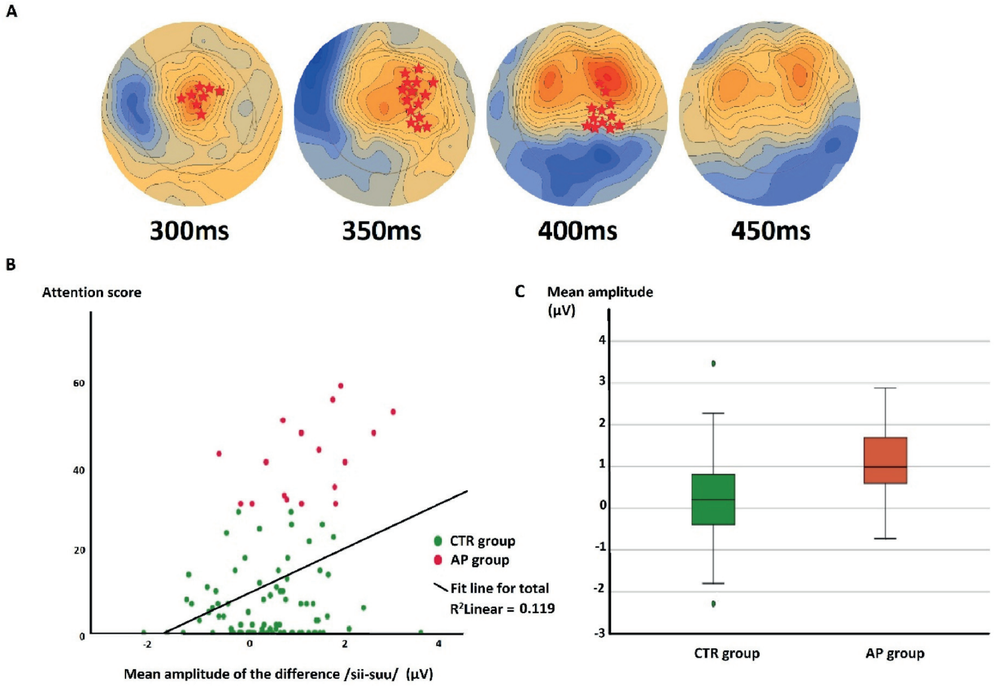

Fig. 6. Correlation test results between the mean amplitude of the difference waves *sii-suu* and the attention score (ATTEX/KESKY) in *CTR* and *AP* groups. (A) The significant cluster distribution for the correlation maps between 300 and 450 ms (highlighted with red the stars). (B) The scatterplot for *CTR* group (in green) and *AP* group (in red) showing the correlation between mean *sii-suu* difference wave amplitude at the time window of 340–360 ms over the significant cluster (E 3 102 103 104 110 116 117 122 123 124). (C) Box plot showing the distribution of the mean amplitude within each group for the same correlation.

correlations were found in the foreign language context within the P3a time window.

3.4. CLARA source reconstruction

3.4.1. Source analysis of the P3a response in CTR and AP groups

The grand average source reconstruction results for the *CTR* and *AP* groups of the native language condition *sii-suu* illustrated in Fig. 8A, and of the native language condition *sai-suu* illustrated in Fig. 8B. The source reconstruction was performed for the difference waves between ≈300 and 450 ms (P3a response) for both native contrasts over the time window showing a significant correlation between the brain responses and the attention scores. The activated sources in the *AP* group seemed to be slightly more posterior compared to the *CTR* group. The group average activations were also larger on the source level in the *AP* compared to the *CTR* group.

In the *sii-suu* contrast, the *CTR* group showed five sources active in the following approximate areas (Brodmann areas are given to aid the identification of the brain regions): the L Brodmann area (BA)36/left inferior temporal region, the R BA48/the right retrosubicular/hippocampal area, the R BA36/the fusiform area in the right temporal region, the L BA23 ventral posterior cingulate gyrus (vPCG) in the left hemisphere, and the L BA10/the left frontopolar/anterior prefrontal cortical area (APC). Similarly to the *CTR* group, the *AP* group showed the activations of five sources, as follows: the L BA36/the left inferior temporal region, the R BA48/the right retrosubicular area, the hippocampal region in the temporal lobe, the L BA48/left retrosubicular/hippocampal area, the R BA10/the right frontopolar/anterior prefrontal cortical area and the R BA23/ventral posterior cingulate gyrus (vPCG) in the right hemisphere.

In the *sai-suu* contrast the *CTR* group showed four active sources in the following areas: the L BA36/the left fusiform area in the left temporal region, the R BA48/the right retrosubicular/hippocampal area in the right temporal lobe, the R BA23/the right vPCG and the R BA10/the right frontopolar/anterior prefrontal cortical area (APC). The *AP* group showed three active sources in the same condition as follows: the L BA36/left fusiform area in the left temporal region, the R BA48/the right retrosubicular area, and the R BA10/the right frontopolar/anterior prefrontal cortical area.

Overall, similar brain areas were found to be active in both groups for both native conditions, with mainly a bilateral activation of the temporal regions and the activation of the frontal and posterior areas of the cingulate gyrus. Source activations were higher in the *AP* group compared to the *CTR* group (for details, see Table 4).

4. Discussion

The purpose of the current study was to investigate the possible differences in speech processing and its brain dynamics associated with the attention switching response (P3a) between two groups: children with attentional problems (*AP*) and typically developed children (*CTR*). Brain responses to speech were investigated using an auditory oddball paradigm with native (Finnish) and foreign (English) language speech items. Furthermore, the study tested how the behavioral evaluations, indicated by the attention scores obtained via ATTEX questionnaire, may correlate with brain activity. The brain sources activated when processing native and foreign speech items in each group were investigated via CLARA source reconstruction technique. Overall, the results of the ERP analysis on the difference waves between the two groups showed similar ERP patterns in both groups. The statistical cluster-based

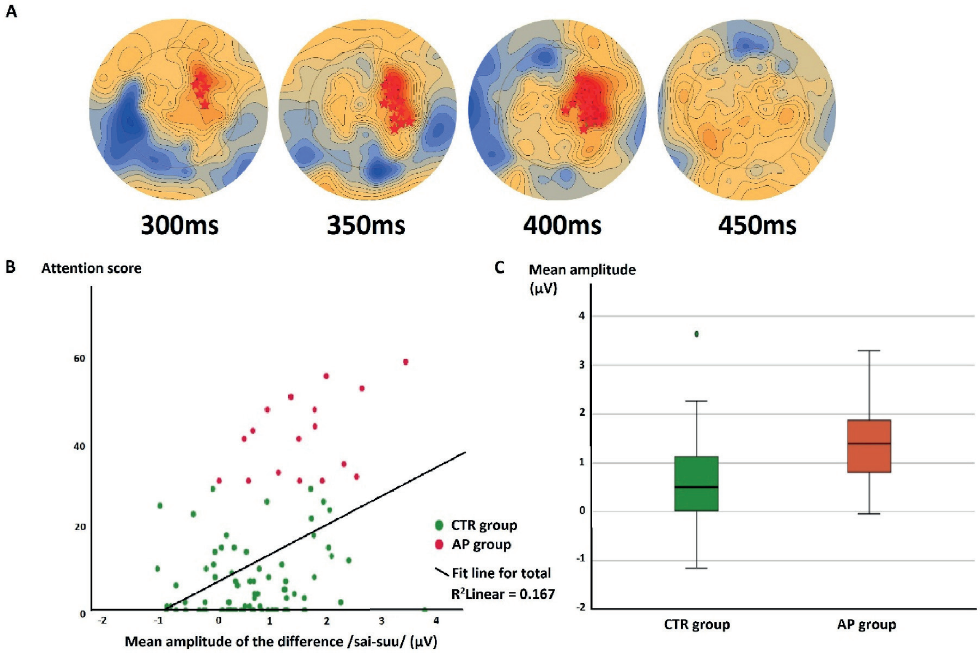

Fig. 7. Correlation test results between the mean amplitude of the difference waves *sai-suu* and the attention score (ATTEX/KESKY) in *CTR* and *AP* groups. (A) The significant cluster distribution for the correlation maps between 300 and 450 ms (highlighted with red stars). (B) The scatterplot for *CTR* group (in green) and *AP* group (in red) showing the correlation between mean *sai-suu* difference wave amplitude at the time window of 380–400 ms over the significant cluster (E 92 93 98 102 103 104 105 110 111 116 117). (C) The box plot showing the distribution of the mean amplitude within each group for the same correlation.

Table 2
Summary of the Pearson and Spearman's rho correlation results between the attention (KESKY/ATTEX) score and the mean amplitude of the difference wave *sii-suu* (in both groups) at the P3a time window between 340 and 360 ms.

		KESKY-score	Diff *sii-suu* P3a mean amplitude
Pearson correlation			
KESKY-Score	Correlation Coefficient	1	0.345[a]
	Sig (2-tailed)		.000
	N	103	103
Spearman's rho correlation			
KESKY-Score	Correlation Coefficient	1	0.254[a]
	Sig (2-tailed)		.010
	N	103	103

[a] Correlation significant at the 0.01 level (2-tailed).

Table 3
Summary table of the Pearson and Spearman's rho correlation results between the attention (KESKY/ATTEX) score and the mean amplitude of the difference wave *sai-suu* (in both groups) at the P3a time window between 380 and 400 ms.

		KESKY-score	Diff *sai-suu* P3a mean amplitude
Pearson correlation			
KESKY-Score	Correlation Coefficient	1	0.409[a]
	Sig (2-tailed)		.000
	N	103	103
Spearman's rho correlation			
KESKY-Score	Correlation Coefficient	1	0.327[a]
	Sig (2-tailed)		.001
	N	103	103

[a] Correlation significant at the 0.01 level (2-tailed).

permutation tests showed a clear difference between the standard and deviant responses within both groups, clearly reflecting the presence of the P3a response in *CTR* and *AP* groups. However, a larger P3a positive amplitude was observed in the *AP* group compared to the *CTR* group. A statistical difference was found between the groups over the P3a time window only for the native language *sai-suu* contrast. No statistical differences were found between the two groups for any of the foreign language contrasts in the same window. In the correlation analysis, the attention scores significantly correlated with the P3a amplitude for both native contrasts over the P3a time window. The correlation results hint at the role of the right frontal area on the attentional processes. No correlation was found for the foreign language. The group-level source reconstruction over the P3a time window showed source activations in the temporal fusiform areas, the temporo-parietal junction area, the ventral posterior cingulate area, and the frontopolar/anterior prefrontal cortical area. The source activity was similar between the two groups. However, higher source activity and larger active areas were found in the *AP* group compared to the *CTR* group. This effect was present for both native conditions, but more clearly observed on both hemispheres in the second condition *sai-suu*. A clear over activation of the frontal source in the *AP* group was also found in both conditions with a tendency to activate the opposite frontal hemispheric area compared to the CTR group.

4.1. ERP findings

In native language processing, the difference (deviant–standard), compared with cluster-based permutation tests, showed a significant

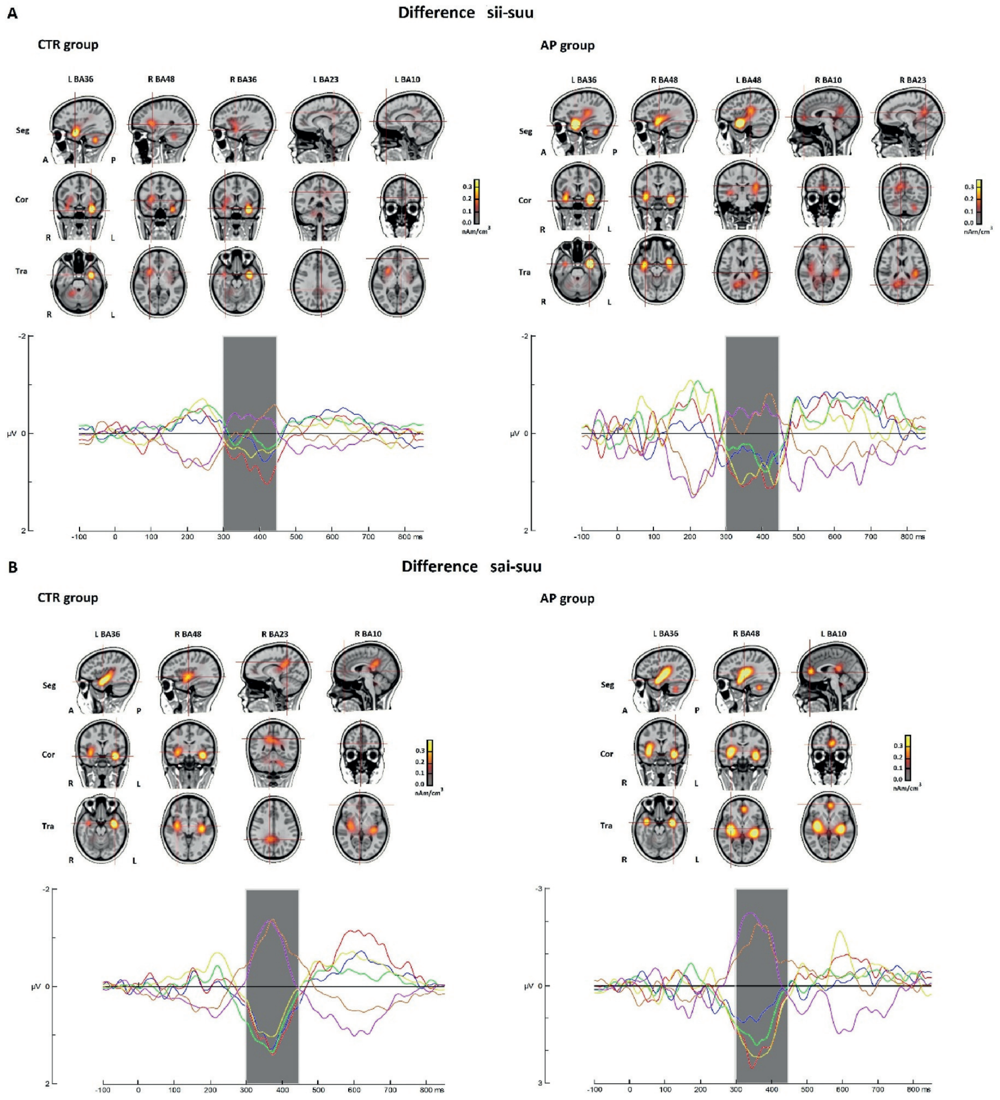

Fig. 8. CLARA source reconstruction for the conditions that showed significant correlations between the KESKY/ATTEX score and the ERP amplitude in the *CTR* group (in the left panel) and in the *AP* group (in the right panel). (A) The active sources between 300 and 450 ms (time window highlighted with the grey box) in the difference *sii-suu*, (B) and in the difference *sai-suu*. The difference waveforms for the following electrodes: F3 (in blue), F4 (in red), C3 (in green), C4 (in yellow), RM (in orange), and LM (in purple) are illustrated respectively for every condition and group in the bottom panel corresponding to each source reconstruction. Note: A (anterior), P (posterior), R (right), L (left), Seg (segmental), Cor (coronal), Tra (transversal).

difference between the *CTR* and the *AP* group at the P3a time window in the native contrast *sai-suu*. This result is in line with our prior hypothesis about difference in brain processes between the two groups typically found at this time window and known to reflect the attentional processes. The ERP responses within groups showed a bigger difference between the standard and deviant processing within the *AP* group compared to the *CTR* group. This may explain the higher P3a amplitude observed in the first group, which may have generated the group difference. The P3a response has been previously reported to differ between typically developed children and children with attentional deficits (Barry et al., 2003; Van Mourik et al., 2007; Tsai et al., 2012), typically with an attention processing deficit in the *AP* group. Considering that most of the previous studies used tone stimuli, very little is known about speech stimuli processing in this context. A larger positivity of the P3a response in the *AP* group or in participants with attentional problems compared to the *CTR* group has previously been reported (Van Mourik et al., 2007; Gumenyuk et al., 2005; Oja et al., 2016). Furthermore, we observed a larger difference in the *sai-suu* contrast compared to the *sii-suu* contrast in both groups. Significant group difference in processing one native contrast (*sai-suu* condition), but not in the other (*sii-suu* condition), may be due to distinct attentional processes generated in the presence of the diphthong [ai]. Differences in the physical features of the stimuli may have created larger differences in the brain responses, as reflected by the larger brain activity found in

Table 4
Summary of the source strength of the different sources found in the condition *sii-suu* and *sai-suu* in *CTR* and *AP* groups.

Condition	Group	Source	Source strength (nAm/cm^3)
sii-suu			
	CTR	L BA36	0.50
		R BA36	0.18
		R BA48	0.18
		L BA23	0.10
		L BA10	0.07
	AP	L BA36	1.10
		R BA48	0.37
		L BA48	0.25
		R BA 10	0.18
		R BA 23	0.18
sai-suu			
	CTR	L BA36	0.57
		L BA 48	0.32
		R BA23	0.23
		R BA10	0.09
	AP	L BA36	0.59
		R BA48	0.57
		L BA10	0.32

the *AP* group. To verify whether the phonological features were the origin of different attentional responses, we calculated the difference in phonological properties by calculating the Euclidean distance (ED) between each contrast's vowels and the center of gravity (COG) between the early fricatives, between each contrast's stimuli (for details, see Table B in the supplement). Surprisingly, the group difference was observed over the condition with the smallest phonological difference contrast. In the native contrast *sai-suu*, the ED between the standard's vowels and the deviant's vowels were almost five times smaller than in the ED between the contrast *sii-suu*. Similar results were also found in the COG when comparing the fricatives between the contrasts stimuli. This shows that the difference in processing the native contrast *sai-suu* observed between the two groups was not based on the physical saliency of the phonological features since this difference was larger in the non-significant contrast (*sii-suu* condition). In this case, the alternative explanation is that further processes seem to be involved in this response, including attentional processes. This could be related to the complexity of the stimuli structures as the stimulus *sai* carries a diphthong/ai/vs the vowel/ii/in the stimulus *sii*, as mentioned earlier. The change from the fricative/s/to a vowel/i/contrasted to one change/-s/to/u/compared to a double change from the fricative/s/to a first vowel/a/then a second vowel/i/contrasted to a single change/-s/to/u/creates probably different processes. It could be that the diphthong in *sai* is more attention-catching due to this complexity, that despite the smaller ED, it seemed to generate a larger P3a response compared to the simple stimulus *sii*. Another possible explanation is the phonological brain mapping of the vowels. Although a bigger physical/phonetic difference was found between *sii* and *suu* in the contrast *sii-suu* when comparing the ED and the COG vs the ED and COG in *sai-suu* contrast, no difference was found between the two groups' ERP responses. This may suggest similar brain processes in *CTR* and *AP* groups in processing this contrast due to the clear difference between the rounded vowel/uu/and the unrounded vowel/ii/. Less defined differences between the vowels may have generated different brain processes between the two groups and may therefore have created the group difference in processing the *sai-suu* contrast (for details, see Figure A, illustrating the Finnish vowel map in the supplement).

Larger P3a response in *sai-suu* could also be linked to higher cognitive processes such as semantic differences between the stimuli as *sii* is a syllable, *suu* and *sai* real words with *suu* a frequent noun and *sai* a frequent verb. These contrasts between syllable-word and word-word with different semantic values may generate different attentional processes, detectable at the P3a time window. This may also cause different attentional brain responses between the *CTR* and the *AP* groups. Previous investigations of attentional processes to words and pseudo-words have shown that brain processes differed between the two types of stimuli (Ziegler et al., 1997; Newman and Twieg, 2001). For example, it has been shown that pseudo-words generated larger brain responses in attended conditions (Shtyrov et al., 2012) and the opposite (smaller responses) in non-attended conditions, indicating that both semantic and attentional processes interact in the final brain response. This idea was supported by a study conducted on second-language learners' sensitivity to semantic meaning. Trofimovich (2008) showed that although learners become more sensitive to the second-language phonological details, the attentional processes dedicated to the meaning processing deleted this sensitivity, an effect found in all experience levels of this second language.

Another possible explanation for the group difference in the contrast *sai-suu* is a deficit in working memory. As has been presented in the literature earlier, a strong link was highlighted between attentional processes, as reflected in the P3a, and working memory (Redick and Engle, 2006; Berti, 2016; Ortega et al., 2020). Particularly in auditory perception studies, working memory was shown to play an important role in this process (Söderlund and Jobs, 2016), with AD/HD typically showing poor working memory skills when compared to controls (Blomberg et al., 2019) and higher magnitude in phonological working memory deficit (Raiker et al., 2019). It has been suggested that working memory controls involuntary attention switching (Berti and Schröger, 2003). Furthermore, previous findings suggested that working memory deficit in AD/HD reflects a combination of central executive and phonological processing deficits (Alderson et al., 2015). Thus, it is possible to attribute the group difference observed in processing the contrast *sai-suu* to a working memory encoding deficit, as suggested by the previous evidence. Here, the group difference may reflect a memory deficit in the *AP* group when processing the diphthong that may have generated a larger P3a response in this case (see Fig. 4, condition *sai-suu*, ERP waveform to the deviant *sai* in *AP* group). Furthermore, the literature has stated that the P3a response could represent the summation of different processes (Wronka et al., 2012), where it could be a combination of the different explanations presented above; for example, a working memory deficit combined with a phonological representation deficit.

The statistical cluster-based permutation test between the two groups showed the group difference in the contrast *sai-suu* to be located over the right frontoparietal area. Previous evidence in the literature showed the role of the frontal cortex in the attentional processes (Michalka et al., 2015). The contribution of the right frontal cortex has been suggested to be involved in the mediation and direction of attention (Foster et al., 1994; Daffner et al., 2000).

In the foreign language processing, the difference waves compared with cluster-based permutation tests did not reveal any significant differences in the foreign language processing between the two groups. The non-native nature of the stimuli, easily recognized at the onset of the sound, seems to generate similar brain responses in both groups. The attentional processes do not seem to show any atypical brain activity in the *AP* group in foreign language processing as no group differences were found, although they were found to be affected in the native language. The *CTR* and *AP* groups both showed the presence of a P3a response in the within-group analysis. As mentioned above, in Trofimovich (2008), second-language learners become more sensitive to the second language phonological details, but this sensitivity is somehow deleted due to an overactivation of the attentional processes to the meaning process. This may be a valid explanation for the lack of group differences in foreign language processing reported in our results. Another possible explanation for the absence of group difference in the foreign language context is the weak phonetic representation in both groups. As both groups may have a weak phonetic representation of the foreign (English) language, it is possible that the difference is so small that it could not be detected in the brain electrical response or could be completely absent due to a neural network that is not fully established.

The limitation of the experimental design with fixed order presentation that may have led to a possible confounded order effect should be considered in results interpretation. This was unavoidable choice due to the oversensitivity to foreign sounds as explained above.

The within-group investigation of the ERP waveforms over the 300–450 ms time window showed significant differences between the standard and deviant for all the conditions in both groups. These results clearly indicate that both groups showed a P3a response for all the contrasts with this difference being larger for the contrast *sai-suu* compared to *sii-suu* in both groups. Interestingly, the statistical cluster-based permutation test within groups revealed a significant difference in the right fronto-parietal area for the contrast *sii-suu*, *sai-suu*, and *she-shoe*. This hemispheric preponderance was less clear for the *shy-shoe* difference (see Fig. 5). These results again hint at a possible contribution of the frontoparietal right area to the attentional processing of these linguistic contrasts.

4.2. Correlations

The correlation analysis between the attention score and the ERP amplitude showed a significant positive correlation in the P3a time window for both contrasts *sii-suu* and *sai-suu*. The larger the teacher-rated ATTEX score, the larger the P3a response. According to this result, the ATTEX is shown to tap into the same attentional processes that are measured by the ERP P3a response. As the ATTEX is based on questionnaire to teachers to evaluate children's attentional problems, the correlation results show that the teachers' observations about non-attentiveness and distractibility are well reflected in larger attentional switching P3a brain activity. Thus, the teachers' observations and the larger P3a brain responses both seem to reflect the same over-sensitivity or attentional catching skills of the stimuli in the environment. This was only valid for the native language processing since no correlations were found between the ATTEX score and the P3a response in the foreign language processing. The lack of the correlation to the foreign language stimuli may reflect the language specificity and supports the idea of weaker representations of the foreign language stimuli (see the above discussion on the phonological representation of foreign stimuli), but also, as stated earlier, attentional processes to meaning in a foreign language may interfere with the attentional response (Trofimovich, 2008), which may explain the absence of such correlations in the foreign language context.

The correlations between ATTEX scores and ERPs found for the native contrasts were in the fronto-parietal region over the right hemisphere. Interestingly, this area is the same area described above, showing statistically significant differences within groups between the standard and deviant in the different contrasts. It is also the same area showing the statistical difference between *AP* and *CTR* groups for the *sai-suu* condition. Thus, we may conclude that the ERP responses in the 300–450 ms window reflect attentional processes with a clear contribution of the right frontoparietal area to this processing, in addition to other sources that were shown to contribute to this effect, mainly in the temporal areas, as found in the source reconstruction results (see Fig. 8). To provide further evidence, we investigated the sources underlying these processes below. The frontoparietal areas have earlier been linked in the literature to attentional networks in environment attention selection (for a review, see Ptak, 2012). Some studies have suggested a top-down input of the frontoparietal area to modulate the auditory cortex during selective attention in speech processing (Lesenfants and Francart, 2020; Wikman et al., 2021). Lesenfants and Francart (2020) reported the modulation of attention effect over the frontal and fronto-central areas, suggesting a top-down frontal attention mechanism similar to that described in the P3a effect (see also Polich, 2007). Some studies identified a so-called attention frontoparietal network as the main part of the alerting network (Fan, 2014), but this was also described later as a contributor in the orienting network (Xuan et al., 2016).

4.3. Source reconstruction

Our results in CLARA reconstruction showed that the P3a component was related to a distributed network. These sources correspond to known sources of auditory perception brain areas. In the *CTR* group, the source reconstruction showed origins in several areas including the temporal regions (the fusiform areas and the retrosubicular/hippocampal area), the parietal region (ventral and posterior cingulate gyrus), and the frontal region (left frontopolar/anterior prefrontal cortical area). The strongest activation was observed in the temporal areas (bilateral fusiform areas BA36 and BA48), where the weaker activation was observed on the frontal and parietal areas (BA 10 and BA 23). In the *AP* group, the source reconstruction showed activations in similar brain areas, always with a stronger activation in the temporal areas and weaker activations in the frontal and the parietal areas. However, the source activation was clearly stronger in the *AP* group than in the *CTR* group. Also, the source waveform structure seemed to correspond to the information obtained in the scalp response (not included in the figure). Although the CLARA reconstruction method has been shown to be a reliable technique for clinical use (Beniczky et al., 2016) with a focal localization (Iordanov et al., 2018), the localization accuracy of the method must be taken into account in the following interpretations as we performed the reconstructions on the ERP group average and on an average age-appropriate MRI template.

Similar brain areas to those found in our results have been described in the literature as part of the attention network in typical participants (for a review, see Ptak, 2012; Lesenfants and Francart, 2020) and in AD/HD participants (Bush, 2010; Salmi et al., 2018). Lesenfants and Francart (2020) evaluated cortical speech tracking and showed the modulation of attention in the frontal and the occipito-parietal areas in speech tracking. The dorsal fronto-parietal network was described to enable the selection of sensory stimuli based on expectations, whereas the ventral fronto-parietal network was described to be involved in saliency detection (for a detailed review, see Corbetta et al., 2008). The contribution of the thalamus, cingulate cortex, and the temporo-parietal junction have also been documented (Konrad et al., 2005; Xuan et al., 2016). The role of the hippocampal and prefrontal areas was also previously reported (Knight, 1984, 1996). In attention deficit context, several studies have agreed that AD/HD was associated with an atypical function of the dorsal system, ventral system, the saliency detection network and the default mode network (Cortese et al., 2012; Castellanos and Proal, 2012; Cao et al., 2014; Rubia et al., 2014). Enhanced activity in the default mode network has also been reported (Salmi et al., 2018).

The source reconstructions in the *CTR* group revealed brain activations of the temporal regions over the fusiform areas in both hemispheres, the frontal region over the cingulate gyrus, the frontopolar APC, and the vPCG areas. Similar brain areas have been reported to be active in the P3 responses to auditory stimuli (Halgren et al., 1995; Volpe et al., 2007; Wronka et al., 2012). Our results correspond closely to those of Wronka et al. (2012), whose source reconstruction study reported activations within the parietal and temporal (occipital regions were also reported). However, that study highlighted a predominant activation of the frontal cortex over the P3a time window, whereas our results showed the strongest source activations over the temporal areas. Wronka et al. described a large widespread network that included most of the structures identified in our results; however, we believe that the LORETA source reconstruction method used in Wronka's study generated some additional areas due to the difference in the reconstruction method (LORETA in Wronka's study vs CLARA used in our study). We also used an average group reconstruction, which may have reduced the number of additional areas, as only consistent and stronger structures remained active in the group average. Furthermore, the difference in the experimental design, as well as the use of different types of auditory stimuli (tones vs speech items), may also have contributed to the differences in results. Moreover, the frontoparietal network role was described as part of the attention network, but also in relation to working memory (for a review, see Ptak, 2012; Polich, 2007). Yago et al. (2003) identified via scalp current density analysis the left frontotemporal, bilateral temporoparietal and prefrontal areas to be the novelty-P3 generators. Volpe et al. (2007) identified the cingulate, frontal, and parietal areas as source generators of the P3a. This supports our previous idea on the role of the working memory in our ERP results. The role of the temporal and frontal areas (including STG/MTG, IFG/MFG and the cingulate/medial frontal gyrus) have been described in previous studies as part of the auditory attention network (Salmi et al., 2009; Alho et al., 2015). The previous studies by Knight (1984, 1996) highlighted the role of the hippocampal and prefrontal area as contributors in the P3 response. All of those previous results support our findings. This literature support is valid not only for the source reconstruction findings, but also for the brain areas identified in the correlation and the cluster-based-permutation analysis, as both suggested that the frontoparietal area, over the right hemisphere, plays a role in attentional processing within *AP* and *CTR* groups. The temporo-parietal and frontal generators of the P3a response were earlier identified from human lesions studies and later confirmed via fMRI and EEG studies (Knight, 1996; Linden et al., 1999; Opitz et al., 1999). A rare target in the oddball paradigm was associated with the activation of the bilateral perisylvian areas in the inferior parietal and frontal lobes and insular cortex (Linden et al., 1999; Opitz et al., 1999).

In the *CTR* group, the source activations and source strength were different between the two native contrasts. The brain areas may have been recruited differently depending on the within contrast's physical properties. It has been recently shown that physical properties can affect the P3a response; the larger the difference between the physical characteristics of the stimuli, the stronger the attention engagement (Wronka et al., 2012). Interestingly, our results suggest the opposite effect, where the stronger source activations were found with the smallest ED (for details, see the description of the ED above). It is also possible that some sources went undetected due to the sensitivity of the method, due to error variance of the data or due to the use of an average reconstruction, which may have created artificially differences between the two conditions.

In the *AP* group, the CLARA reconstruction revealed the activation of similar brain areas as described in the *CTR* group in the same conditions, where only the source strength was different. In the literature, differences in the brain sources activity in auditory oddball tasks have been reported in participants with AD/HD. Abnormalities were reported mainly found in the frontal/frontopolar (BA10) and temporoparietal regions when compared to controls (Bush, 2011; Goepel et al., 2011; Janssen et al., 2016). Similar conclusion could be derived from our source strength results (see Table 4 and Fig. 8), as the *AP* group showed higher activation of the frontal and temporal sources. This higher activity observed at the source level reflects the larger amplitude observed in the P3a ERP waveforms. Although some evidence in the literature has suggested reduced brain activity (Janssen et al., 2015), some other findings have suggested an enhancement (Salmi et al., 2018), which supports our findings.

5. Conclusions and limitations

This study investigated the temporal brain processes of native and foreign language in typically developed children and children with attentional problems using EEG technique that offered a high temporal resolution. The results showed an atypical ERP brain response in the P3a component among children with attentional problems. This component is known to be affected by the attentional processes and attention switching. The atypical P3a response has been linked to attentional deficits and associated with a brain dysfunction, as reflected by an atypical higher ERP amplitude. The correlation analysis showed that the behavioral assessment, quantified by the teacher rating of attentional problems or the attention (ATTEX) score, correlated significantly with the brain responses. This correlation was only valid for the native language, suggesting a higher language sensitivity of the attention switching response and the questionnaire to native speech sounds. The source analysis revealed the main sources contributing to the P3a response, namely the temporal, parietal, and frontal areas. These brain areas are known to be part of the speech perception and attention networks. Furthermore, the results clearly indicated that the auditory and attention network behaved atypically in the *AP* group, where we observed a clear enhanced activity compared to that of the *CTR* group. We should also point to the limitation of the EEG reconstruction method as it is used here to indicate the brain areas involved in the P3a processing. This method still faces the limitation of the reverse solution, so the use of more accurate spatial resolution technique such as fMRI in future studies will give the precise anatomical localization of this neural response. Another limitation of the current study is the use of a group analysis on an average MRI template regarding the absence of individual MRIs, which may have reduced the localization accuracy. Thus, these analyses require further studies in order to offer more details, but also further confirmation such as statistical analysis among and between the *AP* and the *CTR* groups with individual MRIs.

Credit authors statement

NA, OL, JH, PL: Conceptualization, writing, revising, and editing. OL: programming. NA: Data collection, writing the main manuscript, data preprocessing and analysis and creating figures. JH and PL: supervising. All authors contributed to the article and approved the submitted version.

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Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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