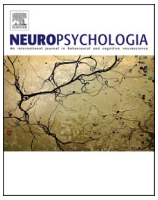
Neuropsychologia 183 (2023) 108506

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia



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

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ARTICLE INFO

Keywords:
Native language
Foreign language
Attentional problems
P3a
ATTEX
Source reconstruction

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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https://doi.org/10.1016/j.neuropsychologia.2023.108506
Received 10 August 2022; Received in revised form 24 January 2023; Accepted 6 February 2023
Available online 9 February 2023

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* [ʃʊ:], *shy* [ʃaɪ] and *she* [ʃi:] as the English stimuli, and *suu* [sʊ:] (mouth), *sai* [saɪ] (got) and *sii* [si:] (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 ([ʊ:], [i:] and [ʊ:], [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.

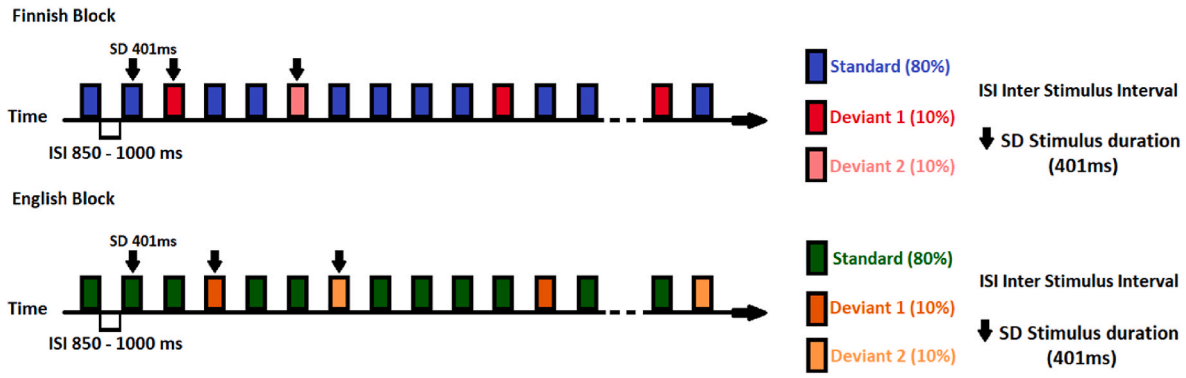

Fig. 1. Schematic illustration of a two-deviant auditory oddball paradigm showing the two sequences: Finnish and English. Each of the sequences contained a standard and two deviants (Deviant 1 and Deviant 2) presented in randomized order.

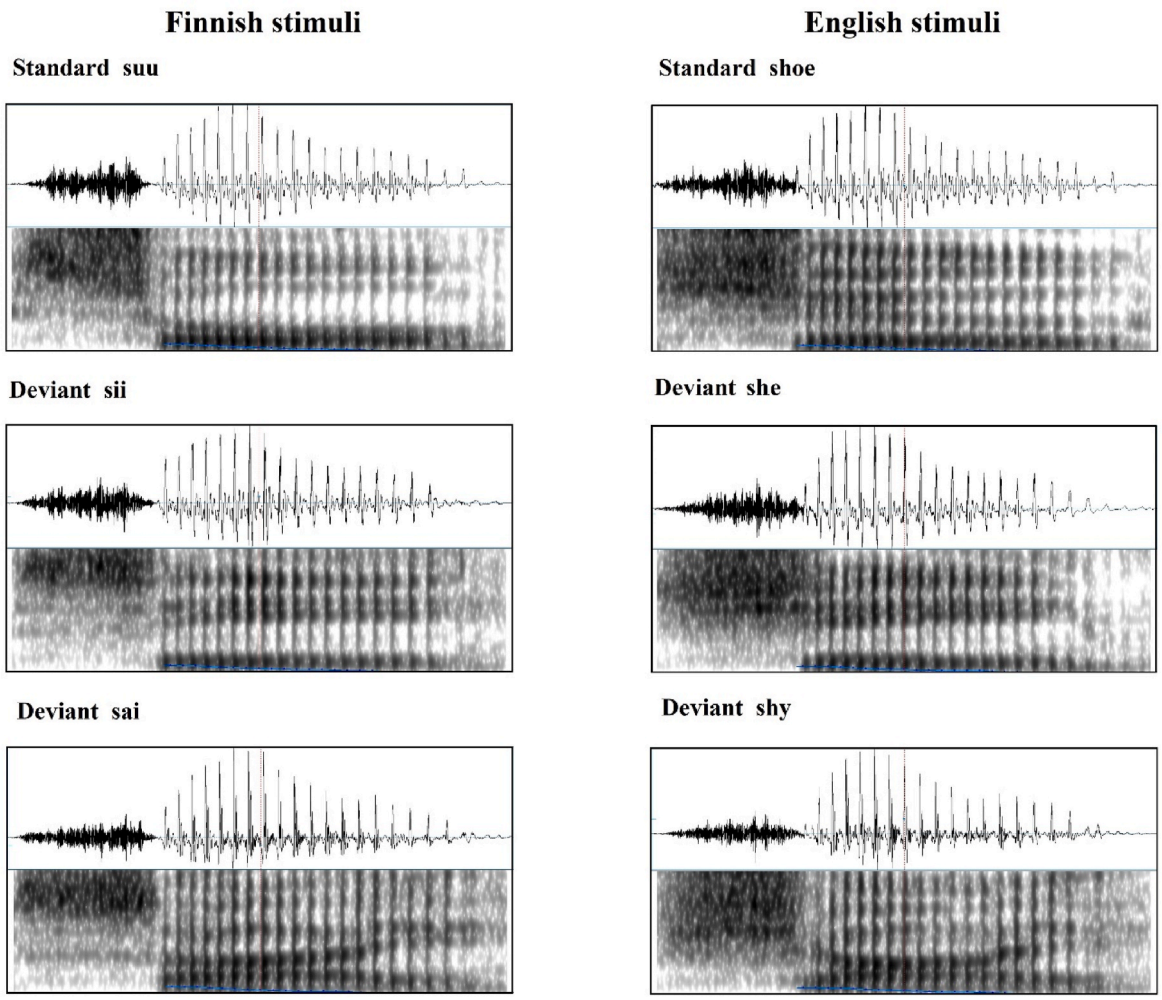

Fig. 2. Spectrograms of the Finnish and English stimuli used in the auditory oddball paradigm. The stimuli fricatives (/s/and/sh/) duration last from the onset of the stimuli at 0 ms until 120 ms where the transition starts with the emergence of the vowels ([ʊ:], [i:] and [aɪ)) that last until the end 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

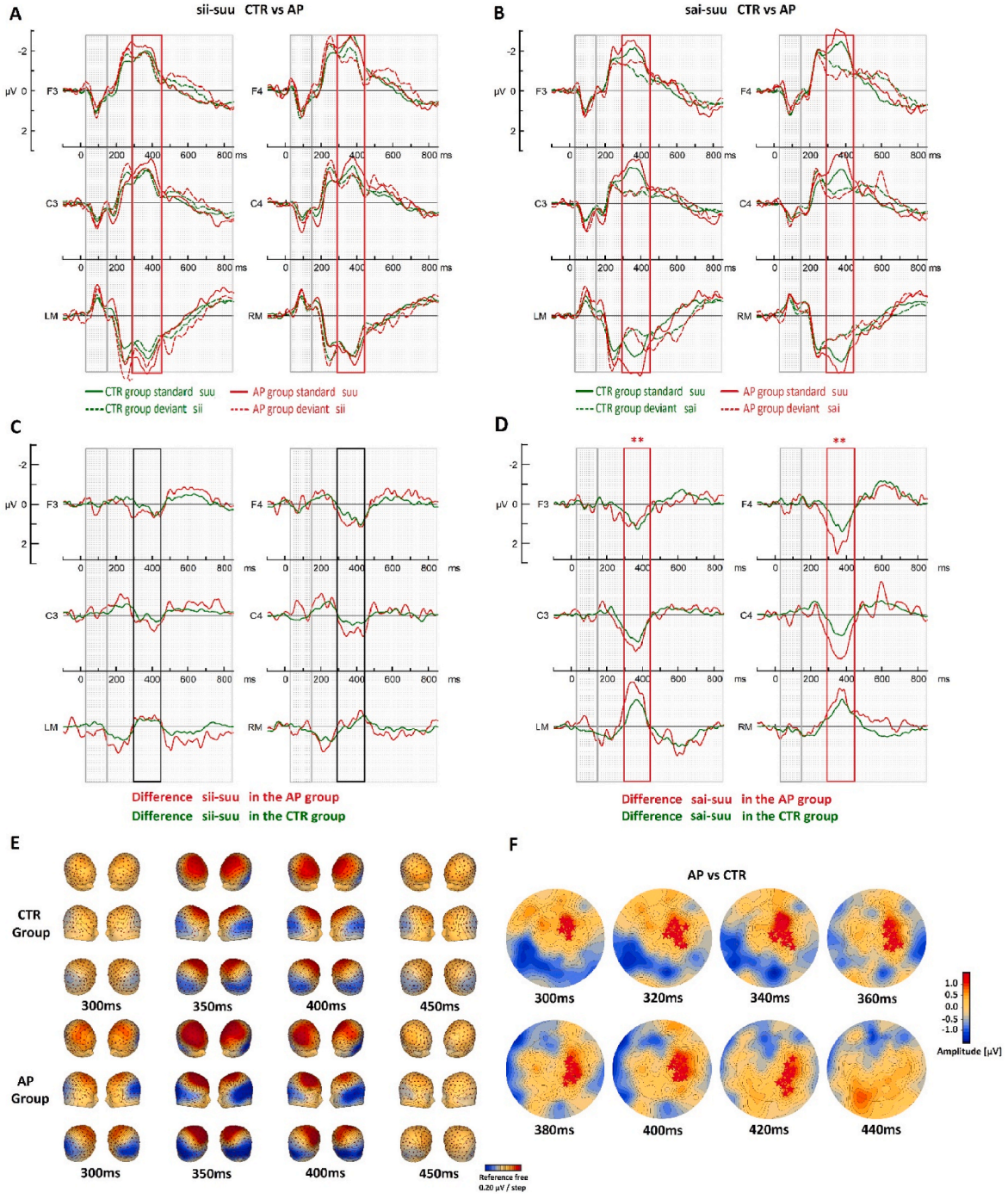

Fig. 3. The ERP waveforms of the standard (pre-deviant) stimuli (solid line) and the deviant stimuli (dashed line) in Control (in green) and in *AP* (in red) groups are presented in the top panel. The native conditions are presented in (A) pre-deviant suu and deviant sii, on the left panel (B) pre-deviant 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

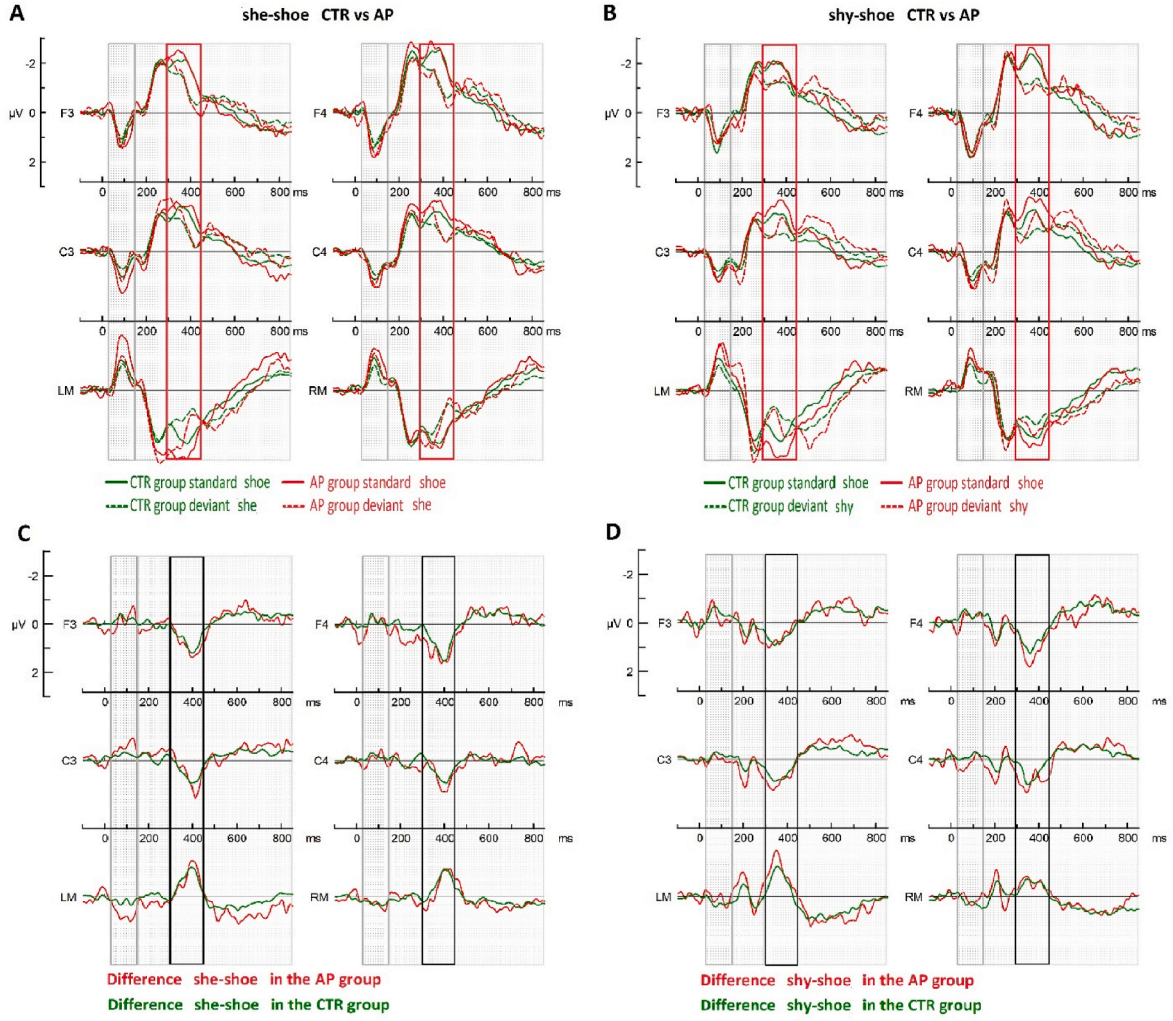

Fig. 4. The ERP waveforms of the standard (pre-deviant) stimuli (solid line) and the deviant stimuli (dashed line) in Control (in green) and in *AP* (in red) groups are presented in the top panel. The foreign conditions are presented in (A) pre-deviant *shoe* and deviant *she* on the left panel, (B) 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

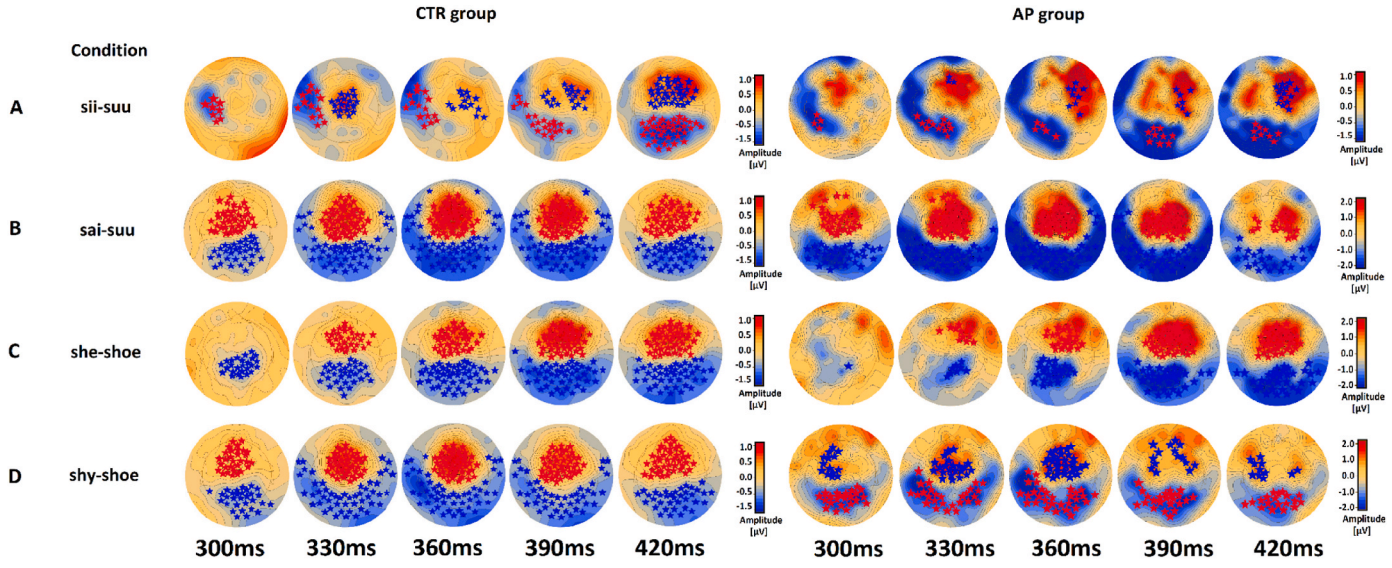

Fig. 5. Cluster-based permutation tests of the P3a component within the *CTR* group (left panel) and the *AP* group (right panel) in the four conditions (A) *sii-suu*, (B) *sai-suu*, (C) *she-shoe* and (D) *shy-shoe* over the P3a time window (300–420 ms). The significant clusters are indicated with stars.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

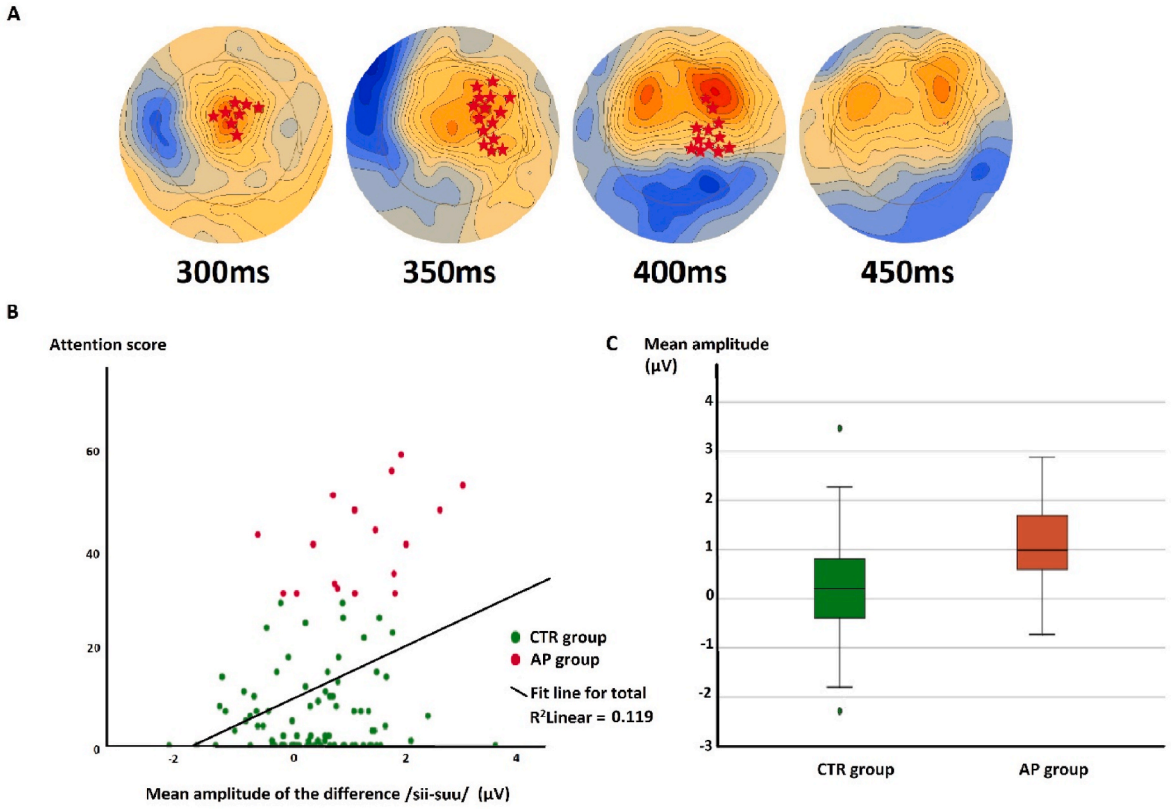

Fig. 6. Correlation test results between the mean amplitude of the difference waves *sii-suu* and the attention score (ATTEX/KESKY) in *CTR* and *AP* groups. (A) The significant cluster distribution for the correlation maps between 300 and 450 ms (highlighted with red the stars). (B) The scatterplot 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

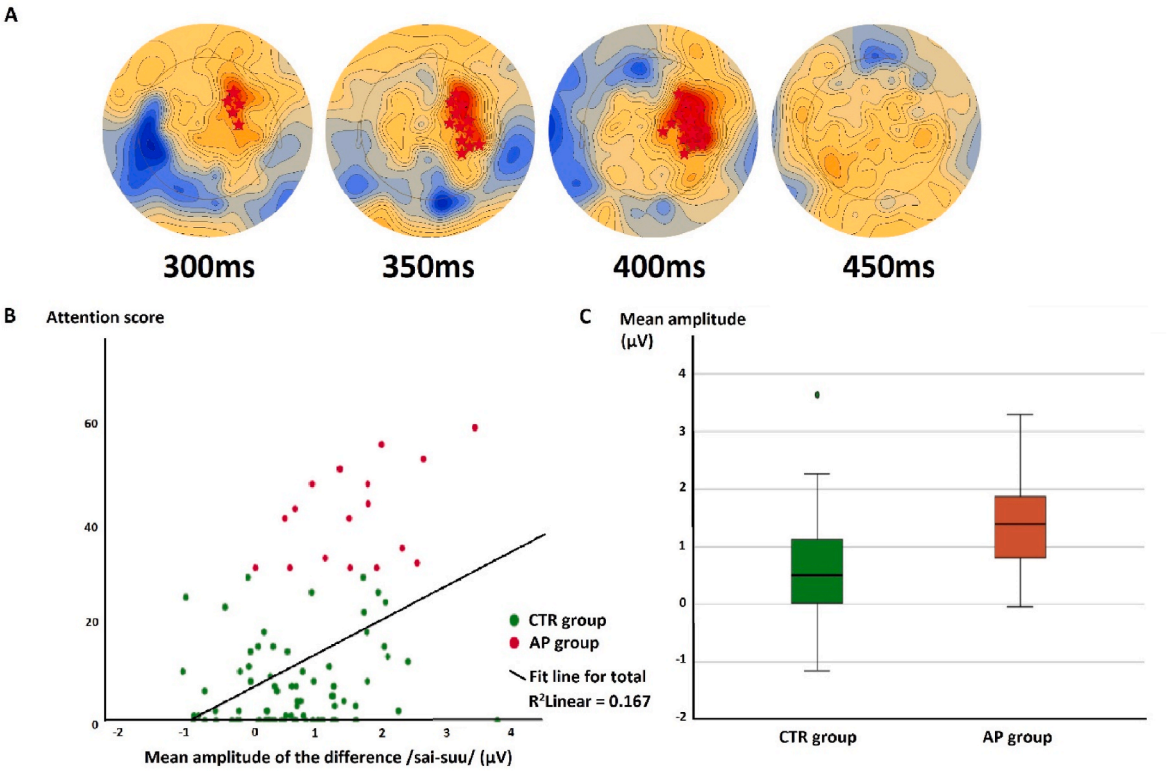

Fig. 7. Correlation test results between the mean amplitude of the difference waves *sai-suu* and the attention score (ATTEX/KESKY) in *CTR* and *AP* groups. (A) The significant cluster distribution for the correlation maps between 300 and 450 ms (highlighted with red stars). (B) The scatterplot for *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

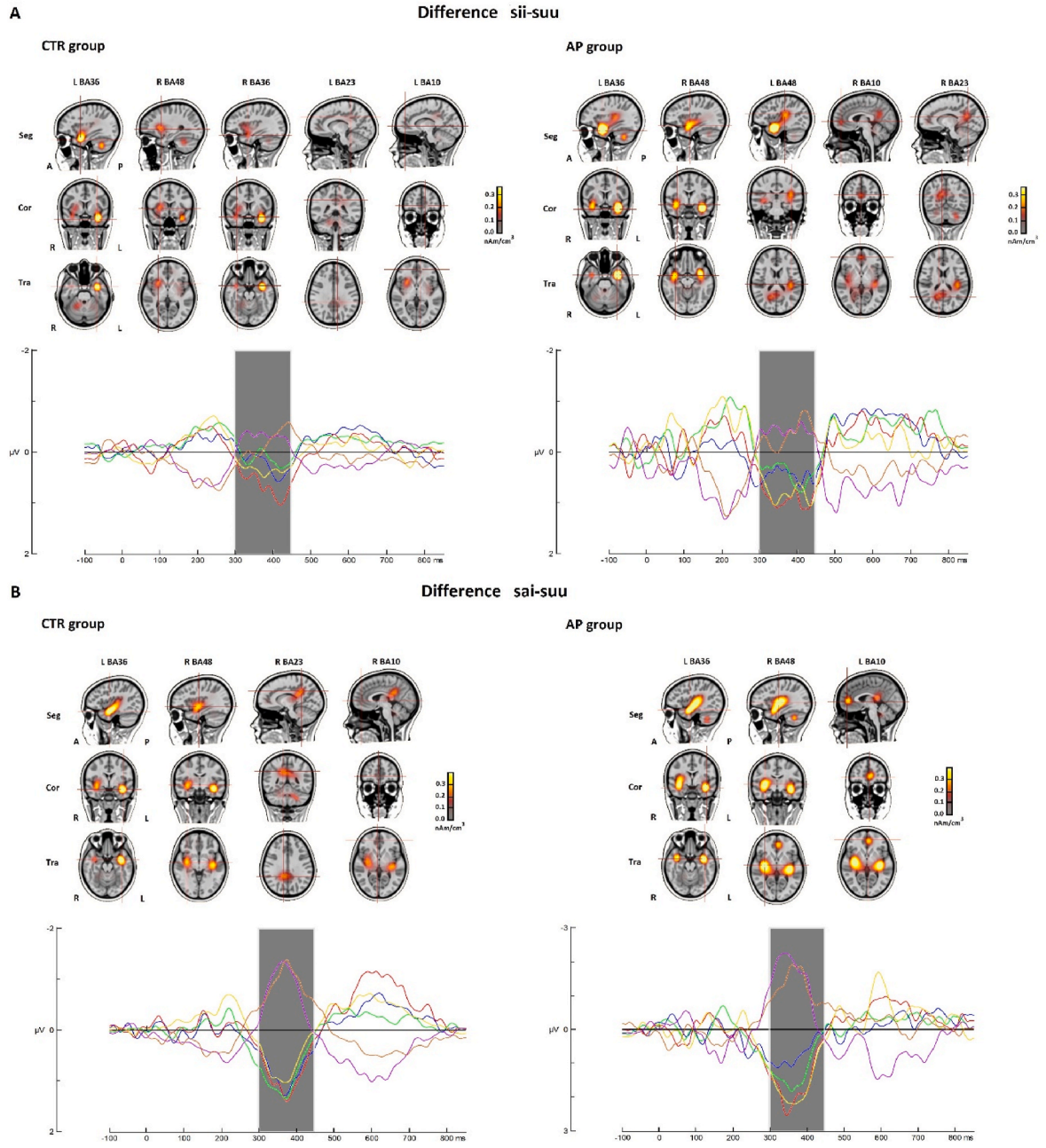

Fig. 8. CLARA source reconstruction for the conditions that showed significant correlations between the KESKY/ATTEX score and the ERP amplitude in the *CTR* group (in the left panel) and in the *AP* group (in the right panel). (A) The active sources between 300 and 450 ms (time window highlighted with 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 fronto-temporal, 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.

Funding

This work was supported by the Predictable (Marie Curie Innovative Training Networks, no. 641858), the Academy of Finland TULOS-program project "eSeek-Internet and learning difficulties: A multidisciplinary approach for understanding reading in new meadia (no. 274022), Niilö Helander foundation and the department of psychology at the University of Jyväskylä.

Data availability

Data will be made available on request.

Acknowledgements

The authors would like to thank all the participants and their families and also the research assistants for their help with data collection.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuropsychologia.2023.108506.

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