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PROCESSING OF LANGUAGE SPECIFIC STIMULI AMONG ESTONIAN AND RUSSIAN NATIVE SPEAKERS: AN EEG STUDY

Master's thesis

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Running head: Quantity processing in native Estonians and Russians

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Abstract

Two almost identical EEG experiments were conducted with about one month between them to examine how the brain processes language specific stimuli among Estonian (n =15, aged 19-27 years) and Russian (n = 15, aged 18-27 years) native speakers. The used stimuli were based on Estonian quantity changes, which are not structurally common for Russian speakers. Two different linguistic stimulus sets (SADA, SAGI) and one physically similar tone stimulus set were used, stimuli differed from each other by duration and tonal change. During the EEG recording, participants had to watch a silent movie while auditory language stimuli were presented in an MMN experimental paradigm to their headphones. An additional speech intelligibility test was conducted on both times and self-reported questionnaire had to be filled before the testing. The tone stimulus elicited a more persistent MMN wave with larger amplitude in both language group, linguistic stimuli elicited a more pronounced MMN response among Estonian native speakers. The study provided a slight support to previous findings, as the Estonians used both durational and pitch cue to discriminate quantities. Only few used conditions elicited MMN among Russian native speakers with no complete clarity if the activity was caused by durational or pitch cue (or both). No consistent lateralization effect was found nor relationships with possible background factors (language abilities, musicality, language experience and time spent in Estonian language environment for Russian native speakers).

Keywords: language processing, Mismatch negativity, linguistic stimuli, non-linguistic stimuli, pitch cue, durational cue

Keelespetsiifiliste stiimulite töötlus erinevatel keelegruppidel: EEG uuring

Lühikokkuvõte

Antud uurimistöö käigus viidi kuu ajase vahega läbi kaks sarnase ülesehitusega katset eesti (n =15, vanuses 19-27 eluaastat) ja vene emakeelt (n = 15, vanuses 18-27 eluaastat) rääkivate inimestega. Magistritöö eesmärgiks on uurida, kuidas toimub keelespetsiifiliste stiimulite töötlus inimeste ajus. Uuringus kasutati eesti keelele omaseid vältestiimuleid, mis ei esine vene keeles. Stiimulitena kasutati kahte erinevat keeleliste stiimulite komplekti (SADA, SAGI) ja lisastiimulina keelestiimulitele füüsikaliselt sarnast tooni, stiimulid erinesid üksteisest põhitooni kestvuse ja helikõrguse muutuse poolest. EEG mõõtmise ajal vaatasid katses osalejad filmi, samal ajal esitati neile katsestiimuleid kõrvaklappidesse. Lisaks läbisid osalejad mõlemal korral kõne arusaadavuse testi ja täitsid eelnevalt enesekohase küsimustiku. Suurema ja ajas püsivama MMN laine kutsus mõlemas grupis esile toon, keelelistele stiimulitele tekkis suurema amplituudiga MMN eesti emakeelega osalejate seas. Tulemused sarnanevad varasemates uuringutes leituga, eestlased kasutavad väldete äratundmisel nii põhitooni pikkust kui helikõrguse muutust. Vene emakeelega katseisikutel tekkis MMN vaid üksikutele keelestiimulitele ja nende tulemuste põhjal ei saa otsustada, kas väldete äratundmisel kasutavad nad põhitooni pikkust või helikõrguse muutust (või mõlemaid). Ajupiirkondade funktsionaalset lateralisatsiooni ei täheldatud, muude võimalike mõjutajatega (musikaalsus, keeleoskus, vene emakeelega osalejatel ka eesti keelekeskkonnas veedetud aeg) olulisi seoseid ei leitud.

Märksõnad: keeletöötlus, lahknevusnegatiivsus, keeleline stiimul, mittekeeleline stiimul, helikõrguse muutus, põhitooni pikkus

INTRODUCTION

Language plays an undeniably crucial aspect in human society. It has provided humans with the means to communicate and the dissemination of knowledge. Although multiculturalization and urbanization have influenced the development and preservation of languages, a number of small languages are at the verge of extinction (or already extinct). At present count, the world still has 7000 and more known languages (www.ethnologue.com). Although studies in psycholinguistics and neurolinguistics have presented us with a large amount of knowledge about the characteristics of various languages, there is still a lack of knowledge and limited understanding regarding how a language is processed in the brain. The main goal of the current study is to examine how Estonian language specific stimuli are processed in the brain of a non-native speaker (Russian) compared to Estonians, and which part of the auditory information carries the most informative importance for them.

Language acquisition is based on the development of specific memory traces that are also used for comprehending the meaning of the perceived sound and identifying phonemes inherent within a native language in the human brain (Näätänen, Lehtokoski, Lennes, Cheour, Houtilainen, Iivonen, Vainio, Alku, Ilmoniemi, Luuk, Allik, Sinkkonen, & Alho, 1997). The development of memory traces takes place at a rather early age; infants are genuinely receptive to language stimuli and thus able to learn any language in the world (Eimas, Siqueland, Jusczyk, & Vigorito, 1971). The language abilities and categorical perception of native language evolve rapidly in the first year of a child’s life (Cheour, Ceponiene, Lehtokoski, Luuk, Allik, Alho, & Näätänen, 1998). Children are able to learn their first (native) language simply by being exposed to the language environment, and experiencing social interaction between people around them. It is believed that there is a certain sensitive period for language acquisition, and the capability to master a new language structure and vocabulary starts to decrease over time (Hurford, 1991).

Neural commitment is a process through which neural networks are shaped by common patterns in native language environment. When language patterns are already active in the brain, they interfere with the acquisition of a new language because characteristics from the new language do not match with a pre-existing mental filter (Kuhl, 2014). That phenomenon is also known as phonological deafness (Dupoux & Peperkamp, 2002). Therefore, learning a new language later in life might not be as easy or an effortless activity, but rather, it requires much intentionality and conscious work to become a proficient user of the second language.

There are various ways to classify languages. The language is considered a tonal language if the meaning of a word is dependent on the variations of intonations (Karlsson, 2002). Pitch is the acoustic equivalent of word tones and intonation of sentences. Children can obtain the ability to use and perceive pitch in their native language independently and quickly, but distinguishing pitch can be more complicated for foreign language learners. Estonian language has previously been considered to be a tonal language (Trubetzkoy, 1939, as cited in Lippus, Pajusalu, & Allik, 2007) but it has now been highlighted that Estonian uses the tone more as a secondary feature in conjunction with quantity (Lippus et al., 2007). Therefore, it would be misleading to consider Estonian as a pure tonal language. The Estonian language uses three different degrees of quantities – short (*´kadus´ – ´disappeared´*), long (*´katus´ – ´roof´*) and overlong (*´kattus´ – ´coincided´*) (Hint, 1998). Quantity changes have an important role in Estonian as it can alter the meaning of the word. Quantity degrees differ from each other by the length of stressed and unstressed syllables, with the importance placed on the relation between the length of the first syllable nucleus as well as the durational pattern of the sound segments in the foot (Lehiste, 1997). Beside duration, previous studies have also shown that one of the main ways for Estonians to distinguish quantities is a pitch cue (Lippus, Pajusalu, & Allik, 2009; Meister, 2011).

Estonian and Russian language systems are structurally considerably different from each other and some examples of this difference are the number of vocals, usage of pitch and quantity changes. Although Russian language does not use quantities, word stress has a comparable significance but is mainly associated with the duration of phoneme (Bondarko, 1977, as cited in Meister, 2011), for example *´му́ка´ – ´agony´*, *´мука́´ – ´flour´* (Hint, 1998). Children growing up in the Estonian language environment can acquire quantity changes naturally in an early age but a person from a different language environment may find it hard to distinguish between quantities, especially when having to differentiate between long and overlong quantity degrees (Lippus, et al., 2007; Meister, 2011). Lippus, Pajusalu and Allik (2009) have previously studied language processing among Estonian native speakers compared with Finnish, Russian and Latvian native speakers. Their results showed that native Estonian speakers use tonal change to determine the quantity while for native speakers of other languages, tone was not an important consideration. Meister (2011) examined the perception of Estonian language specific vocals and quantities between Estonian and Russian native speakers. She found that Estonians used both pitch cue and durational changes of syllables to distinguish between long and overlong quantity degrees while Russian native speakers used only durational changes to distinguish short and overlong stressed syllables. The results were more similar between groups when making the distinction between short and long quantity degrees, which is easily identifiable by the duration of the vocal.

The most commonly discussed and presented approach to language neurobiology is the Classical Model that is also recognized as the “Broca-Wernicke-Lichtheim-Geschwind model” (Tremblay & Dick, 2016). That model focuses on two main areas of the brain – an anterior inferior frontal area (Broca’s area) and a posterior temporal area (Wernicke’s area), which were originally shown to be related to the language abilities of patients with brain lesions, and thought to have an essential role for language functions. Wernicke’s area is associated with semantic processing while Broca’s area is mainly related to syntax and speech production. Also involved in language processing is the superior temporal gyrus, which includes the primary and secondary auditory processing regions that take part of speech processing (Gernsbacher & Kaschak, 2003). Although the mentioned areas are still often used in research, the Classical Model has been shown to be confusing and outdated (Brown & Hagoort, 1999; Tremblay & Dick, 2016). There is no complete consensus between researchers about the exact location of the exact previously mentioned areas, and the model is also limited by its strongly modular approach. More recent studies have shown that language processes are more complex and might take place in numerous areas in the brain (Tremblay & Dick, 2016). Also, neuroplasticity can alter functional localization of the brain influenced by brain damages, developmental changes, handedness, musical and language abilities in a person’s lifetime (Handel, 1993).

The comprehension of spoken language is a complex process where one must be capable to interpret auditory input and distinguish noise from speech-related information. The listener’s first mission is to separate meaningful sound from other auditory input, decoding it, transforming the input into discrete elements (phonetic segments), exploring the segmentation cues, and finally recognizing and interpreting the word. Perceiving and comparing speech against background noise is a relatively simple task due to the highly structural form of a language, but becomes more difficult when other sounds use regular structure as well (Brown & Hagoort, 1999). The effectiveness of speech is measured by speech intelligibility, which is generally worse for non-native speakers (Wijngaarden, Steeneken, & Houtgast, 2002) and individuals with hearing loss (McArdle, Wilson, & Burks, 2005). If individuals with hearing loss may have difficulties to understand speech while background noise is present (Veispak, Ghesquiere, & Wouters, 2015), for foreign speakers, lack of language knowledge and practice is the main reason for not always receiving the whole meaning of the speech (Wijngaarden, et al., 2002). In attempting to understand the whole scale of the processes taking places in human brain while hearing and comprehending sounds, it is crucial to be able to examine the language processes while the brain is currently engaged in language processing. One way to study language perception in vivo is with modern brain imaging technologies.

At present, there has been extensive research conducted with different brain imaging methods: MRI, EEG, PET, MEG, fNIRS (Gernsbacher & Kaschak, 2003; Scott & Wise, 2003). Comparatively, electroencephalography (EEG) is a relatively cheap, non-invasive method that is able to provide a high temporal resolution, and detects any changes in the brain electrical activity in milliseconds allowing the assessment of brain activity in real time. The main deficiency of this method might be relatively poor spatial resolution as EEG is only able to measure the signal close to the scalp, therefore it is not possible to get information about a specific location of the measured brain activity (Brown & Hagoort, 1999). Nevertheless, EEG is used greatly in different fields of study, including in neurolinguistics studies. EEG measures the electrical activity of the brain through electrodes attached to the scalp. One possibility to investigate language perception is through different EEG components. Event related potentials (ERPs) are calculated as a response to perceived stimuli and have been proved to be an efficient way to observe auditory language processes being carried out in the brain cortical areas (Lyytinen, Guttorm, Huttunen, Hämäläinen, Leppänen, & Vesterinen, 2004).

Mismatch negativity (MMN) is part of the event related potentials and has been used to observe auditory processes in sensory memory to recognize differences in received stimuli (Kujala, Tervaniemi, & Schröger, 2007). MMN relies on the predictive coding paradigm, according to which our brain is constantly making (unconscious) predictions about what is going to happen in the environment, and recognizes the discrepancy if a change is detected (Garrido, Kilner, Stephan, & Friston, 2009). MMN appears when different kind of stimuli (deviant stimuli) are presented between repeating identical stimuli (standards), resulting in a negative ERP waveform which peaks between 100 and 250 ms. MMN is based on the existing memory trace created by continuous presentation of standard stimuli (Näätänen, 2001). Various characteristics of language can create MMN, for example changes in sequences, length, intensity, tonality or phonemic changes. For MMN to emerge, participants' attention is not required, so it is a great method to employ when engaging with challenging participants, for example when working with children or clinical subject groups (Näätänen, 2000).

The auditory MMN activity has mainly been reported in frontal and temporal lobes (Shalgi & Deouell, 2007; Deouell, 2007; Dürschmid, Edwards, Reichert, Dewar, Hinrichs, Heinze, Kirsch, Dalal, Deouell, & Knight, 2016). Studies have shown some functional differences between right and left temporal hemisphere in language processing but not all the results confirm the lateralization. Right temporal lobe has been more commonly associated with prosodic attributes like duration and melodic sequences, while left temporal lobe is responsible for substantial processing – understanding the meaning of perceived sound (Kreitewolf, Friederici, & Kriegstein, 2014; Zatorre, & Belin, 2001; McGettigan, Evans, Rosen, Agnew, Shah, & Scott, 2012). Klein, Zatorre, Milner and Zhao (2001) also found a possible difference in lateralization between tonal (Mandarin Chinese) and non-tonal language (English); that in non-tonal languages, tone does not carry the meaning of the word and tone might be comprehended as prosodic information.

Estonian language has been previously used in MMN studies but mainly in comparison with Finnish language. Finnish is strongly associated with Estonian, sharing the same historical background and many structural characteristics. Näätanen and his colleagues (1997) focused on the perception of phonemes in connection of memory traces in Estonians and Finns. They found that Estonian phoneme /õ/, not existent in Finnish language, created a stronger MMN response in Estonian native speakers. Tull (2013) also compared Estonian and Finnish native speakers in an MMN study, and discovered that tone plays an important role for Estonian native speakers to determine quantities while Finnish native speakers rely on the length of the phoneme.

To learn a new language, new recognition patterns for the sounds specific to the target language have to be formed. It is possible to learn new speech sounds when plastic changes in the neuronal circuity take place. Winkler, Kujala, Tiitinen, Sivonen, Alku, Lehtokoski, Czigler, Csepe, Ilmoniemi and Näätänen (1999) compared almost fluent Finnish-speaking Hungarians with Hungarians who did not have any knowledge of Finnish. They found that fluent Finnish-speaking Hungarians developed cortical memory representations for the

Finnish phoneme system which provides their brain with the ability to analyse Finnish phonemes. The fluent speakers group elicited larger MMN to vowel contrast specific to the Finnish language while language-naïve group did not. Chladkova, Escudero ja Lipski (2013) investigated the role of the length of the vocals in Dutch phonology compared to Czech and Spanish. They discovered that vocal length is important only for identification of specific native vocals for Dutch natives. In Spanish, vocal length does not change the meaning of the word, therefore it is not an important characteristic for Spanish native speakers. They only become more sensitive to vocal lengths while hearing other (not-native) languages. That may refer to the possibility that the lack of importance of vocal length in a native language might contribute to learning a second language (which uses vocal length as an indicator of the meaning). However, Wayland and Li (2008) showed that learning a tonal language as a second language is easier for people whose native language is also tonal. Tamminen, Peltola, Kujala and Näätänen (2015) trained the perception of non-native phonemes on their Finnish participants over the duration of three days by simple listen-and-repeat exercises. They used fricative sounds, which do not belong to Finnish phonological system and are hard to learn for Finnish native speakers. Perceiving and recognizing the distinction of fricative sounds during a short period of training demonstrated significantly improved language-learning effects.

This thesis provides a possibility to widen the neurolinguistic knowledge of the perception of tone and quantity changes among Estonian and Russian native speakers, in addition to previous similar research which has until now concentrated more towards the comparison between Estonian and Finnish. The results were gathered from two repeated measurements that present a more detailed look into how non-native speakers' perception of Estonian quantities has the possibility to change over short amount of time in natural language environment, and how that is achieved.

Hypotheses

H1: The discrimination of non-linguistic stimuli elicits similar MMN response for Estonian and Russian native speakers.

H2: For linguistic stimuli Estonian native speakers elicit more pronounced and more left localized MMN response than Russian native speakers.

H3: For discriminating language stimuli, native Estonian speakers use the duration of the stressed syllable and pitch cue while Russian native speakers mostly use the duration of the stressed syllable.

H4: On the second recording session, the MMN amplitude is more pronounced for language stimuli among Russian native speakers compared to the first recording session.

METHOD

Participants

Thirty healthy (with no reported neurological or psychological conditions) volunteers participated in this study. Half (n = 15) of the participants were native Russian speakers (10 female) and half native Estonian speakers (10 female). All but one participants were right-handed. Two participants from Russian speaking group had a second native language (Ukrainian and Karachay-Balkar). Native Russian and native Estonian participants were chosen to be similar by age (+/- one year) and sex. All participants had normal or corrected-to-normal eye-sight, and normal hearing from both ears that was checked with an audiometer (see section Procedure, p. 11). Participants were 18-27 years old, mean age was 23,4 (SD=2.90) years among native Russian speakers and 23,7 (SD=2.80) years among native Estonian speakers. Half of the participants underwent the first experiment with the word SAGI and the other half with the word SADA. 24 (12+12) participants returned for the second time. Average time between the test was 35 (SD=4.75) days in Russian native speakers group and 33.4 (SD=5.93) days in Estonian group. On the second testing time, stimuli were changed between groups. Distribution of participants and stimuli is presented in Table 1. All participants were beforehand informed about the procedure and goal of the experiment and gave a written consent.

Table 1.
Number of participants in two stimulus conditions.

	EST 1	RUS 1	EST 2	RUS 2
SADA	8	8	5	7
SAGI	7	7	7	5

Notes. EST – Estonian native group; RUS – Russian native group; 1, 2 – respective testing time

The study was approved by the Research Ethics Committee of the University of Tartu (based on The Code of Ethics of the World Medical Association (Declaration of Helsinki).

Procedure

Participation invitation was distributed in various social media groups and through university e-mail lists. Participants had to fill in an online questionnaire in Kaemus – a web-based research portal of the Department of Psychology, University of Tartu. The questionnaire consisted of questions about background information (including questions about overall time spent in Estonia, study language, Estonian language courses, time spent in Estonian language environment for Russian native speakers), language skills, relevant medical information (psychological and neurological conditions, drug use), musicality and handedness. On both times, testing included an audiometric measurement, Estonian Words in Noise (EWIN) speech intelligibility test (Veispak et al., 2015), pre- and post-experiment critical flicker frequency test (CFF, Simonson & Brozek, 1952), measuring the level of wakefulness using an adapted Borg CR10 scale (Borg, 1998) before, after, and three times throughout the experiment, subjective scale to register the mood and an EEG measurement (including pre- and post-experiment resting state EEG measurement). The data from CFF measurements, wakefulness and mood ratings, and resting state EEG recordings were not analysed for the current thesis, and therefore these procedures are not further described.

Audiometer

Audiometric measurement was conducted with the Interacoustics AS608 Screening Audiometer (Interacoustics, Minneapolis, USA). Measuring was made for both ears separately and with tones on three different frequency levels (500, 1000, 1500 Hz). The measuring began on the 40 dB sound volume, which was lowered by 10 dB every time the participant gave a response (pushed a button) indicating he/she heard the tone. When the participant did not hear the sound anymore, it was turned louder by 5 dB. The procedure was repeated 2-3 times to calculate individual hearing thresholds The results of the audiometric measurements were used only to determine whether the participants had similar hearing from both ears. The results between the ears did not differ more than 10 dB for none of the participants, and none of the participants were excluded from the experiment.

EWIN

To assess the speech reception, we used EWIN, the first validated speech intelligibility test in Estonian language (Veispak et al., 2015). The test uses carefully chosen simple words, which are part of the vocabulary of children above six years of age. The words are recorded by native Estonian speaker (female voice), and the test consists of 14 set of words (10 words and 33 phonemes in each set). Words were presented in noise and participants were instructed to repeat what they heard. In the current experiment, 6-7 lists with different signal to noise ratios (SNR) were used with each participant to find out the individual speech reception threshold (SRT) at 50% speech recognition of the words in noise. The scores were recorded and calculated by the experimenter. Veispak and her colleagues (2015) have previously shown that the 50% SRT for Estonian adults is -9.3 dB, the EWIN test has not been previously used among Russian native speakers. The test was used with the consent of the author, and calibrated using original instructions. Participants completed the test with left ear.

Experiments took place from October 2016 to May 2017. EEG measurements took place between 10 am and 10 pm, the whole procedure lasted for about 2-2.5 hours for one participant at one time.

EEG recording

EEG recordings were conducted in a dimmed, quiet, and electrically shielded room. Participants were instructed to sit still and avoid extensive movements during the recording of EEG. One recording session consisted of resting state EEG measurements and an EEG experiment consisting of five series, each lasting for about 11 minutes, and after every series, participants had the chance to rest. Bioelectrical activity was recorded with a 64-electrode EEG-system (ActiveTwo, BioSemi B.V., Amsterdam, The Netherlands). Two reference electrodes were connected to ears, four single electrodes were attached to the participants face, close to eyes, to record eye-movements and blinks. For a better recording quality, non-allergic gel SignaGel (Parker Laboratories, Inc.) was used. EEG data was online recorded using 512 Hz recording frequency and 0.6-100 Hz filters.

Participant’s chair was approximately 114 cm away from the Mitsubishi Diamond Pro 2070SB 22" computer screen (Mitsubishi Electric, Tokyo, Japan) which was used to show a cartoon. Auditory stimuli were presented to headphones with custom MATLAB (MathWorks, Natick, Massachusetts, United States) programs. During the presentation of the auditory stimuli, participants watched a soundless cartoon to distract their attention away from the presented sounds.

Stimuli and experimental paradigm

The language stimuli used in the current study were synthesized from two Estonian words (SADA and SAGI) to represent Estonian quantity changes (short, long, overlong). One set of the stimuli (synthesized from the word SADA) has been previously used in similar research by Käthe-Riin Tull (2013), the second set was chosen and synthesized specifically for the current study. All three quantities of the word (short *´sada´ – ´hundred´*, long *´saada´ – ´send´*, overlong *´saada´ – ´to get´*) are commonly used in Estonian. The other word SAGI (short *´sagi´ – ´rush´*, long *´saagi´ – ´catch, harvest´*, overlong *´saagi´ – ´saw´*) was chosen because of its similar structure and carrying a meaning, and the synthesized stimuli were created to match the physical properties of original (SADA) stimuli set. All stimuli were created varying the length of the first vocal, and tone, and were either synthesized from 2nd or 3rd quantity. Stimuli 170- was previously perceived as from long by 99%, 290- as long by 55%, 110\ as long by 85% and 290\ as overlong by 95% of Estonian responders (Lippus et al., 2009). The stimuli were read in and synthesized by Pärtel Lippus with the program Praat (Boerma, & Weenink, 2007). The EEG experiment consisted of five approximately 11 minutes long series– four with linguistic stimuli (see Table 2 for stimuli and Table 3 for series) and one with non-linguistic stimuli (pure tone), which were created to physically resemble the Series 1 (see Table 3). The order of the series was randomized between participants. The sound was always presented with the same volume. We used an optimal paradigm (*optimum*, see Näätänen, Pakarinen, Rinne, & Takegata, 2004) with several (n = 3) different deviant stimuli presented between standard stimuli (every second stimulus being a standard) to elicit an MMN response. Four different stimuli (Table 2; see Appendix 1 for spectrograms of stimuli) were used in one recording series, each stimulus was used as a standard in one series while three others were then used as deviants. The standard stimulus was presented 315 times in each series and every deviant (n = 3) was presented 100 times in each series. In the beginning of each series, standard was first presented 15 times to create a memory trace. The interstimulus interval was 400, 425 or 450 ms.

Table 2.
Description of the characteristics of the stimuli (ms).

	Consonant 1	Vowel 1	Consonant 2	Vowel 2
S170-	100	170	86	101
S290-	93	290	86	101
S110\	93	110	103	74
S290\	100	290	103	74

Note. S represents standard and the following number the length of vowel 1. – marks stable tone and \ descending tone in the first column.

Table 3.
Description of the stimuli used in the experimental series.

	Standard	DEV 1	DEV 2	DEV 3
Series 1	S170-	D290-	D110\	D290\
Series 2	S290\	D290-	D110\	D170-
Series 3	S290-	D290\	D110\	D170-
Series 4	S110-	D290\	D290-	D170-

Note. S marks standard, D/DEV marks deviants and the following number the length of vowel 1. – marks stable tone and \ descending tone in the first column. See Table 2 for description of stiimuli.

EEG data analyses

Brain Vision Analyzer 2.1 (Brain Products GmbH, Munich, Germany) was used for EEG data offline analysis. The average signal from the earlobe electrodes was used as a reference. Butterworth Zero Phase Filter (0.1-30 Hz, 24 dB/oct) and an extra 50 Hz notch filter was used to reduce noise. Gratton and Coles algorithm (Gratton, Coles, & Donchin, 1983) was used to reduce noise caused by eye-movements and blinks. The electrodes of interest were dividend into 8 regions based on their location and the activity pooled together: Frontal (AF3, AF4, AF7, AF8, AFz, F1, F2, F3, F4, F5, F6, F7, F8, Fz, FP1, FP2, FPz), Frontal left (AF3, AF7, F3, F5, F7, FP1), Frontal right (AF4, AF8, F4, F6, F8, FP2), Frontal central (AFz, F1, F2, Fz, FPz), Temporal (C3, C4, C5, C6, CP3, CP4, CP5, CP6, FC3, FC4, FC5, FC6, FT7, FT8, T7, T8, TP7, TP8), Temporal left (C5, CP5, FC5, FT7, T7, TP7), Temporal right (C6, CP6, FC6, FT8, T8, TP8) and Temporal central (C1, C2, CP1, CP2, CPz, Cz, FC1, FC2, FCz). In some cases individual electrodes were excluded if the signal was too noisy for analysis. Segments of EEG were chosen and separated for analysis (-200 ms before to 1200 ms after the stimulus onset). Baseline correction was made at 100 ms before stimulus and artefacts were removed (maximum allowed voltage step was 50 μV, maximal allowed difference in values in intervals 200 μ, minimal allowed amplitude -75 μV and maximum 75 μV, lowest allowed activity in intervals 0.5 μV). To calculate the event-related potentials, signals of every stimuli in every series were averaged for each participant. The individual MMN difference waves were calculated by subtracting the signals to the standard from those to the deviants in every series. Only Series with at least 60 remaining segments were included. The individual data points of the stimulus and MMN waveforms of each participant were exported and analysed by two different distributions of time intervals– narrow (25 ms each): 90-115 ms, 115-140 ms, 140-165 ms, 165-190 ms, 190-215 ms, 215-240 ms, 240-265 ms, 265-290 ms, 290-315 ms, 315-340 ms, 340-365 ms, 365-390 ms, 390-415 ms, 415-440 ms, 440-465 ms, 465-490 ms, 490-515 ms, 515-540 ms; and wide intervals: 100-220 ms, 280-440 ms, and 340-500 ms. Waveforms for each stimulus and MMN for every series were then averaged together over the participants, and specific time intervals and areas of interest were chosen by observation (Figure 1).

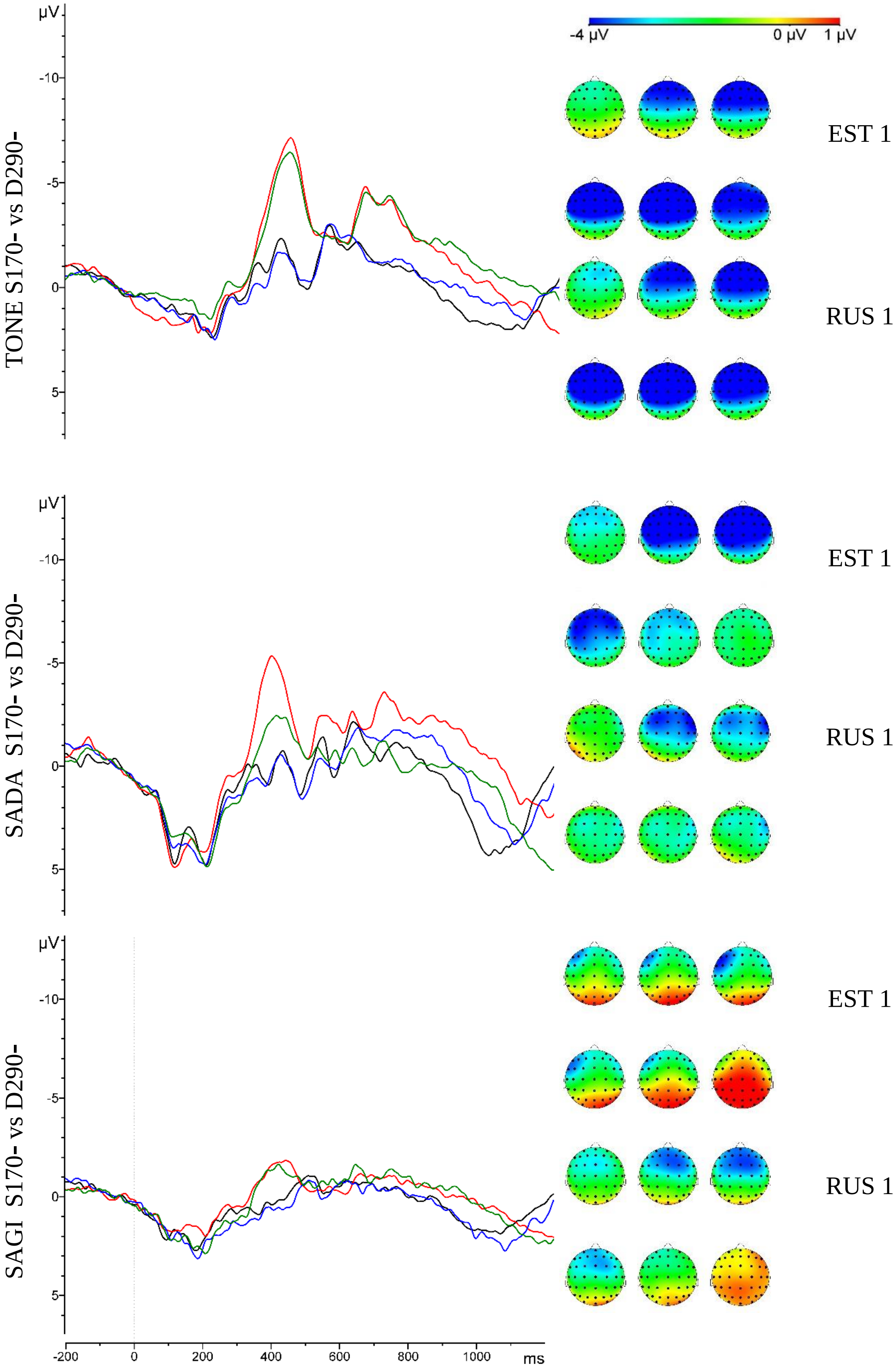

Figure 1. The average standard and deviant wave (**Black** – EST standard, **Blue** – RUS standard, **Red** – EST deviant, **Green** – RUS deviant) for Series 1 (S170-) Condition D290- (tone, SADA, SAGI) and scalp distributions (from upper left: 340-363 ms, 365-389 ms, 391-

414 ms, and from lower left: 416-439 ms, 439-463 ms, 465-488 ms) of MMN in the same Condition. EST – Estonian native speakers, RUS – Russian native speakers. Note that the negative amplitude values are presented on the upper part of the y-axes. See Table 2 for description of stiimuli.

For the further organization of data and analysis Microsoft Exel 2000 (Microsoft, Redmond, Washington, United States), RStudio (RStudio Inc., Boston, United States) and Statistica (StatSoft Inc., Tulsa, United States) were used. Individual values within predefined intervals were used as the dependent variable to create the general linear models in Statistica 8 (StatSoft Inc., Tulsa, United States). All the post-hoc analyses were conducted with Bonferroni's HSD test.

RESULTS

First EEG measurement

The different ERP waves (Figure 1) of the used stimuli (SADA, SAGI) were inspected visually to determine the possibility to average the stimuli together. Eight of the previously chosen Intervals (340-365 ms, 365-390 ms, 390-415 ms, 415-440 ms, 440-465 ms, 465-490 ms, 490-515 ms, 515-540 ms) were included for more comprehensive analysis as the significant differential activity between standards and deviants was detected in those time periods. Several general linear models of repeated measures were used to calculate the difference between the average activity of standards and deviants, Frontal and Temporal areas were chosen for more extensive analysis. Combinations of variables Group (EST, RUS), Order (1,2), Area (Frontal, Temporal), Condition (DEV1, DEV2, DEV3), Stimuli (SADA, SAGI, Tone) and Series (1, 2, 3, 4) were chosen for the models separately to reduce possible interactions. The design of the general linear model included two factors, Stimuli (standards and deviants) x relevant Intervals (8). Bonferroni post hoc tests were used on significant interactions to evaluate the difference between the average result of each deviant and comparable standard in 25 ms time intervals. The results of most representative post hoc calculations that emerged in Series 1, 4 and Tone, results are presented in Table 4. There were only single significant results in Series 2 and 3. In Series 2, Condition D290- showed the difference between standard and deviant processing for Estonians in Frontal area in 390-415 ms time interval (p<.05) and in Temporal area in 365-415 ms Interval (p<.01). In Series 3, the

MMN response was significant only for Stimulus SAGI in Condition D170- in Temporal area in Intervals 490-515 ms (p=0.01) and 515-540 ms (p=0.05).

Table 4.
Differences between standard and deviant stimuli in 25 ms intervals (Tone, Series 1 and 4).

			Time intervals (ms)															
			340-365		365-390		390-415		415-440		440-465		465-490		490-515		515-540	
			F	T	F	T	F	T	F	T	F	T	F	T	F	T	F	T
TONE S170-	D290-	E			**	**	**	**	**	**	**	**	**	**				
		R			*	**	**	**	**	**	**	**	**	**		**		
	D110\	E												**				
		R																
	D290\	E				*	**	**	**	**	**	**	**	**	**	**		
		R				**		**	**	**	**	**	**	**		**		
SER 1 S170-	D290-	E			**	**	**	**		**								
		R																
	D110\	E																
		R																
	D290\	E				**	*	**	**	**	**	**	**	**				
		R		¤¤		¤												
SER 4 S110\	D290\	E					*	**	**	**	*	**		*				
		R					*		**		*							
	D290-	E						**		**		**						
		R																
	D170-	E																
		R																

Note. * p < 0.05, ** p < 0.01, Estonian native speakers (marked as E) results are marked with red, Russian native speakers (marked as R) results are marked with blue. Results for stimulus SAGI are marked with ¤ (instead of * referring to SADA). F – Frontal area, T – Temporal area, E – Estonian native speakers, R – Russian native speakers. See Table 2 for description of stiimuli and series (SER).

To detect possible differences between the left and right hemisphere, another similar set of analyses was conducted within areas Frontal left, Frontal right, Temporal left and Temporal right. Significant main effects were found in Series 1 for Stimulus SADA in

Condition D290\ where the MMN response for both Estonians [*F* (1, 280) = 5.28, η^2p = 0.02, *p* < .05] and Russians [*F* (1, 280) = 4.23, η^2p = 0.01, *p* < .05] was more prominent in Frontal left area (compared with Frontal right area). In Series 1 for Stimulus SADA in Condition D290- only Estonians had a bigger MMN amplitude in Frontal left [*F* (1, 280) = 4.33, η^2p = 0.02, *p* < .05], and in Series 1 for Stimulus SAGI in Condition D290\ only Russians had a bigger MMN amplitude in Frontal left area [*F* (1, 240) = 4.52, η^2p = 0.02, *p* < .05]. No differences between Temporal left and Temporal right areas were found. No lateralization differences were found for Tone series. Because no consistent pattern were found, and left and right side did not show any significant interactions with other variables, only Frontal and Temporal areas were included for more extensive analyses.

Twelve general linear models for repeated measures were conducted separately on every Series (4) and Condition (3), all together with five factor design, including Intervals (8) x Stimuli (SADA, SAGI) x Group (EST, RUS) x Area (Frontal, Temporal) x ERP amplitude (standard, deviant) to identify possible conditions where Stimuli (SADA, SAGI) do not differ significantly and could be analysed together. The results (Table 5) are showing a non-significant main effect of the Stimuli only in 3 models (out of twelve), which means that the two chosen Stimuli (SADA, SAGI) act differently and the following analysis are done separately for them. The decision was supported by several and varying interactions with stimuli.

Table 5.
The results of general linear models (Intervals x Stimuli x Group x Area x ERP scores) for repeated measures presenting main effects of Stimuli (SADA, SAGI).

Standard	Deviant	Df	F	P	Partial eta-squared
1 S170-	D290-	1	5.43	0.02	0.01
	D110\	1	12.51	<0.01	0.01
	D290\	1	47.77	<0.01	0.04
2 S290\	D290-	1	0.54	0.47	<0.01
	D110\	1	2.78	0.1	<0.01
	D170\	1	45.50	<0.01	0.04
3 S290-	D290\	1	12.87	<0.01	<0.01
	D110\	1	0.04	0.83	<0.01

		D170-	1	46.54	<0.01	0.04
4	S110\	D290\	1	68.23	<0.01	0.06
		D290-	1	33.61	<0.01	0.03
		D170-	1	59.00	<0.01	0.05

Note. See Table 2 for description of stiimuli.

Another set of general linear models of repeated measures were composed to explore the interactions between the minimum value of the MMN wave with two main categories of interest– Group (EST, RUS) and Area (Frontal, Temporal). Models were calculated separately for every Series (4) and Stimuli (SADA, SAGI, tone) and Condition (D1, D2, D3). Significant results are presented in tables 6 (Tone) and 7 (SADA). Bonferroni correction was applied for all post-hoc comparisons. The results show a significant difference between chosen brain areas (Frontal and Temporal), the negative MMN wave being overall more prominent in the Frontal area. In Series 1, there are significant differences between Estonian and Russian language group results in Stimulus SADA Condition D290- and D290\, as the MMN wave is more prominent for Estonians compared with Russians. In Stimulus SADA Series 2, the MMN wave for Russians was more pronounced in Condition D170-. For stimulus SAGI only Area was significant in Series 1 Condition S290- and Series 2 Condition D110\. No interactions between Group and Area were significant for neither Group.

Table 6.
Tone: Results of general linear models of repeated measures.

	STANDARD	DEVIANT		Degr. Of freedom	F	p	Partial eta-squared
Tone	SER 1	D290-	Group				
	S170-		Area	1	9.36	<0.00	0.14
		D110\	Group				
			Area	1	7.02	0.01	0.11
		D290\	Group				
			Area	1	6.45	0.01	0.10

Note. The standard of mentioned Series is marked with S and deviant with D. SER – Series. See Table 2 for description of stiimuli.

Table 7.

Linguistic stimuli: Results of general linear models of repeated measures.

	STANDARD	DEVIANT		Degr. Of freedom	F	p	Partial eta-squared
SADA	SER 1	D290-	Group	1	6.21	0.02	0.18
	S170-		Area				
		D110\	Group				
			Area	1	6.92	0.01	0.20
		D290\	Group	1	11.82	<0.00	0.30
			Area	1	4.75	0.04	0.14
	SER 2	D290-	Group				
	S290\		Area				
		D110\	Group				
			Area	1	8.19	0.01	0.23
		D170-	Group	1	6.09	0.02	0.18
			Area				
	SER 3	D290\	Group				
	S290-		Area				
		D110\	Group				
			Area	1	6.10	0.02	0.18
		D170-	Group				
			Area	1	5.13	0.03	0.15
	SER 4	D290\	Group				
	S110\		Area	1	5.79	0.02	0.17
		D290-	Group				
			Area	1	7.07	0.01	0.20
		D170-	Group				
			Area				

Note. The standard of mentioned Series is marked with S and deviant with D. SER – Series. See Table 2 for description of stiimuli.

Second EEG measurement

From the second measuring time, as the post-hoc tests (Table 8) showed significant results only for the Series 1 and 4, only those variables were chosen for further analysis. The Series 2 and 3 were left out because those had only occasional significant interactions.

Table 8.
Second testing differences between standard and deviant in 25 ms intervals (Tone, Series 1 and 4).

			Time intervals (ms)															
			340-365		365-390		390-415		415-440		440-465		465-490		490-515		515-540	
			F	T	F	T	F	T	F	T	F	T	F	T	F	T	F	T
TONE S170-	D290-	E				**	*	**	**	**	**	**		**				
		R			**	*	**	**	**	**	**	**	**	**		**		
	D110\	E				**						**	**	**				
		R										*	**	**				
	D290\	E			**	**	**	**	**	**	**	**	**	**	**	**		
		R							**	**	**	**	**	**				
SER 1 S170-	D290-	E				**		**		** ¤¤								
		R																
	D110\	E																
		R																
	D290\	E																
		R																
SER 4 S110\	D290\	E																
		R																
	D290-	E					**	**	*	** ¤¤	**	**		*				
		R																
	D170-	E																
		R																

Note. * p < 0.05, ** p < 0.01, Estonian native speakers (marked as E) results are marked with red, Russian native speakers (marked as R) results are marked with blue. Results for stimulus SAGI are marked with ¤ (instead of * referring to SADA). F – Frontal area, T – Temporal are, E – Estonian native speakers, R – Russian native speakers. See Table 2 for description of stiimuli.

Lateral differences were found only for the Tone stimulus, where Estonians had larger MMN amplitude in Frontal left area in Conditions D290- [F (1,440) = 4.13, η^2p = 0.01, p < .05] and D290\ [F (1, 440) = 4.19, η^2p = 0.01, p < .05].

Correlations with self-reported features and EWIN

Possible relations between the standardised MMN scores, and self-reported language abilities, musicality, and for the Russian language group, the overall time spent in Estonia, and subjective assessment of time spent in Estonian language environment (subjective evaluation including language classes, entertainment, socializing in Estonian language environment) were analysed with Kruskal–Wallis test. No significant relations were found.

EWIN SRT (speech reception threshold) and slopes at 50% scores based on correctly recognized syllables were calculated in R for each participant and for the whole group on both measuring times (Table 9 and Figure 2). Scoring was made according to the manual. Wilcoxon Matched Pairs Test in Statistica was used to compare the individual scores of SRT and slope between measuring times. Spearman correlation analyses did not indicate any relationship between EWIN scores and MMN activity within either group. Acquired 50% SRT scores are similar (Estonian adults -9.3 dB) to the ones presented in the manual/previous research (Veisbak et al., 2015).

Table 9.
50% SRT scores and slopes for both Groups and measuring times.

	1. time		2. time	
	SRT	Slope	SRT	Slope
EST	-9.09	9.45	-9.30	9.04
RUS	-7.24	9.25	-6.59	7.45

Note. EST – Estonian native group; RUS – Russian native group, SRT - speech reception threshold.

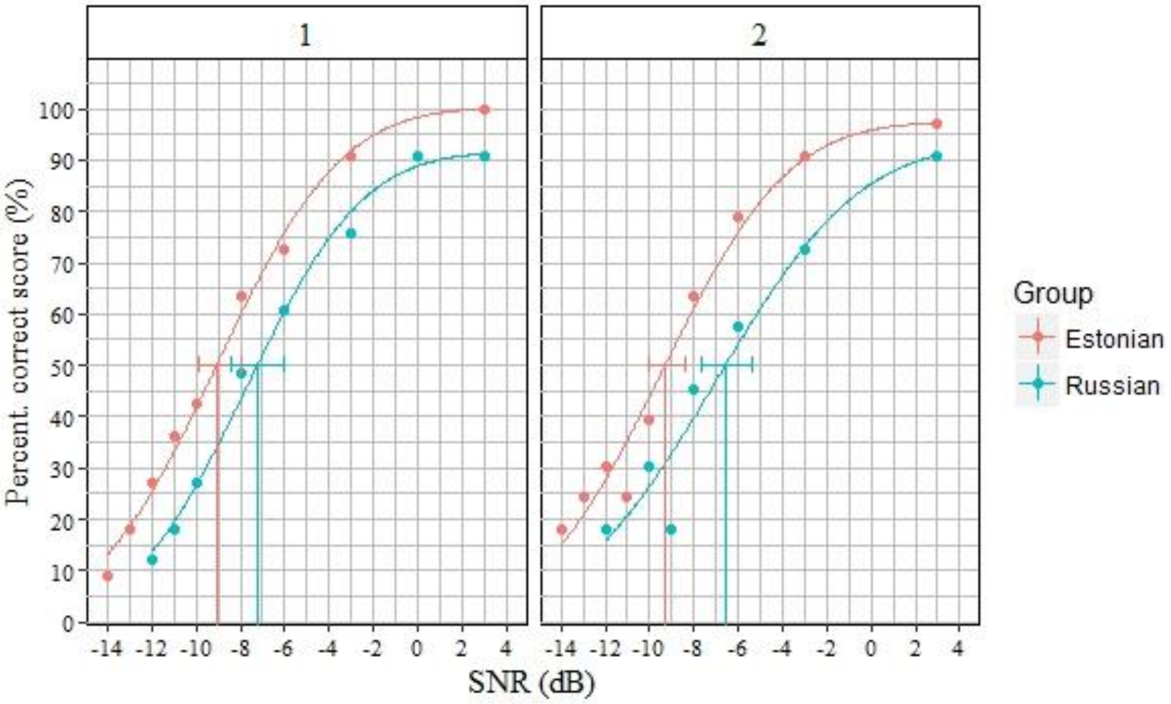

Figure 2.
EWIN performance curve for both Groups and measuring times. 50% scores are marked with vertical line. 1 – first measuring time, 2 – second measuring time. SNR – Signal to noise ratio (dB).

DISCUSSION

The aim of the study was to compare the brain activity during Estonian language quantity processing between Estonian and Russian native speakers. Both language groups participated in the experiment twice in order to further examine possible natural learning effects after being exposed to the language environment. Similar experiments investigating the processing of quantity changes have been carried out previously among Estonian and Finnish native speakers (Tull, 2013), and the current thesis should provide extended information for overall comprehension of neurolinguistics processes.

The MMN response to non-linguistic stimuli was significant for both language groups. Also, the activation pattern was genuinely similar or even almost identical on both experiment times. In Series 1 Condition D110\ seems to be more efficient in evoking the MMN response on the second recording time for both language groups, but it might possibly be a coincidence as the overall results do not show a significant learning effect. The overall results for technically constructed tone stimuli compared to language stimuli are compelling as there is a clear difference in processing either pure tone (meaningless sound) or language stimuli (possibly meaningful sound). MMN was more pronounced (i.e. with a larger amplitude) in both groups for non-linguistic stimuli compared to language stimuli (cf. Tables 4 and 8). Estonians had a larger MMN response for language stimuli compared to Russians, but the negative activity was even stronger and more consistent for non-linguistic stimuli. As both language groups had similar MMN pattern for non-linguistic stimuli, first hypothesis is confirmed.

Previous studies have given different results about possible lateralization of language processes, showing either functional lateralization of two hemispheres in language processing (Partanen, Vainio, Kujala, & Huotilainen, 2011) or similar bilateral activation (Witteman, Ijzendoorn, Velde, Heuven, & Schiller, 2011). The current thesis did not find results that would show any significant lateralization. One possible reason for that is the modest size of the testing group. The initial expectation that the two chosen and physically similar language stimuli will provide similar electrical activity in the brain proved to be false. As a result, both stimuli had to be analysed separately which unfortunately also meant the groups were only half of the expected size. Tull (2013) who used one of the same set of stimuli (SADA) and had a similar experimental design, found lateral differences between Estonian and Finnish native speakers with small number of participants (n = 5 for both language groups). One of the possible reasons for different results might be data processing differences. The current thesis uses pooled electrode cites, Tull (2013) analysed the results of single electrodes and used single T-tests for data analyses. Pooled areas reduce the risk that individual poor signal with single electrodes would change the score, but it also gives away some accuracy if there are only minor differences between lateral sides, which might be averaged out while pooling the activity recorded from several electrodes together. Compared with the previous work by Tull (2013), current study is using a more conservative post-hoc (Bonferroni) test and more complex ANOVA models throughout the study, which may weaken the statistical strength of some results. However, scalp activity maps of processing the stimuli show a possible lateralization effect for language stimuli – Estonian native speakers having a slightly bigger MMN activity in the left and Russian native speakers in the right hemisphere (Figure 1). That might support our lateralization part of second hypothesis but as explained before, the current thesis cannot provide enough significant results to confirm nor completely reject the assumptions.

Results of the EEG data show bigger (i.e. larger in amplitude) and more consistent MMN activity for linguistic stimuli among Estonian native speakers compared with Russian native speakers. This result is consistent with the findings of Pulvermüller and his colleagues (2001) who found larger MMN amplitudes to word-related stimuli compared to pseudowords. In the present study, Estonians had larger MMN amplitudes to Estonian specific language stimuli compared to Russians who could possibly interpret the Estonian language stimuli as pseudowords. A significant difference between the chosen language stimuli was revealed –the two language Stimuli SADA and SAGI gave different activity patterns and were not processed neither qualitatively or quantitatively similarly enough, so that using them together in analysis was not justified. The MMN respose to Stimulus SADA was with larger amplitude than Stimulus SAGI. There were significant results with Stimulus SADA mainly in Series 1 (S170- vs D290- and D290\) and 4 (S110\ vs D290\ and D290-). In both series, the significant MMN results contain both durational and pitch changes. The results showed clearer response to durational cues than to pitch cue for both language groups, the only clear tonal change in Series 2 (S290\ vs D290-), and there were indications of the importance of both durational and pitch change also in Series 1 Condition D290\ (vs S170-). This might refer to a possible usage of pitch cue among Estonian native speakers. Russian native speakers had limited significant MMN results to linguistic stimuli, only significant differences between standard and deviant processing were detected in Series 1 (S170- vs D290\) and Series 4 (S110\ vs D290\). Both of these conditions consist of durational and pitch changes, so a definitive decision if the detection of the difference is purely durational or if the pitch cue is perceived as well, cannot be made right now. Therefor second and third hypothesis found some confirmation about Estonian native speakers but not about Russian native speakers. It might be possible that functional properties of word stress can also be used to detect tonal changes. No learning effects were discovered, rather the MMN results were smaller in amplitude in the second measuring time. That can be incidental or connected with the repeated design of the experiment. Unfortunately it is not possible to assess final hypothesis.

The above reported results also correspond to a previous study from our laboratory (Tull, 2013), which showed the difference in Estonian quantity processing between Estonians and Finns. In the referred study, the same stimulus set SADA and the same experimental series to elicit the MMN were used. The Estonian participants had significant MMN results both for durational and pitch cue while Finnish participants seemed to rely on durational cue. Lateralization effect was also found, MMN was more elicited in left side electrodes for

Estonian participants and right for Finnish participants. The overall results for Estonians were similar to the current study, as both – usage of durational cue and pitch cue – were found to be important in the Estonian subject group. The results of the current study are also in accordance with previous similar language studies (Lippus et al., 2009; Meister, 2011) as it was expected that both duration and pitch cue are of importance for Estonians, and only the durational cue for Russian speaking subjects. However, these results have to be interpreted with caution as the used participant groups were modest in size, and the received result are not consistent enough to make strong conclusions.

The unexpected differences between the stimuli (SADA and SAGI) made it unreasonable to compare the results of the first and the second measuring with each other. The results obtained during the second measuring were similar to the above described results of the first measuring as tone stimuli evoked almost the same activity pattern while the difference processing for language specific stimuli stayed mostly insignificant. The slightly poorer MMN results for linguistic stimuli on the second recording can be possibly explained by smaller number of participants. Processing the pure tone stimuli resulted in similar activation patterns on both recording times and in both language groups. That was an expected result as different activation between language groups was assumed for linguistic stimuli but not for tone. The MMN response to linguistic stimuli clearly differs from the response to the tone, is less pronounced, and shows distinctive differences between Estonian and Russian native speakers. The EEG results did not improve after approximately one month, the chosen time period was possibly too short and uncontrollable.

Possible confounding variables were incorporated into analysis to check for significant correlations with MMN results. Data about musicality and foreign language abilities (Handel, 1993) were collected with a self-reported questionnaire. Also, for Russian participants the possible connections with the overall time spent in Estonia and subjective evaluation of the time spent directly in Estonian language environment were investigated. None of the analysis gave significant results, but again it might have been influenced by the relatively small number of participants as well as possible subjectivity of self-reported questionnaire. Although it was not a specific goal of this thesis, an extra value of this study might be the possibility to collect more results to validate the EWIN test in Estonia. Even though the EWIN results did not correlate significantly with the MMN results, they do support the previously provided 50% SRT score for Estonian adults adding strength to the tests reliability.

Future directions

EEG results provided some interesting possible future directions for research. Series 2 and 3 only provided a few significant results, in both of these series, the standard stimulus had a long (290 ms) first vowel. That may indicate a rather surprising relationship between used standard stimuli and brain activity. At least for Estonian native speakers it could show some kind of an imbalance in quantity processing – it seems to be easier to detect the difference when the comparison is made from a short quantity (that is heard and processed first) to a longer one, but not always the other way around. That could be a potential direction to explore further in future.

One possible explanation to fewer significant results compared with the work of Tull (2013) could be the similarity between stimuli from the SADA set and the Russian word *'сад'* (*сада*) – *'garden'*. The Russian word can sound similar to Estonian long quantity *'saada'*. The most similar to it from the set used was 170- stimulus, that has also been rated to be perceived as a 2nd quantity by Estonian subjects in a behavioural study (Lippus et al., 2009). Possible semantical processing can bring forward unexpected brain activation and the stimulus would not work completely as a foreign meaningless word. However, also Finnish language uses the word *'saada'* – but as Finnish does not have long quantity (only short and overlong) it might sound different enough (Tull, 2013). Future research is needed especially using Russian native speakers to confirm the issue.

For future research, it might be beneficial to use some specific and more controllable language learning or priming program. The natural language environment can probably still affect language processing in the brain but it might need considerably more time or intensive training for these changes to develop notably in the brain. Hisagi, Shafer, Miyagawa, Kotek, Sugawara and Pantazis (2016), and Grimaldi, Sisinni, Fivela, Invitto, Resta, Alku and Brattico (2014) have also concluded that the accelerated school program does not improve the speech perception of second language learners enough in just a few months or even years.

Limitations

Although the selection of the stimuli was made carefully, and the amount of confounding factors were taken to minimum, there still was a significant difference between the results of the two stimulus sets. That created a situation where it was not possible to act according to the original plan of analysing the stimuli together, and the responses to the two stimulus types had to be analysed separately. This however made the experimental groups smaller and therefore weakened the results. More analyses with diverse set of stimuli have to be conducted to investigate why exactly the stimuli were creating the different MMN results. The physical differences were tried to be taken to the minimum but it is obvious that it is impossible to create completely equal and comparable stimuli. One possible explanation could be that different syllables '*da*' and '*gi'* had a co-articulation effect (Hint, 1998), and that might have changed how the previous syllable '*sa*' was perceived. Also, another research questions may rise from here as previous studies (Tull, 2013, Lippus et al., 2009) have concentrated mostly on one set of stimuli (SADA) – how big and what kind of differences can lie between chosen linguistic stimuli, and if different set of words give different results as the current study showed, how generalizable are the results to overall language perception processes? Future research has to address these problems and include a wider set of stimuli.

Another bigger problem was finding the participants and measuring their language experience. When concentrating on participants with certain profile (like different language groups) extra funding and compensation for participants is necessary. In the future, it would be beneficial to develop a specific Estonian language learning program that foreign participants could undertake (Tamminen et al., 2015). This way, it would be better controlled, what the subjects learn and how efficiently. In the current study, Russian participants had considerable amount of diversity among their language experience. In addition, this study included foreign students who stay in Tartu for only limited time, and consequently it was not possible to leave a longer time period between the two EEG measurements, which would be preferred to possibly see the effects of the language environment (another possibility would be to use a specific language learning program).

Future research on a larger sample is needed to further examine the possible modifiers that may affect language processing (including co-articulation).

CONCLUTIONS

To expand the understanding of language processing in the brain, two EEG experiments (with approximately one month between them) measuring the processing of quantity changes were conducted with Estonian and Russian speaking subjects. The results provide some support to previous studies on a similar topic, showing the possible usage of both duration and pitch cues for Estonian native speakers in differentiating between quantities in the language. The evidence for Russian speech processing mechanisms or language learning effects stayed weak. The non-linguistic tone stimuli provided significant and almost identical MMN results in both language groups on both measuring times, showing the difference in brain while processing linguistic or non-linguistic stimuli. No clear lateralization effect was found, but the result may be affected by the group size or methodological choices. No connections between musicality or language ability, and MMN responses were found. Development of comparable stimulus-sets is necessary for generalizability of studies interested in brain mechanisms of representation of language. One future development could also be to use finer source localization methods to access likely structures responsible for the discrimination response. The study added valuable knowledge to our understanding of the complexity of language processing in human brain and created great basis where to continue and develop the future research.

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Appendix 1.

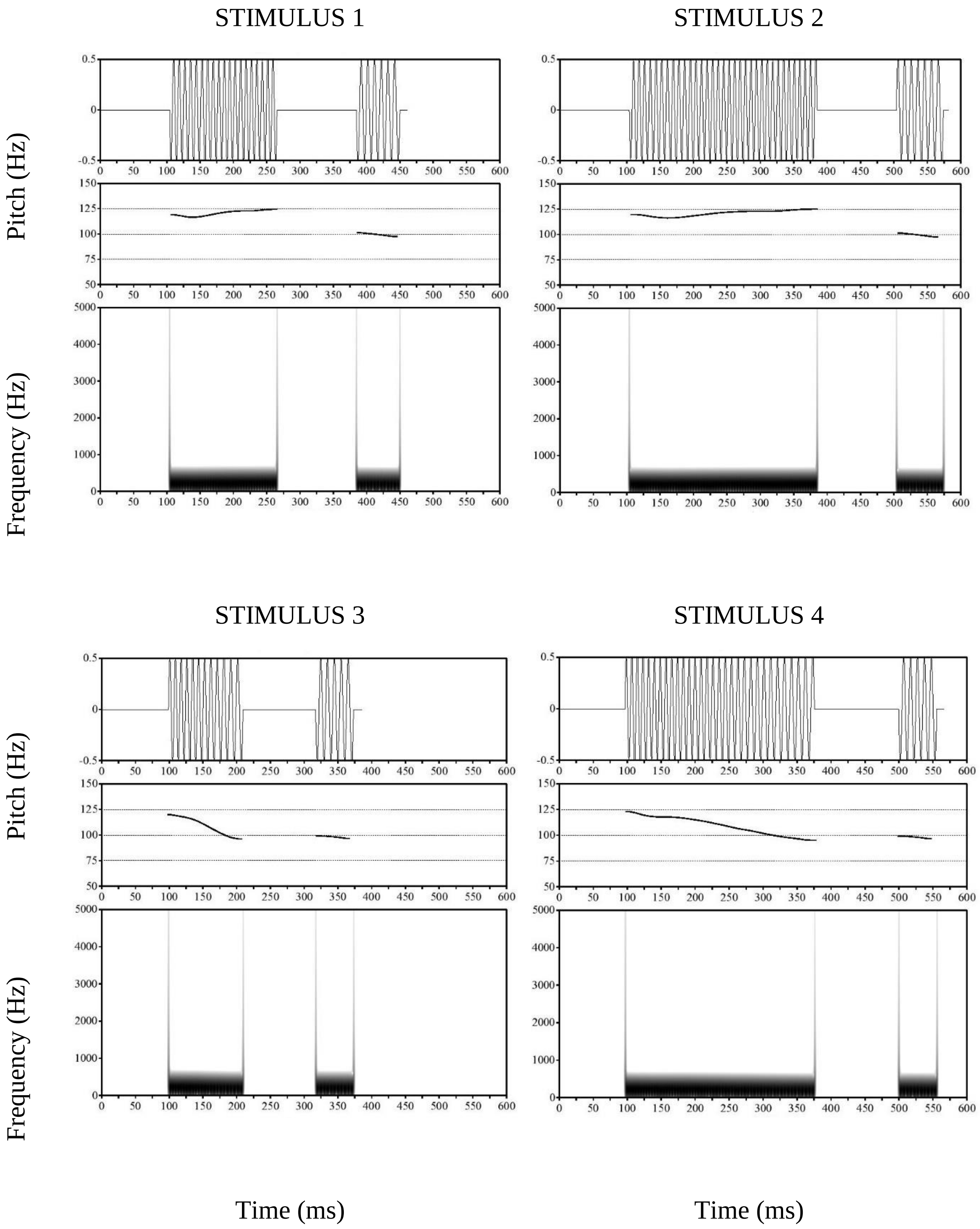

Figure 3. Spectrogram of stimuli set of Tone.

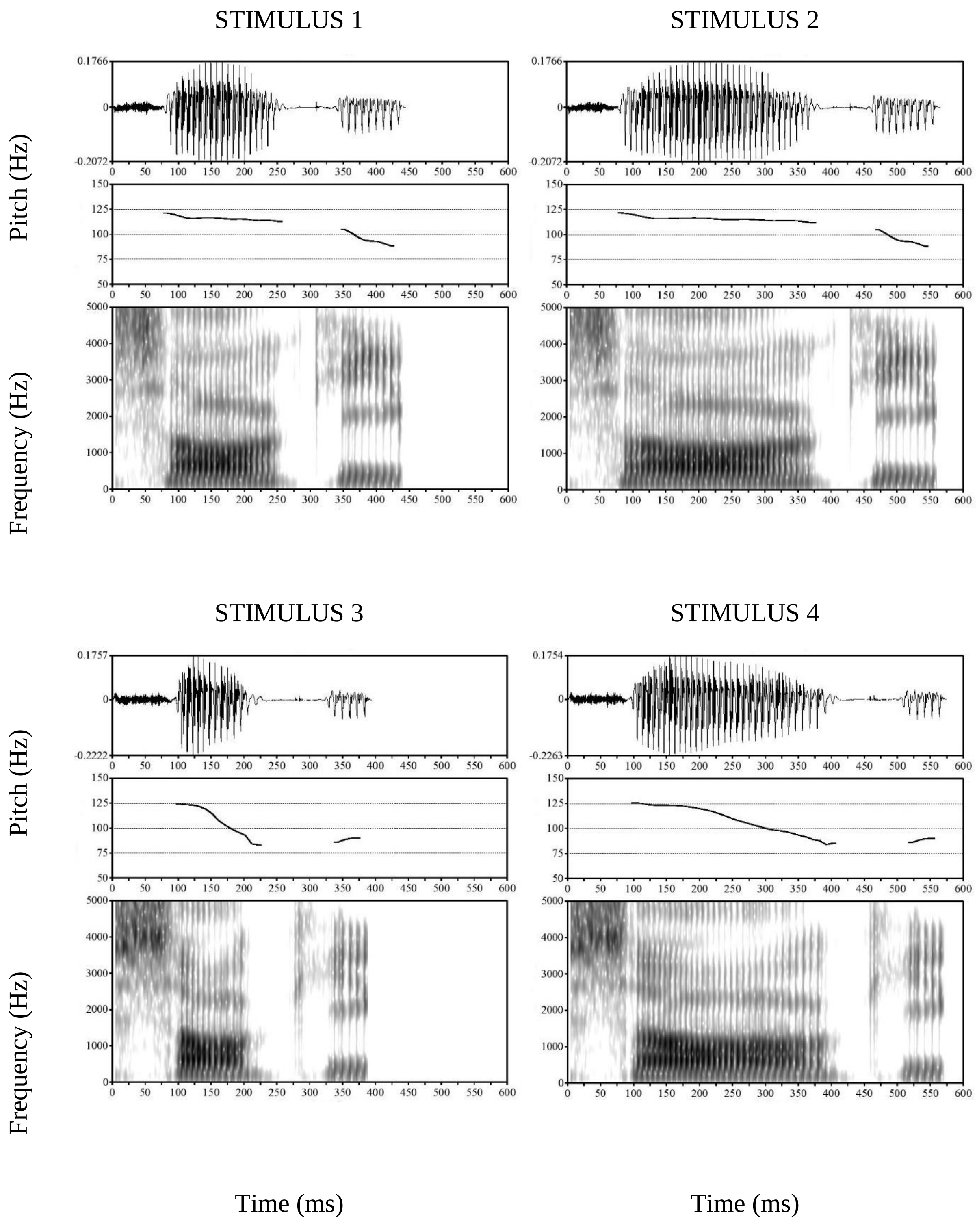

Figure 4. Spectrogram of stimuli set SAGI.

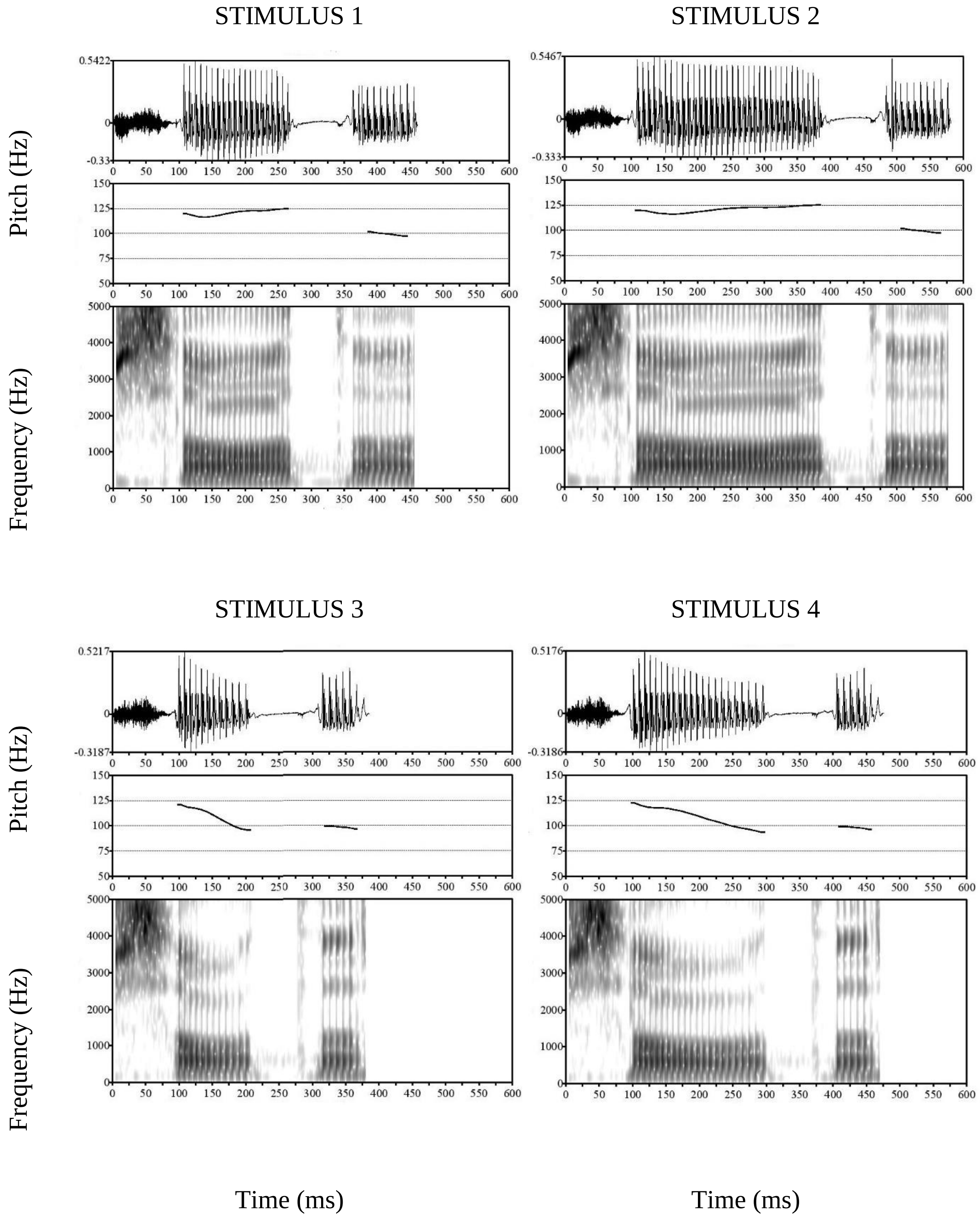

Figure 5. Spectrogram of stimuli set SADA.

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