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THE EFFECT OF BILINGUALISM ON UNFAMILIAR LANGUAGE PERCEPTION

Background. A growing number of scientists are studying the mechanisms of various aspects of language acquisition and perception while searching for new methods to master them. The impact of bilingualism on cognitive functions, such as attention, memory, and concentration, is also important.

Methods. The present study, based on the electroencephalography (EEG) recording techniques, highlights the influence of bilingualism on the perception of different languages, namely the native language (represented by Ukrainian), a second language mastered at a certain level (represented by English), and a language that has not been previously learned at any level (represented by Finnish). These languages belong to different language groups, which makes it impossible to fully or partially understand words or phrases based on associations with similar linguistic structures in familiar languages. The purpose of this study was not just to prove the differences in the perception of various languages but also to provide detailed account of changes in electrical activity in the brain, to investigate which frequency bands and sub-bands are involved, and to identify the brain regions that may be responsible for these functions. For this study, 20 bilingual students aged 18–22 participated voluntarily.

Results. The study results showed a statistically significant difference in the perception of the following language pairs: Ukrainian and English, English and Finnish, and Ukrainian and Finnish. This difference is most pronounced in the β_1 and β_2 frequency sub-bands. The following brain areas are involved in processing languages from different language groups with varying intensities: the occipital area of the right and left hemispheres, the temporal area of the left hemisphere, and the parietal region of the right hemisphere.

Conclusions. The observed neural differences in the perception of known and unknown languages provide further evidence that language comprehension relies on both auditory and cognitive processing mechanisms, engaging different brain regions depending on familiarity with the language. The increased activation in the occipito-temporal and parietal regions during language processing suggests that both linguistic and non-linguistic factors – such as phonological familiarity and semantic expectations – play crucial roles in language perception. A detailed study of bilingualism and mechanisms of language perception opens up prospects for developing improved methods of teaching foreign languages, which will accordingly expand individuals' ability to use large amounts of information to enhance their knowledge and skills.

Keywords: bilingualism, electroencephalography (EEG), neurophysiology, neurolinguistics.

Background

Language is the ability to speak and express their thoughts and associate random symbols with specific meanings to convey ideas, feelings, desires, and emotions. Language is considered a second signal system because it does not simply transmit signals to the brain through electrical impulses; rather, it is a set of nervous processes that occur in the cerebral cortex in response to words and concepts they denote. Individuals use language to share information, feelings, and thoughts when communicating. This communication is mostly based on sound signals generated by the vocal apparatus and perceived by the auditory system. Additionally, written symbols represent language, which is then perceived by the visual sensory system.

Human language consists of phonemes. A phoneme is the smallest segmental element of morphemes. Therefore, phonemes are essential for recognizing and distinguishing morphemes, the smallest semantic units of words. We cannot determine the meaning of words using phonemes alone, but they are the semantic units of morphemes. Different languages have different numbers of phonemes; for instance, Ukrainian has 38, English has 44, and Finnish has 25. According to modern research, the ability to speak

is an inborn property of the human brain (Yamoah, Pavlinkova, & Fritzsich, 2023).

Bilingualism is the ability of a person to speak two languages at the level of fluency or high competence. A bilingual individual can use both languages in everyday life, communication, work, and other situations. Bilingualism can result from various factors, such as bilingual upbringing, intercultural interaction, education in a bilingual environment, or relocation to a country with a different language. Research in neurobiology and psychology shows that speaking more than one language significantly impacts human brains, ranging from the mechanisms of memorizing and word mapping in the brain to overall memory and attention capabilities.

Recent studies have pointed to the positive effect of bilingualism on cognitive abilities. For instance, bilingual children aged 7–12 have different selective attention mechanisms compared to monolingual children, primarily associated with potentially more successful learning (Phelps, Attaheri, & Bozic, 2022). This interesting feature is associated mainly with the different mechanisms of attention coding in bilingual versus monolingual children, as the necessity of mastering two languages forces the brain to constantly inhibit the language that is not currently

in use. Therefore, when using one language, we mostly do not use the words and grammatical structures of the other.

Neuroimaging studies have clearly shown that the regions of the brain responsible for the native language are also involved in the acquisition of a foreign language. Moreover, different brain activity during speech production is observed in individuals with varying levels of second language proficiency. Lower levels of language proficiency may correspond to a more extensive representation of activity in different brain regions (Martín-Fernández, Gabarrós, & Fernandez-Coello, 2022). However, these neural differences, which correspond with language proficiency, disappear once a native speaker acquires a high level of a second language proficiency. In the initial stages of second language acquisition, additional brain activity is observed in the left prefrontal cortex during speech production.

There are generally two main neural differences in the processing of native and second language speech. First, increased brain activity associated with the second language is seen in areas that also mediate the native language, such as Broca's area. Second, there is specific involvement of additional brain structures outside of left language networks, such as those associated with cognitive control – such as left prefrontal cortex and left caudate nucleus (Abutalebi, 2008). In the first case, bilingual speakers with low language fluency may compensate for lower efficiency by engaging these areas more strongly, and the greater activity observed in non-native speech production may reflect the increased number of neurons required to perform a complex task such as speaking a non-native language. In the second case, the specific involvement of control structures may emphasize that, unlike the mother tongue, the non-native language is not processed automatically but rather in a 'controlled' manner (DeAnda et al., 2016). However, this mechanism of 'interaction' between the two languages is not yet fully understood and requires further research.

Additionally, numerous studies have established a correlation between bilingualism and the later development of cognitive impairment associated with organic brain diseases, such as dementia. At the same time, a systematic review showed that bilingualism had an impact on delaying dementia but not on reducing the risk of the disease. The period the disease occurred later depends on different conditions influenced by education, living conditions, and other factors (Brini et al., 2020). Furthermore, several studies have pointed to delaying the progression of Alzheimer's, compensating for pathological and age-related cognitive impairment (Taylor et al., 2022). This is currently associated with the flexibility caused by bilingualism, which allows for the engagement of alternative cerebral networks and the strengthening of existing networks as compensatory mechanisms (Marian, & Shook, 2012). Research into both the nature and prevention of Alzheimer's disease is an important topic in modern science, thereby, it is actively studied, particularly regarding the impact of bilingualism.

The impact of bilingualism on individuals with autism spectrum disorders (ASD) has not yet been widely studied. Still, a few articles point to the possible positive effect of bilingualism in the context of flexibility in social tasks in children with ASD, which is more significant when the second language is introduced at an early age (Romero, & Uddin, 2021). More recently, research on adults with ASD and the impact of bilingualism on their social habits and quality of life has begun to appear, showing a small but statistically significant contribution of bilingualism to the

self-assessed quality of social life among adults with ASD (Digard et al., 2020).

While many articles provide overviews and analyses of data collected from the studies of bilingualism based on questionnaires and surveys, a significant number of studies involve neuroimaging techniques, such as electroencephalography (EEG), which allows to collect and process the data on the electrical activity of different brain areas during the performance of certain tasks or perception of various stimuli (Gallo et al., 2025). EEG studies play a crucial role in the study of speech mechanisms. Recent studies indicate that brain oscillations in different frequency bands are responsible for various types of brain activity. For example, attention is associated with changes in α and γ activity, while working memory (Wen et al., 2022) and long-term memory processes involve θ , β , and γ activity. Speech perception and listening comprehension of sentences are associated with several ranges of brain oscillations, including both low-frequency components such as δ and θ oscillations and high-frequency components such as β and γ oscillations. It is also known that brain oscillations in EEG recordings made while listening to one's native language (Broderick et al., 2018) are predominantly reflected in the θ (4–7 Hz) and α (7–13 Hz) frequency bands (Beres, 2017).

Interestingly, when translating words into a second language from one's native language, increased brain activity in the same frequency bands is observed, provided that the words are translated successfully (Mai et al., 2016). Such activity is much less common when listening to unknown words in a foreign language. Our study was performed using EEG, and further data processing was done using the EEGLAB software add-on based on the MATLAB engineering package. The novelty of the work lies in the detailed description of the difference in brain electrical activity across various bands and sub-bands during the perception of other languages by bilingual individuals. Furthermore, we aim to identify the brain areas involved in the processing of auditory stimuli and showing a statistically significant difference during the perception of languages at various levels of listening comprehension.

Methods

EEG captures and records the brain's electrical activity using electrodes placed on the scalp. The method records the electrical potentials that occur in the brain due to neural activity and is widely used to diagnose neurological diseases and brain damage. It allows the detection of abnormalities in electrical activity of the brain associated with various neurological pathologies, such as epilepsy, migraine, and neurodegenerative diseases.

EEG is also used to assess cognitive abilities, including attention, memory, and concentration. Such studies improve learning systems and can help diagnose various disorders of these functions early.

Another application of EEG is to diagnose various sleep disorders, such as insomnia, apnoea, and parasomnias, which aids in the development of effective treatments.

EEG is recorded using electrodes, an encephalograph, and a computer. The electrodes, previously placed on the subject's head, record electrical stimuli generated by the brain. In this study, 25 electrodes were used, placed according to the '10–20 %' system approved by the International Association of Electroencephalography and Clinical Neurophysiology (Fig. 1). The location of each electrode is represented by a Latin letter and a number corresponding to certain brain regions: C for central sulcus, O for occipital, P for parietal, T for temporal, F for frontal and Fp for prefrontal. Even numbers indicate the

location on the right hemisphere, while odd numbers on the left. Additionally, two electrodes were located in electrically neutral areas; in this study, they were the earlobes, which do not register potentials and, therefore, are called passive or reference electrodes.

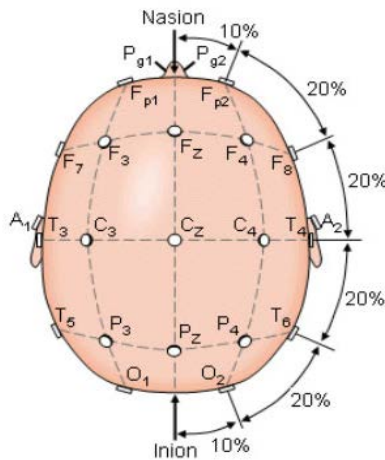


Fig. 1. Scheme of electrode placement according to the 10–20 % system (American Academy of Sleep Medicine, 2013)

Each electrode is connected to an encephalograph, which enhances the signal and records it in the computer's memory. This way, the electrical potentials generated by the brain and recorded by the EEG can be monitored and presented in real-time mode on the computer screen (Fig. 2).

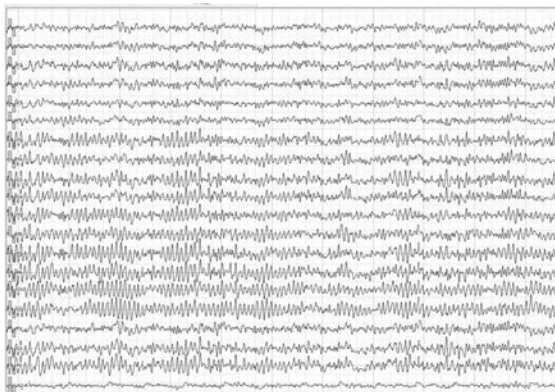


Fig. 2. An example of an EEG of a healthy person with a pronounced resting state α rhythm

The study was conducted in a closed laboratory room that partially screened out noise caused by electrical devices and minimized unnecessary sound and visual stimuli to ensure the accuracy of the results.

The subject group comprised 10 men and 10 women aged between 18 and 22. Participants were informed about the content of the stimulation program, and written informed consent was obtained in accordance with the World Medical Association (WMA) Declaration of Helsinki – Ethical Principles of Medical Research Involving Humans (Helsinki, Finland, June 1964), Declaration of Principles of Tolerance (28th Session of the General Conference of UNESCO, Paris, November 16, 1995), Conventions for the Protection of Human Rights and Human Dignity in the Use of Biology and Medicine: Convention on Human Rights and

Biomedicine (Oviedo, April 4, 1997). Each participant provided personal consent to the study and confirmed that they had no health issues that would interfere with the examination or affect the research outcomes. The participants confirmed their consent with a signature in the laboratory journal.

All participants were classified as bilingual since they were proficient in both Ukrainian and English. Although some of them were partially acquainted with other languages, these were not considered in the experiment because either those languages represented the same language group (such as Russian and Ukrainian or German and English), or the participants' language proficiency levels were insufficient. The level of English was previously determined by the oral interview with each participant and was determined to be within the B1 to C1 range of the Common European Framework of Reference for Languages.

EEG recordings were performed using the Neurocom hardware and software complex ('KhAI Medica,' Kharkiv, Ukraine). According to the international system, '10–20 %' electrodes were placed on the head.

The experimental design was as follows: the participants' resting state with eyes closed was recorded for 1 minute, followed by three series of sound stimuli in three different languages: Ukrainian, English, and Finnish. Each of these series lasted up to 20 seconds, and after each series, a 20-second resting state was recorded.

The obtained data were processed using the EEGLAB software add-on based on the MATLAB engineering package. The primary recordings were processed – filtering (2–30 Hz) and ICA analysis – to remove the artifactual components (oculomotor, neck muscle tension, etc.). Segments of 20 seconds were selected for analysis, which matched the time of listening to audio stimuli and resting state.

Statistical data processing focused on the following frequency bands: θ (3.5–7.4) Hz, α_1 (7.5–9.4) Hz, α_2 (9.5–10.7) Hz, α_3 (10.8–13.5) Hz, β_1 (13.6–19.9) Hz, β_2 (20–30) Hz. MATLAB provides a variety of functions and tools for group statistical processing. One of the most important packages for statistical analysis in MATLAB is the Statistics and Machine Learning Toolbox, which has several important functions used in this study.

Statistical analysis of the results was performed on MatLab using the EEGLAB software. Permutation tests were conducted to determine statistically significant differences among subject groups (p -value < 0,05).

Results

Comparisons were made between the perception of Ukrainian and English, English and Finnish, and Ukrainian and Finnish. The differences in brain activity were studied across the following frequency ranges: θ (3.5–7.4) Hz, α_1 (7.5–9.4) Hz, α_2 (9.5–10.7) Hz, α_3 (10.8–13.5) Hz, β_1 (13.6–19.9) Hz, and β_2 (20–30) Hz. A statistically significant difference in the perception of different languages was recorded mainly in the α and β frequency bands, which will be described in this section. For processing, fragments of the recording of direct listening to the languages that lasted 20 seconds each were selected.

When analyzing the electrical activity of the brain in the β_2 frequency sub-band (20–30 Hz) while listening to Ukrainian compared to English, a statistically significant difference was found in the occipital area of the right hemisphere of the brain (42.4 $\mu V^2/Hz$ and 43.3 $\mu V^2/Hz$, respectively) (Fig. 3). When analyzing the electrical activity of the brain in the α frequency range (9.5–10.7 Hz) while listening to Finnish compared to English, a statistically significant difference was found in the occipital part of the left hemisphere of the brain (59 $\mu V^2/Hz$ and 57 $\mu V^2/Hz$) (Fig. 4).

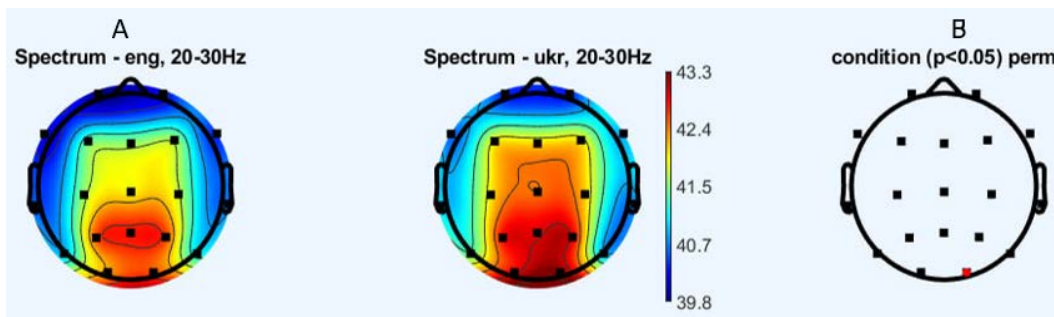


Fig. 3. Topographic map of changes in the spectral power of β_2 – EEG sub-band in the group of bilinguals during the perception of English (eng) and Ukrainian (ukr) (n = 20) (A) and the results of statistical comparison of these changes (B). Colour indicates significant changes at $p < 0,05$

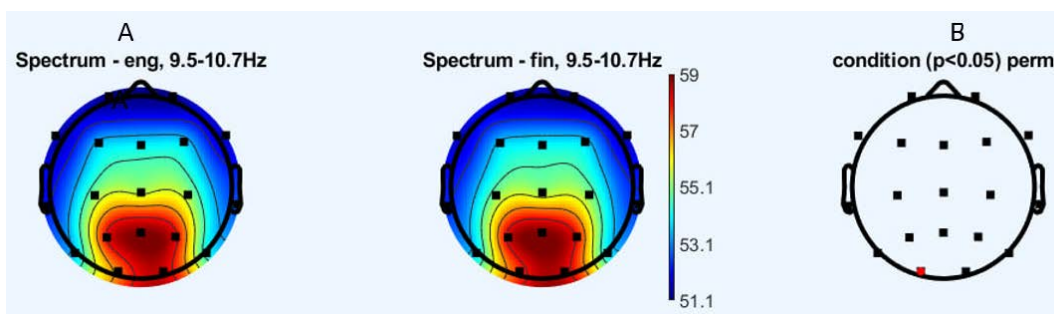


Fig. 4. Topographic map of changes in the spectral power of the α_2 sub-band of the EEG in the group of bilinguals when perceiving English (eng) and Finnish (fin) (n = 20) (A) and the result of statistical comparison of these changes at $p < 0,05$ (B)

The analysis of brain electrical activity in the β sub-bands (13.6 19.9 Hz and 20 30 Hz) while listening to Ukrainian compared to Finnish revealed statistically significant differences in several brain regions (Figs. 5 and 6): the spectral power topography shows an increased activity in the parietal, temporal and occipital areas of the right hemisphere

in the β_1 frequency sub-band; the spectral power topography in the β_2 sub-band shows a stronger activation of the brain during the perception of Ukrainian speech. In addition, when comparing the results of EEG processing in these two sub-bands, a stronger difference in comprehension of Ukrainian compared to Finnish becomes apparent.

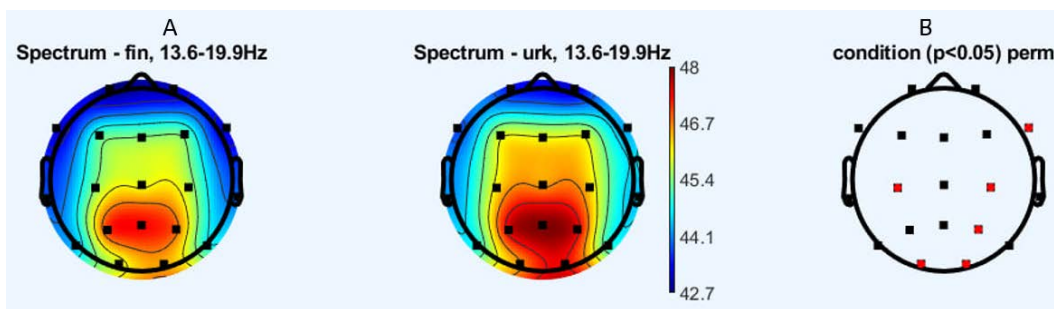


Fig. 5. Topographic map of changes in the spectral power of the β_1 sub-band of the EEG in the group of bilinguals when perceiving Finnish (fin) and Ukrainian (ukr) speech (n = 20) (A) and the result of statistical comparison of these changes (B)

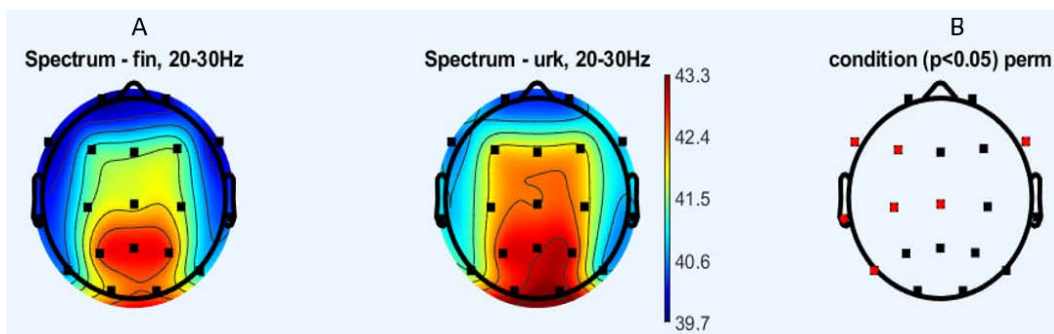


Fig. 6. Topographic map of changes in the spectral power of β_2 – EEG sub-band in the group of bilinguals during the perception of Ukrainian (ukr) and Finnish (fin) languages (n = 20) (A) and the result of statistical comparison of these changes (B)

Discussion and conclusions

The β_2 frequency sub-band is associated with internal mental activity, attention concentration, and the cognitive processing of the perceived material (Barry et al., 2007). Considering the topographic maps of changes in spectral power (Fig. 3, A), it can be concluded that the perception of the native language causes greater internal mental activity compared to a language that is understandable but not native. The significant difference in activity in the right zone indicates emotional arousal and the autonomic accompaniment of this arousal (increased blood pressure, changes in cardiac rhythm, and sweating). Previous laboratory studies on the perception of Ukrainian and Russian languages prior to the full-scale invasion proved a more emotional and positive cognitive response to the perception of the Ukrainian language among all subjects (both Ukrainians and Russians). Post-examination surveys confirm that of the three languages – English, Finnish, and Ukrainian – listening to the native language was the most enjoyable for participants.

The occipital region of the left hemisphere corresponds to Wernicke's area, which is involved in speech perception. All the functions of this brain area are not yet understood; however, some studies indicate that this area is more highly developed in multilingual individuals compared to monolinguals. The results of the analysis of the spectral power of the α_2 sub-band indicate greater intensity of cognitive and imaginative thinking when listening to Finnish compared to English.

We will first discuss the analysis of the β_1 frequency sub-band. The differences in the perception of Ukrainian and Finnish are evidenced not only by the statistically significant findings but also by the topography of the spectral power. Increased activity in the right hemisphere's parietal, temporal, and occipital areas indicates a strong emotional and cognitive response to the perception of Ukrainians. At the same time, the associative parietal regions are mostly involved in the perception of the Finnish language, which indicates increased activation of memory and associations. It is as if the brain is trying to recall something similar to unknown sound stimuli, as sentences in Finnish were difficult to perceive not only in terms of meaning but also due to the phonetic components, which is very different from those of Eastern Slavic languages. The β_1 sub-band is associated with external attention and concentration on what comes from the outside rather than on one's own emotions. Therefore, we can say that these results indicate a difference in the processes of understanding and awareness of these languages.

The results of the β_2 sub-band analysis also show a clear difference in the perception of Finnish compared to Ukrainian. As mentioned above, the β_2 sub-band is responsible for the internal state of the psyche and consciousness. In this case, it has been observed that the Ukrainian language causes strong emotional arousal and subjective experiences. Activation in the left hemisphere indicates verbal activity, i.e., participants understood the sentences while listening and may have repeated them to themselves. It is worth noting that the topographic maps of Finnish language perception in the β_1 and β_2 sub-bands are almost identical, while this difference is obvious in Ukrainian. In this case, we can talk about emotional and cognitive resonance in the perception of Ukrainian instead of Finnish (Brismar, 2007).

The analysis of the results shows that previous experience of language learning actively influences the perception of this language and other types of languages,

which is accompanied by the activation of high-frequency bands of EEG activity in the brain (β_1 and β_2). A higher level of proficiency in a foreign language is associated with a decrease in the statistical significance of the differences between the perception of foreign and native languages.

These findings have several important implications. First, they support the idea that bilingualism enhances cognitive flexibility by requiring the brain to continuously regulate language use and processing. The observed neural differences in the perception of familiar and unfamiliar languages provide further evidence that language comprehension relies on both auditory and cognitive processing mechanisms, engaging different brain regions depending on familiarity with the language. Increased activation in the occipito-temporal and parietal regions during language processing suggests that both linguistic and non-linguistic factors – such as phonological familiarity and semantic expectations – play a crucial role in language perception.

From a practical perspective, this research might contribute to improving foreign language learning methodologies. By understanding how different frequency bands correlate with cognitive effort and comprehension, educators can design more effective training approaches that optimize learning conditions. For instance, immersive learning environments that engage multiple cognitive processes may facilitate better retention and fluency in a second language. Additionally, findings on the involvement of emotional and cognitive engagement in native language perception could inform new strategies for enhancing motivation and retention in language acquisition.

In conclusion, this study highlights the complex interplay between language experience, neural activity, and cognitive engagement. It reinforces the significance of bilingualism not only in terms of linguistic proficiency but also in relation to broader cognitive functioning, emphasizing its role in learning, adaptation, and even neurological resilience.

Authors' contributions: Yelyzaveta Reshetniak – conceptualisation; methodology; source analysis, preparation of literature review or theoretical framework, empirical data collection and validation; empirical research. Elina Rula – writing (revision and editing). Mariia Chernykh – conceptualisation, writing (revision and editing).

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ВПЛИВ БІЛІНГВІЗМУ НА СПРИЙНЯТТЯ НЕЗНАЙОМОЇ МОВИ

Вступ. Зростаюча кількість науковців працює над вивченням механізмів сприйняття різних мов та пошуком нових методів їхнього опанування. Важливим також є питання впливу білінгвальності на когнітивні функції – увагу, пам'ять, концентрацію тощо.

Методи. Ця робота, виконана з використанням методики ресстрації ЕЕГ, висвітлює питання впливу білінгвізму на сприйняття різних мов, а саме рідної (представлена українською), опанованої на певному рівні другої мови (представлена англійською) та тієї, що раніше не була вивченою на жодному рівні (представлена фінською). Ці мови належать до різних мовних груп, що унеможливує повне або часткове розуміння слів чи висловів на основі асоціацій зі схожими мовними структурами у знайомих мовах. Метою дослідження було не тільки довести різницю у сприйнятті різних мов, а й детально описати саме зміну електричної активності головного мозку, дослідити, які частотні діапазони й піддіапазони до цього залучені, які ділянки мозку можуть відповідати за цю функцію.

До дослідження було залучено 20 білінгвальних і полілінгвальних студентів віком 18–22 роки, що на добровільних засадах погодилися взяти участь в обстеженні.

Результати. Результати дослідження показали наявність статистично значущої різниці у сприйнятті таких мов попарно: української та англійської, англійської й фінської, української та фінської. Найвиразніше ця різниця простежується в бета-1 та бета-2 частотних піддіапазонах. До обробки мов різних мовних груп із різною інтенсивністю залучені такі ділянки головного мозку: окципітальна частина правої та лівої півкуль, темпоральна частина лівої півкулі, парієтальна частина правої півкулі.

Висновки. Детальне дослідження білінгвальності та механізмів сприйняття мов відкриває перспективи створення вдосконалених методів навчання іноземних мов, що відповідно розширить можливості людей у всьому світі якісно використовувати більші масиви інформації для покращення своїх знань та навичок.

Ключові слова: білінгвізм, електроенцефалографія (ЕЕГ), нейрофізіологія, нейrolінгвістика.

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