FEATURES OF EEG MICROSTATE ANALYSIS IN POST-STROKE APHASIA

Gulyaev SA[1,2] ✉, Khanukhova LM[2], Garmash AA[1]

[1] Institute for Physics and Engineering in Biomedicine, National Research Nuclear University MEPhI, Moscow, Russia

[2] La Salute Clinic, Moscow, Russia

Knowledge about the specificity of changes in the activity of neural networks associated with realization of thought processes can be used to construct the personalized medical rehabilitation systems. This approach is of particular interest for people with the speech function disturbance due to stroke, since the development of aphasia with the loss of speech leads to severe social maladaptation that worsens the disease outcome. The study was aimed to assess the functional activity of individual neural networks based on the theory of combining the EEG microstate identification technique with the method of determining spatial localization by solving the EEG inverse problem in 27 individuals (15 males and 12 females) with an average age of 52 years, who had speech impairment due to acute atherothrombotic stroke. Mathematical analysis of the scalp bioelectrical activity multichannel recording from the system for EEG microstate model isolation was carried out under changing environmental conditions caused by the auditory-speech load together with the EEG inverse problem solution for each subject. It was found that the speech disorder development depends not only on the fact of damage to brain structures, but also on the deep functional restructuring of both neural streams involved in implementation of brain function and the entire speech connectome. The disease with a predominant motor disorder, that has shown the possibility of transferring functions to the intact hemisphere prefrontal structures, in contrast to sensory disorders representing global changes in the entire speech connectome, can probably be considered the most favorable variant of aphasia.

Keywords: electroencephalography, speech function, brain rhythms, diagnostics, rehabilitation, cerebral stroke, aphasia

Author contributions: the authors contributed equally to the study.

Compliance with ethical standards: the study was approved based on the contract between the National Research Nuclear University MEPhI and La Salute Clinic (protocol № 09-01/23 of 09 January 2023), approved by the ethics committee of the National Research Nuclear University MEPhI (protocol of 25 May 2023), and conducted in accordance with the principles of biomedical ethics set out in the Declaration of Helsinki (1964) and its subsequent updates.

✉ **Correspondence should be addressed:** Sergey A. Gulyaev
Ramenki, 31, k. 136, Moscow, 119607, Russia; s.gulyaev73@gmail.com

Received: 20.06.2023 **Accepted:** 22.07.2023 **Published online:** 13.08.2023

DOI: 10.47183/mes.2023.025

ОСОБЕННОСТИ АНАЛИЗА ЭЭГ-МИКРОСОСТОЯНИЙ ПРИ ПОСТИНСУЛЬТНОЙ АФАЗИИ

С. А. Гуляев[1,2] ✉, Л. М. Ханухова[2], А. А. Гармаш[1]

[1] Инженерно-физический институт биомедицины Национального исследовательского ядерного университета «МИФИ», Москва, Россия

[2] Общество с ограниченной ответственностью «Клиника Ла Салюте», Москва, Россия

Знания о специфичности изменений активности нейронных сетей, связанных с реализацией мыслительного процесса, могут быть использованы в построении систем персонализированной медицинской реабилитации. Особый интерес данный подход представляет для лиц, потерявших речевую функцию в результате развития церебрального инсульта, так как развитие афазии с потерей речевой коммуникации приводит к выраженной социальной дезадаптации, ухудшающей прогноз заболевания. Целью исследования было определить функциональную активность отдельных нейронных сетей, основываясь на теории комбинированной технологии определения ЭЭГ-микросостояний с методикой определения пространственной локализации с помощью решения обратной задачи ЭЭГ у 27 человек (15 мужчин и 12 женщин) со средним возрастом — 52 года, с нарушением речевой функции вследствие развития острого атеротромботического инсульта. Для всех обследованных был осуществлен математический анализ многоканальной записи скальповой биоэлектрической активности с системы выделения модели ЭЭГ-микростостояний с решением обратной задачи ЭЭГ для каждого из них в изменяемых внешних условиях, вызванных проведением слухо-речевой нагрузки. Обнаружено, что развитие речевых нарушений зависит не только от самого факта повреждения мозговых структур, но и от выраженной функциональной перестройки как отдельных нейронных сетей, вовлеченных в реализацию мозговой функции, так и всего речевого коннектома. Наиболее благоприятным вариантом афазий, вероятно, можно считать заболевание с преобладанием моторных нарушений, демонстрировавшее возможность передачи функций на префронтальные структуры интактного полушария, в то время как сенсорные нарушения представляли глобальные изменения всего речевого коннектома.

Ключевые слова: электроэнцефалография, речевая функция, мозговые ритмы, диагностика, реабилитация, мозговой инсульт, афазия

Вклад авторов: все авторы внесли равнозначный вклад в данное исследование.

Соблюдение этических стандартов: исследование одобрено на основании договора ИФИБ НИЯУ МИФИ и ООО «Клиника Ла Салюте» (протокол № 09-01/23 от 09 января 2023 г.) и этическим комитетом НИЯУ МИФИ (протокол от 25 мая 2023 г.), проведено в соответствии с принципами биомедицинской этики, сформулированными в Хельсинкской декларации 1964 г. и ее последующих обновлениях.

✉ **Для корреспонденции:** Сергей Александрович Гуляев
Раменки, д. 31, к. 136, г. Москва, 119607, Россия; s.gulyaev73@gmail.com

Статья получена: 20.06.2023 **Статья принята к печати:** 22.07.2023 **Опубликована онлайн:** 13.08.2023

DOI: 10.47183/mes.2023.025

Speech represents a higher cognitive function closely linked to the person’s integration into society, that is why speech impairment is among severe conditions resulting in profound social maladaptation and therefore worsening the outcome of rehabilitation.

The first research into post-stroke aphasia reported by P. Broca and C. Wernicke revealed the major speech centers of the human brain and paved the way to the disorder objective diagnosis [1, 2]. In 1980s, the doctrine of two-stream model providing the basis for the functional speech connectome, which made it possible to objectively assess the aphatic disorders diversity and explain the features of speech function rehabilitation in the post-stroke period, was developed based on the new data obtained using the dynamically developing magnetic resonance imaging techniques [3]. It was this theory that triggered an interest in monitoring the subdominant hemisphere prefrontal cortical structures' involvement in the process of speech function restoration [4, 5], thereby allowing the group of European experts to recommend the use of neurostimulation applied to these areas as one of the rehabilitation methods aimed at restoring speech in the post-stroke period [6].

However, determining the features of speech organization is currently a major technological challenge posed by the characteristics of modern medical equipment. The widely used method of functional magnetic resonance imaging (fMRI) demonstrates the changes in the nervous tissue oxygen consumption resulting from the increase in metabolic activity associated with the nervous tissue excitation, which lead to the pronounced temporal delay preventing recording of the characteristics of information transmission between various nerve centers responsible for speech function realization.

This is especially important in the context of post-stroke speech impairment rehabilitation [7], since the patient-centered approach to the lost function restoration is more effective than the use of standardized and formalized technologies.

The synaptic connection activity recording that forms the basis of electroencephalography (EEG) and magnetoencephalography (MEG) makes it possible to reveal rapid excitation processes. However, MEG systems are not mainstream enough yet and are virtually non-existent in the clinics. Furthermore the existing EEG technique that is based on the principles proposed by H. Jasper in 1940–1954 [8] has some serious technical limitations hampering assessment of activity in distinct brain structures. These limitations are related to the visual and phenomenological analysis technology not allowing one to obtain information about the association between the recorded activity and the brain's anatomical structures comparable to that provided by neuroimaging methods, since the technology deals only with the total activity values of multiple nervous system structures.

However, the concept of EEG microstates is considered to be a solution. In 1998, D. Lehmman identified certain overall scalp potential variants and concluded that electrical activity of the brain detected by routine EEG could be represented by the repeating sequence of individual fixed time patterns of biopotential distribution over the scalp related to the activity of some finite number of neural networks producing rhythmic activity within a limited period of time [9, 10]. It was also concluded that the duration of single microstate could be interpreted as an indicator of the underlying neuronal assembly preservation and stability, while frequency of occurrence could be interpreted as activity (activation) of the underlying neural generators during execution of certain brain function. Further investigation of this phenomenon showed that four most representative configurations belonged to the EEG microstate classes A, B, C, D and were related to the activity of the brain's default mode network structures, while changes in external verbal conditions affected the duration, occurrence and coverage of microstates due to involvement of other neuronal pools related to realization of the overall function of the brain [11, 12].

Subsequent research has confirmed that measurement of EEG microstates is sensitive to the neuronal activity changes in the cortical areas responsible for modality-specific processing via certain tasks (state-dependent effects) [13]. Assessment of intersubjective and intrasubjective relationships between the features of microstates in 29 healthy subjects has shown that the dynamics of microstates can reflect transitions between the global states characterized by selective inhibition of certain intracortical areas and have functional and behavioral effects on sensory processing and cognitive functions [14]. In 2021, the use of similar technique in the subjects being in the wakeful rest state made it possible to conclude that memories were consolidated by the brain mainly during the "offline" periods, when an individual was not engaged in task execution and when his/her attention was not focused on executing certain task [15].

The above reports allowed one to formulate the concept of using the EEG microstate model as a tool to help identify distinct components of the entire continuous EEG recording that were associated with the functional activity of certain neuronal groups. However, identification of spatial relationships between certain EEG microstates and anatomical structures these were produced by was still an outstanding issue.

In 1994–1997, the EEG inverse problem solution system was proposed that was based on the technique involving matching the dipole localization and the layered head model that was referred to as low resolution electromagnetic tomography (LORETA) and solved the problem of the EEG signal source cortical localization. Starting from 1999, the method was supplemented by quantitative neuroanatomy based on the digitized Talairach Atlas provided by the Brain Imaging Centre of the Montreal Neurological Institute (MNI). The combination of these innovations brought LORETA to the level comparable to that of conventional functional imaging methods, such as PET and fMRI [12, 16]. In 2008, it was shown that LORETA provided the best solution for single source localization in terms of both zero localization error and false sources compared to other software products using similar techniques to solve the EEG inverse problem [17]. In 2014, simultaneous fMRI-EEG studies aimed at determining the relationship between the default mode network (DMN) activity and the power of the EEG frequency bands suggested that the LORETA technique used to determine the EEG power of the alpha, beta, delta, and theta frequency bands in the region of interest helped reveal a close relationship between the spontaneous BOLD fluctuations in the brain's default mode networks and various EEG rhythms. The use of the technique also suggests that individual neural network is characterized by specific "electrophysiological signature" produced by the combination of various brain rhythms [18]. However, as early as in 2010, the differences in organization of stimulation paradigms used in EEG and fMRI experiments were noted, and the question arose whether it was possible to effectively localize the evoked EEG activity using the constantly changing intensity of the features occurring in the natural stimuli presented within rather long time periods. In particular, there was a question whether the aspects of the stimulus-driven EEG signal would be localized along with appropriate fMRI BOLD signal [19]. Today, EEG source reconstruction includes the process, in which the best results are achieved using conditional functional models [20] resembling the technique proposed in 2014 [21], in which the number of conditional neural networks involved in realization of the studied function would be comparable with the number and activity of microstates identified during the EEG test.

Thus, the current development of EEG analysis technologies makes it possible to obtain a new tool for exploration of the brain cortical structures' functional activity that can be used to assess the status of higher neural functions, such as speech, and determine the possibility of function restoration in individuals with various types of speech impairment developed due to the disease [22, 23].

The study was aimed to determine the functional activity of individual neural networks based on the theory of combining the EEG microstate identification technique with the method of determining spatial localization by solving the EEG inverse problem in individuals with speech function impairment due to acute cerebrovascular accident.

METHODS

A total of 27 individuals (15 males and 12 females) were assessed, who contacted La Salute Clinic for treatment and rehabilitation after ischemic (atherothrombotic) stroke in the area supplied by the left middle cerebral artery that was followed by the development of persistent neurological deficit (cerebral stroke), one of the syndromes of which was aphasia. Inclusion criteria: Russian speakers with the left hemisphere dominance confirmed by the development of post-stroke aphasia; no problems with speech production before the disease.

Exclusion criteria for the study group: traumatic brain injury with functional impairment, mental disorder; constant use of psychoactive substances (ongoing or prior); verified diagnosis of epilepsy; dysarthria due to neurological disorder.

As a result, the study group included individuals with an average age of 52 years (minimum — 21 years, maximum — 68 years; Mo — 49 years, Me — 54 years; 1st quartile — 46 years, 3rd quartile — 61 years). In all of them both the fact of damage to speech connectome and the speech disorder with predominance of motor, sensory or total (mixed) speech impairment itself (motor variant of the disorder was found in 11 subjects, 9 subjects had a sensory variant, while in 7 subjects we failed to identify the aphasic disorder predominant type) were considered. No epileptic seizures were reported in the surveyed patients, no specific epileptiform activity in perifocal areas of the cerebral infarction lesion was recorded. The degree of functional impairment according to the Rankin scale did not exceed 3 in all patients.

All participants underwent an EEG at relative rest (passive relaxed wakefulness with no auditory-speech load) and under a load (listening to a short story in the passive relaxed wakefulness state with eyes closed). A total of 54 tests were performed, and the results were used for further analysis.

Characteristics of methods

The T1-weighted and T2-weighted MRI in the suppression and diffusion nodes showed that the average lesion volume was 82 cm3 (Me — 30.8; 1st quartile — 1, 3rd quartile — 176). EEG was recorded in a darkened, relatively soundproof room in the relaxed wakefulness state with eyes closed. Recording was performed using the 52-channel EEG system (Medical Computer Systems, Zelenograd, Russia). The analog-to-digital converter sampling rate was 500 Hz. The tests involved the use of the electrode placement scheme with an average reference allowing one to obtain equal values of the recorded voltage and scalp biopotential. The native signal bandwidth was 0.5–70 Hz, with the inclusion of the 50 Hz notch network filter.

No recording was performed within the first minute after connecting the volunteer to the device in order to suppress physiological artifacts associated with disadaptation and the need to become habituated to the test. The total electrode resistance, impedance, was controlled within the limits of 10 kOm and constantly checked during the entire study in accordance with the manufacturer's guidelines.

The loading test involved assessment under auditory-speech load in the form of listening to one short story (the same for all subjects) in the native language (Russian) taken from the open access online library. This made it possible to create the conditions of the altered state comparable with the passive relaxed wakefulness state based on common characteristics, but determined by activation of only one cognitive function (speech in this case) having a relatively well understood cortical analyzer architecture [24].

The listening test was selected due to minimization of muscle activity and as a test able to activate the maximum number of speech centers including both gnosis centers of speech and the centers responsible for generation of imagined speech.

Subsequent data acquisition, processing, and analysis were performed in several phases. The first phase involved minimization of artifacts. For that the by-standing electrical devices that generated parasitic electromagnetic fields were switched off, interface impedance was controlled, temperature in the room was adjusted, and parasitic movements of the

Table 1. Registration of the EEG activity frequency characteristics over the areas of the main speech centers

	Predominance of motor impaiment			
	Broca's area oscillation frequency (areas 44, 45 on the left)	Wernicke's area oscillation frequency (areas 39, 40 on the left)	Intact hemisphere prefrontal cortex oscillation frequency (areas 8, 9, 10, 11, 12, 13, 14, 24, 25, 32, 44, 45, 46, and 47)	
Average	0	15,6 ± 6,5	19,3 ± 1,9	*
	Predominance of sensory impairment			
	Broca's area oscillation frequency (areas 44,45 on the left)	Wernicke's area oscillation frequency (areas 39,40 on the left)	Intact hemisphere prefrontal cortex oscillation frequency (areas 8, 9, 10, 11, 12, 13, 14, 24, 25, 32, 44, 45, 46, and 47)	
Average	17,0 ±1,2	0	0	*
	Total (mixed) variants			
	Broca's area oscillation frequency (areas 44, 45 on the left)	Wernicke's area oscillation frequency (areas 39, 40 on the left)	Intact hemisphere prefrontal cortex oscillation frequency (areas 8, 9, 10, 11, 12, 13, 14, 24, 25, 32, 44, 45, 46, and 47)	
Average	13,5 ± 2,5	16,3 ± 2,9	18,0 ± 4,6	**

Note: (ANOVA-test), * — $p < 0.001$; ** — $p > 0.05$.

Table 2. Changes in the characteristics of EEG microstates relative to their contribution to formation of the head's overall bioelectric field

Major syndrome	Class/test	A	B	C	D	I	II
Motor	Load	0,04	0,06	0,02	0,05	0,06	0,07
	No load	0,16	0,11	0,12	0,2	0,17	0,24
	p	*	**	*	**	*	*
Sensory	Load	0,22	0,26	0,05	0,21	0,14	0,12
	No load	0,19	0,11	0,12	0,1	0,37	0,11
	p	**	*	**	*	**	**
Total (mixed)	Load	0,18	0,17	0,09	0,05	0,09	0,43
	No load	0,23	0,13	0,26	0,11	0,09	0,18
	p	**	**	*	**	**	**

Note: *t*-test, * — $p < 0.05$; ** — $p > 0.05$.

muscles were minimized. During the second phase the resulting data pool was subjected to standardization of basic assembly to create a common electrode space, as well as to artifact removal via extraction of independent signal components. This made it possible to purify the native signal of various physiological artifacts that had not been eliminated by filtration. During the third phase the EEG signal segmentation was performed to extract individual EEG microstates by clustering and allocating six classes of individual microstates (conventional A, B, C, D and two (I and II) extra ones, considering of their variability). The final phase of the study involved analysis of the activity source localization for each of the allocated EEG microstate classes using the EEG inverse problem solution algorithm implemented in the sLORETA v. 20210701 software package (University of Zurich; Switzerland).

The results provided information about six distinct classes of EEG microstates, including the following characteristics: 1) microstate lifetime (duration) in seconds; 2) frequency of microstate recording per 1 s (occurrence); 3) contribution of EEG microstate to the structure of the scalp energy total energy spectral characteristics (coverage); 4) localization of the main cortical structure generating the EEG microstate according to the Brodmann area atlas (atlas issued by the Montreal Neurological Institute, MNI).

Statistical processing of the results was performed in accordance with the earlier reported guidelines [25] using the GNU-PSPP software (v. GNU PSPP ver. 1.6.2-g78a33a) for OC Linux Mate 10.10. The Shapiro–Wilk normality test, Pearson correlation coefficients, and analysis of variance (ANOVA) with Bonferroni correction for the small number of independent samples were used. The Student's t-test was used for paired samples with normal distribution. The same degree of freedom was used for all calculations, the significance level was set as $\alpha < 0.05$.

RESULTS

Changes in frequency characteristics of EEG signal recorded over the main speech centers

The results of rhythmic activity localization over the areas of the main speech centers identified by spatial fixation of the EEG electrodes' position matched the characteristics of anatomic lesion, patient's diagnosis and MRI findings (Table 1). An EEG test involving the use of the technology for extraction of individual EEG microstates combined with the EEG inverse problem solution showed that it was impossible to record rhythmic phenomena over the affected areas of individuals with severe anatomical defects since the area's neural network was disrupted, and the rhythmic phenomena, specifically those recorded in slow activity ranges, were reduced by the tissues surrounding the primary focus. At the same time, in cases of the dominant hemisphere Broca's area (areas 44,

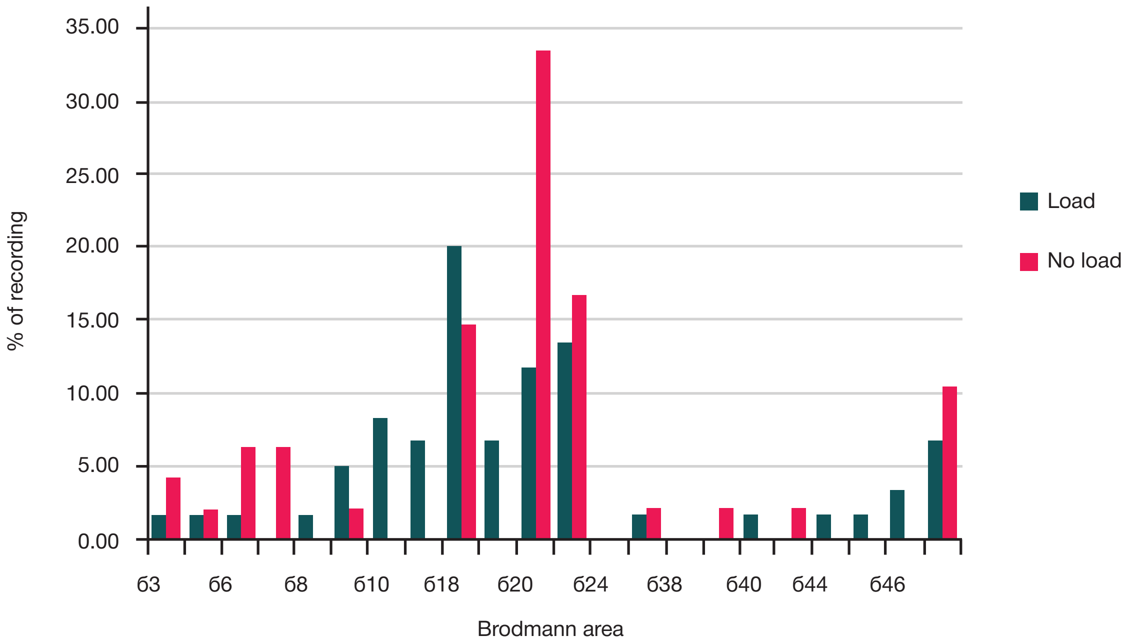

Fig. 1. Histogram of EEG activity (in %) over individual Brodmann areas in cases of motor aphasic disorder variant predominance, $p < 0.05$ (Pearson's test)

Table 3. Changes in the characteristics of EEG microstates relative to their frequency of occurrence per 1 s

Major syndrome	Class/test	A	B	C	D	I	II
Motor	Load	3,2	3,4	1,9	1	2,4	3,3
	No load	2,3	1,9	3	3	4,4	3,1
	p	**	**	**	**	**	**
Sensory	Load	4,3	4,7	1	5,8	4,3	2,3
	No load	30,2	15,7	19,6	18,6	30,2	20,8
	p	*	*	*	*	*	*
Total (mixed)	Load	2,5	1,8	2,2	1,3	2,8	5,3
	No load	36,8	46,7	50,3	44,5	33,8	26,5
	p	*	**	*	**	*	**

Note: *t*-test, * — $p < 0.05$; ** — $p > 0.05$.

45) anatomical disruption, the expected changes in rhythmic activity were recorded over the intact hemisphere prefrontal cortical structures. Such activity was observed in the same frequency range (17–24 Hz); it showed signs of activation response to auditory-speech load (Fig. 1). However, as stated above, it was almost diffuse and arouse in all structures of the intact hemisphere prefrontal cortex (areas 8, 9, 10, 11, 12, 13, 14, 24, 25, 32, 44, 45, 46 и 47).

A lesion in the Wernicke's area (Fig. 2) and disruption of sensory areas (39, 40) made it impossible to identify rhythmic phenomena over the Wernicke's area, which was expected due to neural network disruption in this area, and the intact hemisphere structures. Rhythmic EEG phenomena were recorded over the Broca's area only, however, there was no activation response to speech-auditory load.

In individuals with the total (mixed) variant of impairment (Fig. 3), rhythmic phenomena arose in the affected hemisphere over both Broca's and Wernicke's areas, but these findings had low significance (ANOVA test > 0.05), which suggested incomplete injury of both major speech centers. However, low significance resulted probably from limitations of both applied technique and relatively low number of observations.

Charasteristics of distinct EEG microstates

Analysis of the EEG microstate characteristics under auditory-speech load allowed us to find out that these characteristics showed significant differences ($p < 0.05$) in their contributions to overall scalp potential (except for classes B and D) in individuals with predominant motor aphasia. At the same time, in individuals with sensory aphasia, this indicator, by contrast, showed a significant response to the load. In individuals with total aphasia, significant differences were reported for class C only (Tables 2–4), which was considered as a sign of both structural damage to certain neuronal assemblies and information processing disorder prevailing in cases of sensory aphasia.

There were no significant responses to the loading test in terms of occurrence and duration of individual EEG microstates in individuals with motor impairment, however, individuals with prevailing sensory or total impairment showed significant changes of these characteristics, especially in cases of sensory impairment (for almost all indentified classes) and cases of total impairment (for classes A and I).

DISCUSSION

Interpretation of the data obtained needs to be further discussed. Thus, splitting the entire continuous EEG recording into a sequence of individual EEG microstates allows the researcher not only to consider common characteristics of total postsynaptic activity, but also to indentify distinct components of such activity associated with the activity of individual neural structures, thereby making it possible to create an affordable

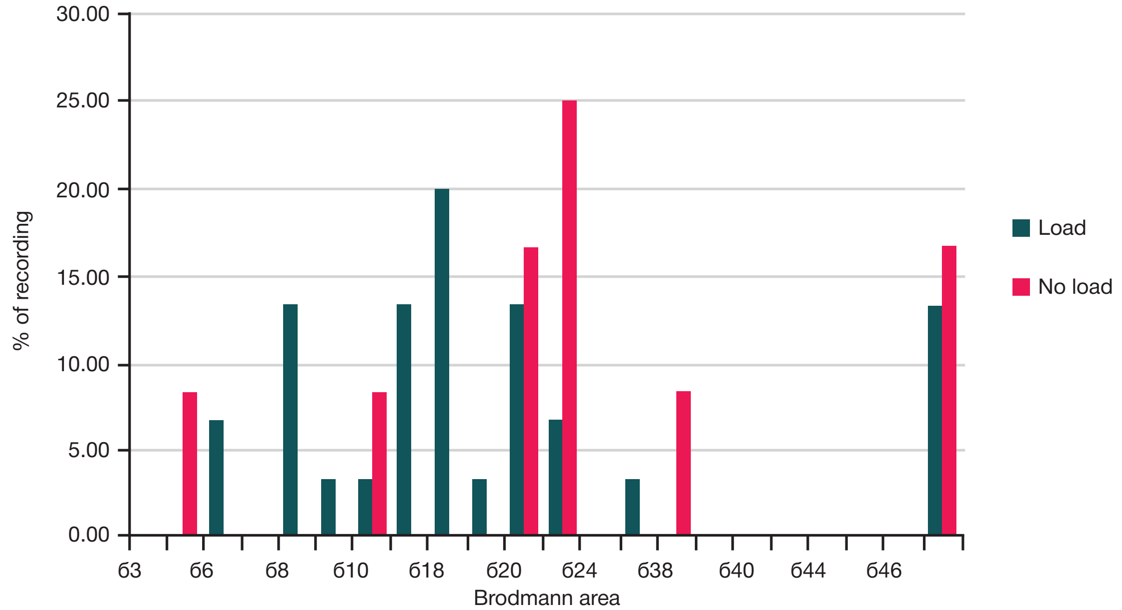

Fig. 2. Histogram of EEG activity (in %) over individual Brodmann areas in cases of sensory aphasic disorder variant predominance, $p < 0.05$ (Pearson's test)

Table 4. Changes in the characteristics of EEG microstates relative to their duration in 1 s

Major syndrome	Class/test	A	B	C	D	I	II
Motor	Load	0,04	0,06	0,02	0,05	0,06	0,07
	No load	0,05	0,04	0,03	0,05	0,04	0,07
	p	**	**	**	**	**	**
Sensory	Load	0,05	0,06	0,04	0,04	0,03	0,04
	No load	0,01	0,01	0,01	0,01	0,01	0,01
	p	**	*	**	*	**	**
Total (mixed)	Load	0,06	0,08	0,05	0,04	0,03	0,1
	No load	0,02	0,01	0,02	0,01	0,01	0,02
	p	*	*	**	**	*	**

Note: *t*-test, * — $p < 0.05$; ** — $p > 0.05$.

system for neurophysiological diagnosis of certain brain functions, particularly speech [26].

The study results obtained by conducting the functional loading test involving listening for different variants of aphasia show differences in both nature of rhythmic phenomena recorded on the scalp surface and spatial localization of these phenomena, which can be interpreted from the perspective of consistent various neural networks' participation in the speech function realization [13].

The development of speech impairment resulting from cerebral stroke is due to both infarction affecting various brain structures [7] and functional rearrangement of the neural networks system, which is reflected by changes in the EEG microstate characteristics [14] that may become the key factors to assess objectively the speech functional state and the changes in speech function resulting from the disorder. In our study this was confirmed by changes in characteristics of individual EEG microstates.

Thus, in cases of predominant motor impairment (preserved auditory information receipt systems), was observed the transfer of the speech production function to the intact hemisphere prefrontal cortex. But this answer was presented as the general response observed over the entire surface of the prefrontal cortex, not only within the limits of the well-formed neural centers (44, 45 Brodman's fields).

In sensory variant of aphasia, the changes in bioelectrical activity showed no variants of transferring the affected function to the contralateral (intact) hemisphere, which was manifested in identification of non-specific rhythmic phenomena, and demonstrated disruption of the sequence of class C and D EEG microstates that was considered to be associated with the structures responsible for tertiary information processing in tertiary areas (Brodmann's areas 6 and 7) [24, 27]. That is why sensory variant of aphasia could be characterized not only as profound impairment of certain brain networks' activity, but also as a more severe damage to the entire connectome system affecting both ventral stream responsible for information acquisition and the lateral one responsible for processing and comprehension. However, total variants of aphasia were associated with the less pronounced changes; the EEG microstate analysis revealed predominant involvement of the speech ventral stream structures and preserved tertiary structures responsible for constructive analysis [28].

In all cases of aphasia, the most interesting was the activity increase over the Brodmann areas 47 and, consequently, 37, showing maximum representation in individuals with predominant sensory aphasia. Their activity suggests involvement of phylogenetically older mechanisms underlying auditory tone perception that are found in children aged 2–5 and apes. This leads to the assumption that conventional system of phonemes and morphemes, the speech function can be replaced by the system of auditory tone perception and musical tone (onomatopoetic) reproduction, as reported in the number of studies focused on rehabilitation of feral

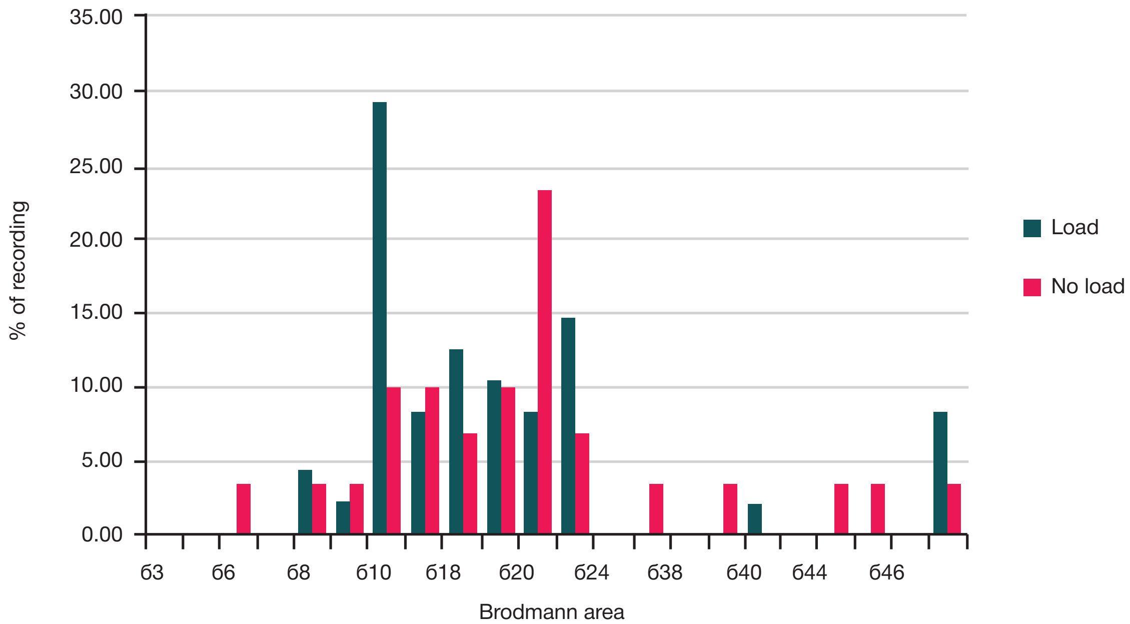

Fig. 3. Histogram of EEG activity (in %) in cases of total (mixed) aphasic disorder variant predominance, $p < 0.05$ (Pearson's test)

children and children with autism spectrum disorders, who failed to develop a normal human speech system [29, 30].

Limitations of the study

The study limitations are related to a relatively small number of observations (27 individuals) forcing us to adjust statistical data when performing calculations, as well as to the features of EEG technique applied associated with the scalp electrode positioning. The use of the medium-density EEG montage (10–10 system) did not put any meaningful restrictions relative to the 10–5 system or any other high-density EEG system, since it enabled acquisition of native data with the lower number of nonspecific physical artifacts occurring in high-density systems due to short interelectrode distances.

CONCLUSIONS

The study has shown that recording of the brain bioelectrical activity using modern computing power and mathematical methods optimization allows one to record individual bioelectrical phenomena closely related to the distinct brain structures' responses to the presented functional load. This opens up new prospects for creating diagnostic systems to study functional links between distinct higher nervous functions. Today, affordability is one of the benefits of the proposed method, since modern digital EEG does not require expensive equipment or maintenance provided by special repair and engineering units. Furthermore, it is not demanding to housing conditions, which enables its wide introduction in both research centers and medical institutions providing treatment and rehabilitation services to the population. The proposed brain bioelectrical activity processing system can provide the basis for the development of new diagnostic systems for human thought processes assessment, thereby allowing to expand the human body capabilities in the context of growing perceived information amount, as well as to provide new approaches to rehabilitation of higher nervous functions impaired due to the disease.

References

1. Broca P. Remarks on the Seat of Spoken Language, Followed by a Case of Aphasia (1861). Neuropsychology Review. 2011; 21 (3) 15: 227–9. Available from: https://doi.org/ 10.1007/s11065-011-9174-x.
2. Wernicke C. Grundriss der Psychiatrie in klinischen Vorlesungen. Theil II, Die paranoischen Zustände. Leipzig: Verlag von Georg Thieme. American Journal of Psychiatry.1897; 53 (4): 581–3. Available from: https://doi.org/ 10.1176/ajp.53.4.581.
3. Mishkin M Ungerleider LG Contribution of striate inputs to the visuospatial functions of parieto-preoccipital cortex in monkeys. Behav Brain Res. 1982; 6 (1): 57–77. Available from: https://doi.org/10.1016/0166-4328(82)90081-x.
4. Sul B, Kim JS, Hong BY, Lee KB, Hwang WS, Kim YK, et al. The Prognosis and Recovery of Aphasia Related to Stroke Lesion. Ann Rehabil Med. 2016; 40 (5): 786–93. Available from: https://doi.org/ 10.5535/arm.2016.40.5.786.
5. Harvey DY, Podell J, Turkeltaub PE, Faseyitan O, Coslett HB, Hamilton RH. Functional Reorganization of Right Prefrontal Cortex Underlies Sustained Naming Improvements in Chronic Aphasia via Repetitive Transcranial Magnetic Stimulation. Cogn Behav Neurol. 2017; 30 (4): 133–44. Available from: https://doi.org/ 10.1097/WNN.0000000000000141.
6. Lefaucheur JP, Antal A, Ayache SS, Benninger DH, Brunelin J, Cogiamanian F, et al. Evidence-based guidelines on the therapeutic use of transcranial direct current stimulation (tDCS). Clin Neurophysiol. 2017; 128 (1): 56–92. Available from: https://doi.org/ 10.1016/j.clinph.2016.10.087.
7. Lefaucheur JP, Aleman A, Baeken C, Benninger DH, Brunelin J, Di Lazzaro V, et al. Evidence-based guidelines on the therapeutic use of repetitive transcranial magnetic stimulation (rTMS): An update (2014–2018). Clin Neurophysiol. 2020; 131 (2): 474–528. Available from: https://doi.org/ 10.1016/j.clinph.2019.11.002.
8. Penfield W, Roberts L. Speech and Brain Mechanisms Princeton University Press, 2014, 302 p. Available from: https://doi.org/10.1515/9781400854677.192.
9. Michel CM, Koenig T. EEG microstates as a tool for studying the temporal dynamics of whole-brain neuronal networks: A review. Neuroimage. 2018; 180 (Pt B): 577–93. Available from: https://doi.org/ 10.1016/j.neuroimage.2017.11.062.
10. Mishra A, Englitz B, Cohen MX. EEG microstates as a continuous phenomenon. Neuroimage. 2020; 208: 116454. Available from: https://doi.org/ 10.1016/j.neuroimage.2019.116454. Epub 2019 Dec 10.
11. Milz P, Faber PL, Lehmann D, Koenig T, Kochi K, Pascual-Marqui RD. The functional significance of EEG microstates--Associations with modalities of thinking. Neuroimage. 2016; 125: 643–56. Available from: https://doi.org/ 10.1016/j.neuroimage.2015.08.023.
12. Milz P, Pascual-Marqui RD, Lehmann D, Faber PL. Modalities of Thinking: State and Trait Effects on Cross-Frequency Functional Independent Brain Networks. Brain Topogr. 2016; 29 (3): 477–90. Available from: https://doi.org/ 10.1007/s10548-016-0469-3.
13. Seitzman BA, Abell M, Bartley SC, Erickson MA, Bolbecker AR, Hetrick WP. Cognitive manipulation of brain electric microstates. Neuroimage. 2017; 146: 533–43. Available from: https://doi.org/ 10.1016/j.neuroimage.2016.10.002.
14. Croce P, Quercia A, Costa S, Zappasodi F. EEG microstates associated with intra- and inter-subject alpha variability. Sci Rep. 2020; 10 (1): 2469. Available from: https://doi.org/ 10.1038/s41598-020-58787-w.
15. Poskanzer C, Denis D, Herrick A, Stickgold R. Using EEG microstates to examine post-encoding quiet rest and subsequent word-pair memory. Neurobiol Learn Mem. 2021; 181: 107424. Available from: https://doi.org/ 10.1016/j.nlm.2021.107424.
16. Pascual-Marqui RD, Esslen M, Kochi K, Lehmann D. Functional imaging with low-resolution brain electromagnetic tomography (LORETA): a review. Methods Find Exp Clin Pharmacol. 2002; 24 Suppl C: 91–5. PMID: 12575492.
17. Grech R, Cassar T, Muscat J, Camilleri KP, Fabri SG, Zervakis M, et al. Review on solving the inverse problem in EEG source analysis. J Neuroeng Rehabil. 2008; 5: 25. Available from: https://doi.org/ 10.1186/1743-0003-5-25.
18. Neuner I, Arrubla J, Werner CJ, Hitz K, Boers F, Kawohl W, et al. The default mode network and EEG regional spectral power: a simultaneous fMRI-EEG study. PLoS One. 2014; 9 (2): e88214. Available from: https://doi.org/ 10.1371/journal.pone.0088214.
19. Whittingstall K, Bartels A, Singh V, Kwon S, Logothetis NK. Integration of EEG source imaging and fMRI during continuous viewing of natural movies. Magn Reson Imaging. 2010; 28 (8): 1135–42. Available from: https://doi.org/ 10.1016/j.mri.2010.03.042.
20. Abreu R, Soares JF, Lima AC, Sousa L, Batista S, Castelo-Branco M, et al. Optimizing EEG Source Reconstruction with Concurrent fMRI-Derived Spatial Priors. Brain Topogr. 2022; 35 (3): 282–301. Available from: https://doi.org/ 10.1007/s10548-022-00891-3. Epub 2022 Feb 10.
21. Thatcher RW, North DM, Biver CJ. LORETA EEG phase reset of the default mode network. Front Hum Neurosci. 2014; 8: 529. Available from: https://doi.org/ 10.3389/fnhum.2014.00529.
22. Gulyaev SA. EEG Microstate Analysis and the EEG Inverse Problem

Solution as a Tool for Diagnosing Cognitive Dysfunctions in Individuals Who Have Had a Mild Form of COVID-19. Hum Physiol. 2022; 48 (5): 587–597. DOI: 10.1134/S0362119722600217. Epub 2022 Oct 13. PMID: 36258795; PMCID: PMC9559548.

23. Gulyaev SA. Neurophysiological Solution of the Inverse Problem of EEG Research at Rest and under Conditions of Auditory-Speech Load. J Evol Biochem Phys. 2022; 58: 585–97. Available from: https://doi.org/10.1134/S0022093022020259
24. Johnson F, Beeke S, Best W. Searching for active ingredients in rehabilitation: applying the taxonomy of behaviour change techniques to a conversation therapy for aphasia. Disabil Rehabil. 2021; 43 (18): 2550–60. Available from: https://doi.org/ 10.1080/09638288.2019.1703147.
25. Sarter M, Fritschy JM. Reporting statistical methods and statistical results in EJN. Eur J Neurosci. 2008; 28 (12): 2363–4. Available from: https://doi.org/10.1111/j.1460-9568.2008.06581.x.
26. Gulyaev SA, Lelyuk VG. Neurophysiological isolation of individual rhythmic brain activity arising from auditory-speech load. Brain Netw Modul. 2023; 2 (2): 47–52. Available from: https://doi.org/ 10.4103/2773-2398.379340.
27. Seitzman BA, Abell M, Bartley SC, Erickson MA, Bolbecker AR, Hetrick WP. Cognitive manipulation of brain electric microstates. Neuroimage. 2017; 146: 533–43. Available from: https://doi.org/ 10.1016/j.neuroimage.2016.10.002. Epub 2016 Oct 11.
28. Poskanzer C, Denis D, Herrick A, Stickgold R. Using EEG microstates to examine post-encoding quiet rest and subsequent word-pair memory. Neurobiol Learn Mem. 2021; 181: 107424. Available from: https://doi.org/ 10.1016/j.nlm.2021.107424. Epub 2021 Mar 22.
29. Zuk NJ, Murphy JW, Reilly RB, Lalor EC. Envelope reconstruction of speech and music highlights stronger tracking of speech at low frequencies. PLoS Comput Biol. 2021; 17 (9): e1009358. Available from: https://doi.org/ 10.1371/journal.pcbi.1009358.
30. Schoen SA, Lane SJ, Mailloux Z, May-Benson T, Parham LD, Smith Roley S, et al. A systematic review of ayres sensory integration intervention for children with autism. Autism Res. 2019; 12 (1): 6–19. DOI: 10.1002/aur.2046. Epub 2018 Dec 12. PMID: 30548827; PMCID: PMC6590432.

Литература

1. Broca P. Remarks on the Seat of Spoken Language, Followed by a Case of Aphasia (1861). Neuropsychology Review. 2011; 21 (3) 15: 227–9. Available from: https://doi.org/ 10.1007/s11065-011-9174-x.
2. Wernicke C. Grundriss der Psychiatrie in klinischen Vorlesungen. Theil II, Die paranoischen Zustände. Leipzig: Verlag von Georg Thieme. American Journal of Psychiatry.1897; 53 (4): 581–3. Available from: https://doi.org/ 10.1176/ajp.53.4.581.
3. Mishkin M Ungerleider LG Contribution of striate inputs to the visuospatial functions of parieto-preoccipital cortex in monkeys. Behav Brain Res. 1982; 6 (1): 57–77. Available from: https://doi.org/10.1016/0166-4328(82)90081-x.
4. Sul B, Kim JS, Hong BY, Lee KB, Hwang WS, Kim YK, et al. The Prognosis and Recovery of Aphasia Related to Stroke Lesion. Ann Rehabil Med. 2016; 40 (5): 786–93. Available from: https://doi.org/ 10.5535/arm.2016.40.5.786.
5. Harvey DY, Podell J, Turkeltaub PE, Faseyitan O, Coslett HB, Hamilton RH. Functional Reorganization of Right Prefrontal Cortex Underlies Sustained Naming Improvements in Chronic Aphasia via Repetitive Transcranial Magnetic Stimulation. Cogn Behav Neurol. 2017; 30 (4): 133–44. Available from: https://doi.org/ 10.1097/WNN.0000000000000141.
6. Lefaucheur JP, Antal A, Ayache SS, Benninger DH, Brunelin J, Cogiamanian F, et al. Evidence-based guidelines on the therapeutic use of transcranial direct current stimulation (tDCS). Clin Neurophysiol. 2017; 128 (1): 56–92. Available from: https://doi.org/ 10.1016/j.clinph.2016.10.087.
7. Lefaucheur JP, Aleman A, Baeken C, Benninger DH, Brunelin J, Di Lazzaro V, et al. Evidence-based guidelines on the therapeutic use of repetitive transcranial magnetic stimulation (rTMS): An update (2014–2018). Clin Neurophysiol. 2020; 131 (2): 474–528. Available from: https://doi.org/ 10.1016/j.clinph.2019.11.002.
8. Пенфильд В., Робертс Л. Речь и мозговые механизмы. М.: Медицина, 1964; 260 с.
9. Michel CM, Koenig T. EEG microstates as a tool for studying the temporal dynamics of whole-brain neuronal networks: A review. Neuroimage. 2018; 180 (Pt B): 577–93. Available from: https://doi.org/ 10.1016/j.neuroimage.2017.11.062.
10. Mishra A, Englitz B, Cohen MX. EEG microstates as a continuous phenomenon. Neuroimage. 2020; 208: 116454. Available from: https://doi.org/ 10.1016/j.neuroimage.2019.116454. Epub 2019 Dec 10.
11. Milz P, Faber PL, Lehmann D, Koenig T, Kochi K, Pascual-Marqui RD. The functional significance of EEG microstates--Associations with modalities of thinking. Neuroimage. 2016; 125: 643–56. Available from: https://doi.org/ 10.1016/j.neuroimage.2015.08.023.
12. Milz P, Pascual-Marqui RD, Lehmann D, Faber PL. Modalities of Thinking: State and Trait Effects on Cross-Frequency Functional Independent Brain Networks. Brain Topogr. 2016; 29 (3): 477–90. Available from: https://doi.org/ 10.1007/s10548-016-0469-3.
13. Seitzman BA, Abell M, Bartley SC, Erickson MA, Bolbecker AR, Hetrick WP. Cognitive manipulation of brain electric microstates. Neuroimage. 2017; 146: 533–43. Available from: https://doi.org/ 10.1016/j.neuroimage.2016.10.002.
14. Croce P, Quercia A, Costa S, Zappasodi F. EEG microstates associated with intra- and inter-subject alpha variability. Sci Rep. 2020; 10 (1): 2469. Available from: https://doi.org/ 10.1038/ s41598-020-58787-w.
15. Poskanzer C, Denis D, Herrick A, Stickgold R. Using EEG microstates to examine post-encoding quiet rest and subsequent word-pair memory. Neurobiol Learn Mem. 2021; 181: 107424. Available from: https://doi.org/ 10.1016/j.nlm.2021.107424.
16. Pascual-Marqui RD, Esslen M, Kochi K, Lehmann D. Functional imaging with low-resolution brain electromagnetic tomography (LORETA): a review. Methods Find Exp Clin Pharmacol. 2002; 24 Suppl C: 91–5. PMID: 12575492.
17. Grech R, Cassar T, Muscat J, Camilleri KP, Fabri SG, Zervakis M, et al. Review on solving the inverse problem in EEG source analysis. J Neuroeng Rehabil. 2008; 5: 25. Available from: https://doi.org/ 10.1186/1743-0003-5-25.
18. Neuner I, Arrubla J, Werner CJ, Hitz K, Boers F, Kawohl W, et al. The default mode network and EEG regional spectral power: a simultaneous fMRI-EEG study. PLoS One. 2014; 9 (2): e88214. Available from: https://doi.org/ 10.1371/journal.pone.0088214.
19. Whittingstall K, Bartels A, Singh V, Kwon S, Logothetis NK. Integration of EEG source imaging and fMRI during continuous viewing of natural movies. Magn Reson Imaging. 2010; 28 (8): 1135–42. Available from: https://doi.org/ 10.1016/j.mri.2010.03.042.
20. Abreu R, Soares JF, Lima AC, Sousa L, Batista S, Castelo-Branco M, et al. Optimizing EEG Source Reconstruction with Concurrent fMRI-Derived Spatial Priors. Brain Topogr. 2022; 35 (3): 282–301. Available from: https://doi.org/ 10.1007/s10548-022-00891-3. Epub 2022 Feb 10.
21. Thatcher RW, North DM, Biver CJ. LORETA EEG phase reset of the default mode network. Front Hum Neurosci. 2014; 8: 529. Available from: https://doi.org/ 10.3389/fnhum.2014.00529.
22. Gulyaev SA. EEG Microstate Analysis and the EEG Inverse Problem Solution as a Tool for Diagnosing Cognitive Dysfunctions in Individuals Who Have Had a Mild Form of COVID-19. Hum Physiol. 2022; 48 (5): 587–597. DOI: 10.1134/S0362119722600217. Epub 2022 Oct 13. PMID: 36258795; PMCID: PMC9559548.
23. Gulyaev SA. Neurophysiological Solution of the Inverse Problem of EEG Research at Rest and under Conditions of Auditory-Speech Load. J Evol Biochem Phys. 2022; 58: 585–97. Available from: https://doi.org/10.1134/S0022093022020259
24. Johnson F, Beeke S, Best W. Searching for active ingredients in rehabilitation: applying the taxonomy of behaviour change

techniques to a conversation therapy for aphasia. Disabil Rehabil. 2021; 43 (18): 2550–60. Available from: https://doi.org/10.1080/09638288.2019.1703147.

25. Sarter M, Fritschy JM. Reporting statistical methods and statistical results in EJN. Eur J Neurosci. 2008; 28 (12): 2363–4. Available from: https://doi.org/10.1111/j.1460-9568.2008.06581.x.
26. Gulyaev SA, Lelyuk VG. Neurophysiological isolation of individual rhythmic brain activity arising from auditory-speech load. Brain Netw Modul. 2023; 2 (2): 47–52. Available from: https://doi.org/10.4103/2773-2398.379340.
27. Seitzman BA, Abell M, Bartley SC, Erickson MA, Bolbecker AR, Hetrick WP. Cognitive manipulation of brain electric microstates. Neuroimage. 2017; 146: 533–43. Available from: https://doi.org/10.1016/j.neuroimage.2016.10.002. Epub 2016 Oct 11.
28. Poskanzer C, Denis D, Herrick A, Stickgold R. Using EEG microstates to examine post-encoding quiet rest and subsequent word-pair memory. Neurobiol Learn Mem. 2021; 181: 107424. Available from: https://doi.org/ 10.1016/j.nlm.2021.107424. Epub 2021 Mar 22.
29. Zuk NJ, Murphy JW, Reilly RB, Lalor EC. Envelope reconstruction of speech and music highlights stronger tracking of speech at low frequencies. PLoS Comput Biol. 2021; 17 (9): e1009358. Available from: https://doi.org/ 10.1371/journal.pcbi.1009358.
30. Schoen SA, Lane SJ, Mailloux Z, May-Benson T, Parham LD, Smith Roley S, et al. A systematic review of ayres sensory integration intervention for children with autism. Autism Res. 2019; 12 (1): 6–19. DOI: 10.1002/aur.2046. Epub 2018 Dec 12. PMID: 30548827; PMCID: PMC6590432.