ISSN 2312-5160

Current Issues of Mass Communication, Issue 27 (2020)

Journal homepage: http://comstudies.org

INTERDISCIPLINARY RESEARCH

https://doi.org/10.17721/2312-5160.2020.27.51-63

UDC 159.91:612.82:57.048

Language-Specific Synchronization of Neural Networks in the Human Brain

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ABSTRACT

This study examines language-specific characteristics of the electric activity in bilinguals' brains. The aim of this study was to evaluate language-specific characteristics of functional connectivity related to the perception of verbal information in different languages. Increasing synchronization of gamma band was detected in the association regions of left hemisphere during the Russian sonnets, alongside with interhemispheric coherence. The increase in synchronization exclusively in the left hemisphere was observed as in the case of English and Ukrainian sonnets. Increase of the coherence was shown in the left lateral and medial supplementary motor area when listening to Russian sonnets in comparison with Ukrainian. Decrease of coherence while listening to the Russian sonnets in comparison with Ukrainian was present in angular gyrus and superior parietal lobule. This evidence could indicate relatively lesser involvement of memory and attention when listening to Russian in comparison with the Ukrainian. Despite high proficiency of the participants, the mechanism of language perception could be different. Perhaps, an emotional response does not depend on the level of knowledge of the language but rather on its phonetic structure and prosody.

KEYWORDS: bilingual, verbal information, perception, EEG, coherence

ISSN 2312-5160

УДК 159.91:612.82:57.048

Мовно-специфічна синхронізація нейронних мереж у мозку людини

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Резюме

У цьому дослідженні розглядаються мовно-специфічні характеристики електричної активності в мозку людей, які володіють двома або більше мовами. **Метою** цього дослідження було оцінити мовно-специфічні характеристики функціональної когерентності, пов'язаної зі сприйняттям словесної інформації різними мовами. Під час прослуховування сонетів російською мовою, поряд з міжпівкульною когерентністю, в регіонах асоціації лівої півкулі було виявлено посилення синхронізації гамма-діапазону. Посилення синхронізації виключно в лівій півкулі спостерігалося як у випадку з сонетами англійською та українською. Підвищення когерентності було продемонстровано в лівій латеральній та медіальній додатковій руховій ділянці при прослуховуванні сонетів російською, порівняно з українською. Зниження когерентності під час прослуховування сонетів російською у порівнянні з українською спостерігалося в кутовій звивині та верхній тім'яній часточці. Ці результати можуть свідчити про відносно меншу участь пам’яті та уваги при слуханні російської мови в порівнянні з українською. Незважаючи на високу кваліфікацію учасників, механізм сприйняття мови може бути іншим. Можливо, емоційна реакція залежить не від рівня знання мови, а від її фонетичної структури та просодії.

Ключові слова: двомовний, словесна інформація, сприйняття, ЕЕГ, когерентність

Introduction

Language serves as a means of creating the conception of the world. It can be assumed that these generalized everyday representations are universal for people of different cultural and linguistic backgrounds, especially if it concerns simple concepts or emotions. By using language, a person expresses thoughts, feelings and emotions. Even if the structures and lexical units of different languages differ from each other, the content of this verbal communication remains unchanged. Globalization, the Mass Media, Internet, migration promote the development of the multilingual and multicultural societies (Abutalebi & Weekes, 2014).

Human beings are able to learn and use more than one language. The interesting fundamental issue of differences between the perception of information in different languages is highly relevant in both psychology and physiology. There is a concept that there are linguistic universals that together constitute a natural semantic metalanguage, and that despite differences in the world perception, there are general constructions, and universal concepts in all languages (Wierzbicka, 1992; 2003). The abstract commonalities of languages with respect to the preference of "short dependencies" are determined by the inherent limitations of effective information processing by the human brain (Fedzechkina, Chu & Florian, 2017). In support of this, there are specific brain regions for language-independent semantic representations of narratives (Dehghani et al, 2017). Other of the main questions of neurolinguistics lies in shared/segregated neural substrates ('language centers') for two or more languages. Gandour and colleagues pointed to a unitary neural system for two languages despite the age of language acquisition (Gandour et al, 2007). Bilinguals are better able to control their attention while performing both linguistic and non-verbal tasks compared to monolinguals. The experience of learning and maintenance of two or more languages with different grammatical and lexical structures allows bilinguals to better formulate an understanding of how the language works, quickly isolate grammatical constructions in unfamiliar languages. Bilinguals have more developed skills in comparison with monolinguals: increased attention control, working memory, metalinguistic awareness, and abstract and symbolic representation skills. Moreover bilingualism is closely related to many cognitive processes, including planning, cognitive flexibility, abstract thinking, highlighting rules, selecting appropriate sensory information, initiating adequate actions and inhibiting inadequate ones (Adesope et al, 2010). However, the need to manage two languages simultaneously can dictate higher requirements for working memory. This suggests that bilingualism can impede the effective processing of information due to cognitive overload imposed on working memory. On the other hand, the well-developed ability of bilinguals to suppress one language while using the other can increase the efficiency of their working memory, since the working memory resources are properly managed by the inhibition mechanism (Bialystok, Craik & Luk, 2008). The cognitive advantage of bilinguals over monolinguals can be explained due to the fact that bilingualism causes experience-related structural changes at level of augmented grey or white matter density in both cortical (the frontal lobes, left inferior parietal lobule, the anterior cingulate cortex) and subcortical (the left caudate and putamen) structures of the executive control network (Abutalebi & Weekes, 2014).

From the neurolinguistics' point of view the question remains open how brain mechanisms specializing in the verbal information processing are consistent with several independent systems and keep them separate. The question should also be considered of how one language interacts with others, depending on the circumstances of the acquisition of each language - the age and time of acquisition, retention and the learning of new lexical elements. Multilingual persons provide an opportunity to test various hypotheses in this direction. Do different languages involve different areas of the brain, at least in part, and do multilingual people have differences in the neural organization of language systems in comparison with monolinguals?

The meta-analysis determined 30 activation clusters and definite functional fields that form the three distributed networks of the temporal and frontal regions and reveal the functional organization of speech in the left hemisphere of the brain (Vigneau et al, 2006). It turned out that the primary auditory and the motor representation of the mouth zones take part both in production and understanding of individual components, creating an elementary audio-motor network. There are overlap zones between phonological and semantic processing, in particular, a zone that selectively analyzes the human voice and is the place of processing of all three components of the language.The region of the posterior part of the inferior frontal gyrus is involved in syntactic processing, and the posterior part of the superior temporal gyrus is selectively activated when processing sentences and text. Based on this, a hypothesis was created that various neural networks are involved in the processing of various components of the language, which proves the existence of a large-scale network as opposed to the modular organization of verbal information in the left hemisphere (Vigneau et al, 2006). Above-mentioned the inferior frontal gyrus performs the role of the semantic hub (encoding, retrieval, and combining semantic content) (Fellner & Hanslmayr, 2017).

A similar meta-analysis on the organization of verbal information in the right hemisphere has shown that most right-hemispheric phonological clusters include auditory and motor cortex in bilateral order (Vigneau et al, 2011). In particular, the motor representation of the mouth and the phonological working memory regions are exclusively left-sided, which confirms the hypothesis that there are no phonological representations in the right hemisphere. The involvement of the right frontal zone is not characteristic for the linguistic component, and it seems that the right frontal zone are associated in a non-specific way with attention and working memory. Participation of the right hemisphere in performing lexical and semantic tasks was limited to executive activation, which is consistent with the hypothesis that when the content of verbal information is processed, the left hemisphere actively inhibits the right hemisphere. Specific unilateral right-side activation during the processing of sentences and text is involved in context processing. These results are consistent with data that the right hemisphere has a limited vocabulary without phonological abilities, but is actively involved in context processing. Despite the predominance of the left hemisphere for most verbal tasks, the right hemisphere can play an important role in the comprehension of complex natural language. A voxel-based focal lesion-behaviour mapping study have allowed (Roswandowitz et al, 2017) to assert that the right posterior/mid temporal lobe plays an exceptional role in voice-identity recognition while the inferior parietal lobe is subsidiary region in this process.

The comprehension of the natural language (stories, talks, conversations, written text) is a very simple process for the subject and very complex in terms of cognitive science. Many studies have focused on how a person is able to decode written and oral verbal information, get the meaning of words and parse syntax. There is evidence of the existence of three separate components of semantic processing, which are crucial for the comprehension of the natural language - semantic activation, semantic integration and semantic choice (Jung-Beeman, 2005). Each process is presented in both cerebral hemispheres, but it seems that the right hemisphere performs rough calculations of the overall process. Despite the activation of the classical language areas (Broca's and Wernicke's areas) of the left hemisphere in the performance of speech tasks, there is also a weak activation of the homologous regions of the right hemisphere (Beeman, 1998). With increasing complexity of the verbal stimulus, more areas of the brain are involved, in particular, the front temporal zones of the right hemisphere, which are homologues of classical language centers of the left hemisphere (Démonet, Thierry & Cardebat, 2005; Xu et al, 2005).

Although both hemispheres are sensitive to the context, only the left hemisphere is sensitive to semantically similar words (Federmeier & Kutas, 1999). The comprehension of metaphorical verbal information involves specific neural mechanisms of semantic processing, which differ from processing information with literal content. Activation of the left ventrolateral frontal cortex reflects semantic processing while the arousal of the medial prefrontal cortex relates to the process of interpretation of metaphorical concepts and their agreement with the semantic component (Shibata et al, 2007).

In addition, the primary right hemisphere activity is reported during high-level tasks such as metaphor comprehension (the right middle/superior temporal areas) (Sotillo et al, 2004), jokes (Coulson & Wu, 2005), discourse processing (St George et al, 1999), the construction-integration framework/drawing conclusions (dorsolateral prefrontal cortex and the right-hemisphere language areas) (Mason & Just, 2004), selecting the best sentence structure (right lateral temporal cortex) (Kircher et al, 2001), correcting grammatical errors, the identification of plot inconsistencies and the definition of the sequence of events stories (the right prefrontal cortex) (Knutson, Wood & Grafman, 2004). This means that the right hemisphere contributes to all the above functions. Language areas of the right hemisphere are better tuned to perform tasks previously performed by the left hemisphere. The right hemisphere can facilitate speech restoration. It has been shown that children with brain damage, even if the left hemisphere was completely removed during early childhood in order to treat epilepsy, can restore most of the linguistic abilities (Cohen et al, 2004).

Brain scans using such methods as PET and fMRI can provide detailed information about lateralization of language function (Nenert et al, 2017), language learning (Krishnan et al, 2016), language memory and integration of verbal information into a single whole (Hartzell et al, 2016; Henderson et al, 2016; Lopopolo et al, 2017). However, these methods are much less able to talk about the dynamics of the language network of the brain. The analysis of EEG coherence/functional connectivity in the context of written and oral speech can help create new concepts for the functioning of language centers. The contribution of functional connectivity, coherent EEG analysis to the study of language comprehension and processing has been demonstrated by many studies (Weiss & Mueller, 2003; Elmer & Kühnis, 2016; Decker, Fillmore & Roberts, 2017; Kepinska et al, 2017). Namely based on the EEG coherence studies (Weiss & Mueller, 2003) advanced an idea on “transient functional language centers”.

High coherence between two EEG signals of a certain range determines the degree of interaction and synchronization between the two brain regions - it can be argued that these zones are involved in one task. The following patterns of functional connectivity has been described (Bastiaansen & Hagoort, 2006): operations involving memory are mainly accompanied by an increase in synchronization in the theta frequency range (4-7 Hz) in the central frontal areas, but uniting operations induce synchronization of high frequencies (beta (12-30 Hz) and gamma rhythm (above 30 Hz). The increase of coherence between the right and left frontal regions in theta, alpha and gamma frequency ranges was observed while memorizing single words in combination with musical accompaniment (Peterson & Thaut, 2007).

Besides, various roles of synchronization of high and low frequency components of the EEG during the processing of verbal information were established. Synchronization of theta rhythm (3-7 Hz) reflects the consolidation of memory, which is associated with verbal information. Coherence in the theta range is increased if the problem requires more efficient processing of information (Weiss & Rappelsberger, 2000). Increase of the alpha rhythm coherence in the temporal parietal and central zones reflects the processing of sensory information. The high-frequency alpha subband (10-12 Hz) is significant for semantic processing (Weiss & Rappelsberger, 1996).

Davidson & Indefrey (2007) found the increase in the spectral power of the beta range (14-30 Hz) for syntactically correct sentences comparing to sentences that contain syntactic errors. These results were reproduced and supplemented by the fact that semantically incorrect words, which were similar to semantically correct ones, caused power increase in the gamma rhythm (Rommers et al, 2013).

The study of EEG coherence in professional bilingual translators revealed crucial "nodal points" for language translation: the increase in connectivity of the uppermost beta frequency range (24-32 Hz) in the left temporal area have a functional meaning for the translation of the

ISSN 2312-5160

text (Petsche, Etlinger & Filz, 1993). The lexico-semantic processes are reflected in changes in the synchronization/desynchronization patterns of theta (4-7 Hz) and alpha-rhythm (8-13 Hz) in parietal zones. It was noted high synchronization in the theta range and desynchronization in the alpha-2 (10-13 Hz) range when translating low frequency words versus high frequency words. Stronger desynchronization in the alpha frequency range in the left hemisphere was observed for the successful translation of the low frequency words as opposed to those that were not translated (Grabner et al, 2007).

The current published data level regarding EEG correlates of comprehension of verbal remains incomplete on data systemacy and consistency the processing of verbal information involves both left and right hemispheres, but their functions and processing mechanism are different. Neurophysiologists are well aware that the left hemisphere of the brain specializes in processing verbal information and how this can differ in multilingual people still needs to be investigated. In this paper, we aim to conduct a neurophysiological study of neocortical mechanisms for the verbal information perception related to language knowledge in conditions and stimuli that may be close to everyday life.

We set the following objective:

• To identify the patterns of the functional connectivity for verbal information.

• To assess the differences in the electrical activity of the brain when perceiving information presented in different languages.

Methods

Participants. 25 healthy right-handed volunteers (10 males and 15 females), first-third year students from the Taras Shevchenko National University of Kyiv (**Educational and Centre "Institute of Biology and Medicine" and Faculty of Psychology)** aged 18 to 22 years (M_{age} = 18.35, SD = 1.1 years) participated in this study. All participants were native Ukrainian speakers and fluent in both Ukrainian and Russian. The level of auxiliary language (English) proficiency (understanding, speaking, writing) of the subjects was B2 according to Common European Framework of Reference for Languages. The participants were eligible to enroll in the study if they had no clinical manifestations of mental or cognitive impairment. Exclusion criteria were: the use of psychoactive medication, drug or alcohol addiction and psychiatric or neurological complaints.

The study was approved by the Bioethics Commission of Educational and Scientific Centre "Institute of Biology and Medicine", Taras Shevchenko National University of Kyiv and each subject provided written informed consent in accordance with the World Medical Association (WMA) declaration of Helsinki – ethical principles for the medical research involving human subjects (Helsinki, Finland, June 1964), the Declaration of Principles on Tolerance (28th session of the General Conference of UNESCO, Paris, November 16, 1995), the Convention for the protection of Human Rights and Dignity of the Human Being with regard to the Application of Biology and Medicine: Convention on Human Rights and Biomedicine (Oviedo, April 04, 1997). All volunteers participated in the study for course credits.

Verbal stimuli. We used poetic fragments (William Shakespeare sonnets 23, 27, 47, 141) in three languages - English, Russian (translation by Samuel Marshak) and Ukrainian (translation by Dmytro Palamarchuk). Sonets were voiced by professional actors of Kyiv drama theaters.

Experimental design. In the beginning of the experiment a participant was given 30 seconds to adapt him/herself to the conditions of the experiment. After that, we recorded a background EEG with closed eyes during 3 minutes and the participant listened to three poetic fragments (2,5 min). The aftereffect recordings of EEG with closed eyes (3 min) were performed after the last set of words.

EEG recordings. During EEG recording the participants were in a soundproof dark chamber, in an armchair in a comfortable reclining position with eyes closed. The EEGs were recorded using EEG 23 Ch system Neurocom (Ukraine, XAI-MEDICA). The electrodes (silver/silver chloride) were placed on the scalp at symmetrical anterior frontal (Fp1, Fp2), frontal (F3, F4, Fz, F7, F8), central (C3, C4, Cz) parietal (P3, P4, Pz), occipital (O1, O2) and temporal (T3, T4, T5, T6) recording sites according to the international 10-20 scheme. All electrodes were referenced to the interconnected ear reference electrodes. The interelectrode impedance levels were below 5 kΩ. EEG analog signals were digitized at a 100 Hz. A high-frequency filter with a 30 Hz cut-off frequency and a power network filter (50 Hz) were used; the time constant of the amplification tract was 0.3 sec. We analyzed separate artifact-free EEG segments (rest state, listening to verbal stimuli, and aftereffect) records. Using a special software based on an algorithm of Fast Fourier Transformation (FFT) we have calculated interhemispheric and intrahemispheric mean coherence across all segments of EEG in the following frequency bands: delta (δ) (1-4 Hz), low theta (θ1) (4,1-5,86 Hz), high theta (θ2) (6,05-7,42 Hz), low alpha (α1) (7,62-9,38 Hz), middle alpha (α2) 9,57-10,74 Hz, upper alpha (α3) (10,94-12,89 Hz), low beta (β1) (13,09-19,22 Hz), upper beta β2 (20,12-30,0 Hz), gamma (γ) (from 30 Hz).

To establish electroencephalographic correlates of perception of verbal information we performed a coherent EEG analysis in the frequency range from 0.2 to 45 Hz while listening to poetry and during rest state.

Data analysis. Statistical processing of the collected data was performed using the Wilcoxon rank-sum test, the nonparametric Mann-Whitney test, and the Kolmogorov-Smirnov test (StatSoft STATISTICA 64, version 10.0.1011.0). Differences were considered statistically significant if the $p < 0.05$.

Results and discussion

First of all we did not reveal any significant differences in the delta, theta, alpha and beta frequency ranges during listening to verbal information in all three languages. We found a significant differences in distant connections in the gamma-band during the perception of verbal information (Figure 1), which indicates the integration of sensory information with memory processes (Danilova, 2006a), unification operations (Bastiaansen & Hagoort, 2006), information binding for meaningful representation (Fellner & Hanslmayr, 2017), attention, binding, object representation, and language (Herrmann, Fründ & Lenz, 2010), complex linguistic processes, such as syntactic and semantic processing (Weiss & Rappelsberger, 1998), successful memory formation from perceptual and contextual information (Nyhus & Curran, 2010).

The listening to verbal stimuli was accompanied by the strengthening of average coherence in gamma frequency band between the left angular gyrus and the associative visual zone of the left hemisphere only for the English sonnets (Figure 1.1) and their Ukrainian translation (Figure 1.2). It is known that the occipitoparietal junction is involved not only in spatial perception, but also reflects the work of visual memory (Rämä et al, 2001). It can be assumed that such a pattern of activation is associated with active recall and verbal image representation. However, it remains an open question why a similar coherent link was not observed in the case of a stimulus in Russian. The content-related emotional importance of information determines by native or non-native language of bilinguals but the adequate perception of the important verbal information delivered in two different languages the recipients requires the fluency in these languages (Plakhotnyk et al, 2015). In addition, the response determines by the emotional importance of information. We assume that in this case the observed peculiarities are due to the fact that the Russian language was close but not-native language. In addition, listening to poetic fragments in Russian was characterized by an increase in the mean connectivity in the associative regions of the left hemisphere and a strengthening in interhemispheric coherence (Figure 1.3).

It should be noted that the similarity of languages is an important factor in the allocation of brain resources of bilinguals. D'Anselmo and colleagues (D'anselmo et al, 2013) clearly recognized various lateralization patterns and ways of processing the second language if the first and second languages have different origins - strong left-sided lateralization is observed when the second and first languages are typologically similar, regardless of the age of learning and the level of language proficiency. In this study increase of the coherence was shown in the marginal gyrus, the left lateral and medial supplementary motor area when listening to Russian sonnets in comparison with Ukrainian (Figure 2). Such changes of distant synchronization of EEG can indicate the perception of emotionally colored information in an auditory way, as evidenced by studies that have revealed a connection between the simultaneous activation of the Wernicke's area, the lateral and medial supplementary motor cortex with the memorization of emotionally relevant verbal information (Rämä et al, 2001). Decrease of coherence while listening to the Russian in comparison with Ukrainian was detected in angular gyrus (part of the Wernicke's area) and in the region of the superior parietal gyrus. Synchronous activation of these zones is associated with the processing of metaphorical information (Shibata et al, 2007). The strengthening of distant connections in gamma frequency band during the processing of auditory information characterizes the processes of memory and voluntary attention (Danilova, 2008). This evidence could indicate relatively lesser involvement of memory and voluntary attention when listening to Russian in comparison with the Ukrainian.

Our data in many respects confirm the importance of analyzing the behavior of gamma rhythm in the perception of verbal information and, in particular, are consistent with the statement that the discrete nature of the activity of gamma generators and their frequency independence allows more accurately differentiate brain activity levels in comparison with the depression of alpha rhythm (Danilova, 2010). Gamma phase synchronization of distant brain loci is considered as a more universal and basic mechanism of communication between neural networks, which provides a wide variety of interactions between sensory, executive and cognitive processes, including memory (Danilova, 2006b). Increase in gamma rhythm was observed when working not only with sensory, but also with semantic information (Danilova, 2010). Narrow-band gamma generators perform a communicative function, integrating sensory processes with memory processes already as part of a sensory response, ensuring the fusion of two information streams: "bottom-up" and "top-down" (Danilova, 2006a; 2008). Synchronized gamma activity is associated with auditory perception of the speech syllable and implicated in interhemispheric transfer of auditory information (Steinmann et al, 2014). The increase in gamma-rhythm power was observed when listening to sentences in the native language of Spanish and Italian monolingual subjects. Such phenomena were not observed when listening to sentences in a monologically similar or monologically distinct language. On the basis of these data, it can be assumed that the gamma-rhythm power reflects the coordination of the nervous ensembles participating in the processing of long segments of language (Peña & Melloni, 2012). We can safely say that the above features of the involvement of gamma-rhythm in the processing of verbal information directly correlate with the data of our study.

Association areas of both hemispheres are involved in perception of native languages, while the perception of language, which was learned later in life, mainly affects primary auditory and association areas of left hemisphere. Despite the closeness of Russian and Ukrainian languages and high proficiency of the participants, the mechanism of language perception could be different. Perhaps, this response does not depend on the level of knowledge of the language but rather on its phonetic structure and prosody.

ISSN 2312-5160

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Figure 1. Changes in mean connectivity of gamma rhythm during the listening to verbal stimuli (1 - in English language, 2 - in the Ukrainian language, 3 - in Russian language). The data represent in comparison with the initial state.
Red/blue line - significant increase/ decrease of coherence of gamma rhythm ($p<0,05$).

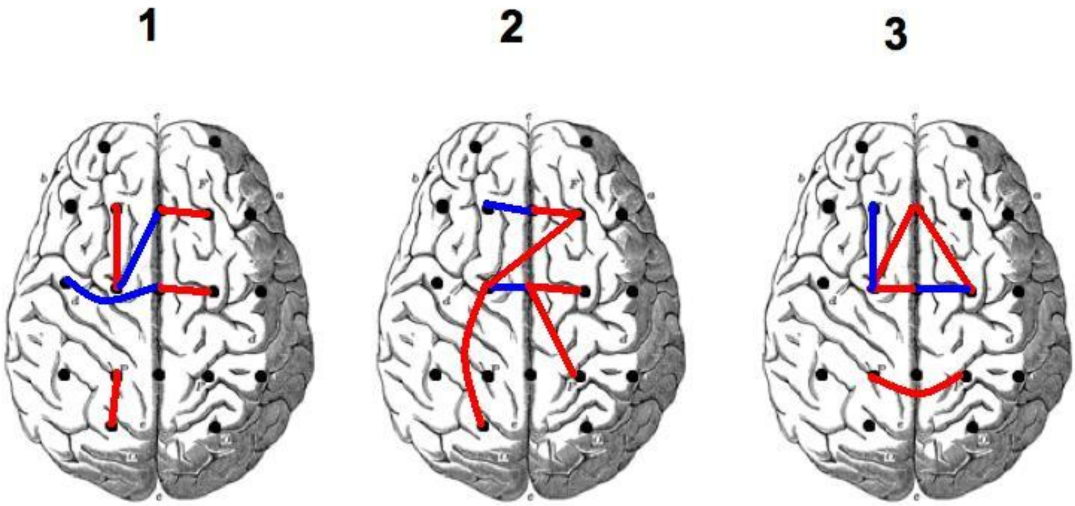
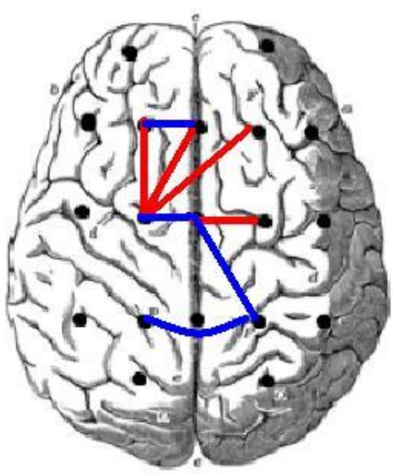


Figure 2. Changes in mean connectivity of gamma rhythm during the listening to verbal stimuli in Russian in comparison with the Ukrainian language.
Red/blue line - significant increase/ decrease of coherence of gamma rhythm ($p<0,05$).



References

Abutalebi, J., & Weekes, B. S. (2014). The cognitive neurology of bilingualism in the age of globalization. *Behavioural neurology*, 2014, 536727. PMCID: PMC4034485 doi: 10.1155/2014/536727

Adesope, O. O., Lavin, T., Thompson, T., & Ungerleider, C. (2010). A systematic review and meta-analysis of the cognitive correlates of bilingualism. *Review of Educational Research, 80*(2), 207-245. doi: 10.3102/0034654310368803

Bastiaansen, M., & Hagoort, P. (2006). Oscillatory neuronal dynamics during language comprehension. *Progress in brain research, 159,* 179-196. doi: 10.1016/S0079-6123(06)59012-0

Beeman, M. (1998). Coarse semantic coding and discourse comprehension. In Beeman, M., & Chiarello, C. (Eds.). (1998). *Right hemisphere language comprehension: Perspectives from cognitive neuroscience.* (pp. 255-284). Lawrence Erlbaum Associates

Bialystok, E., Craik, F., & Luk, G. (2008). Cognitive control and lexical access in younger and older bilinguals. *Journal of Experimental Psychology: Learning, memory, and cognition, 34*(4), 859-873. doi: 10.1037/0278-7393.34.4.859

Cohen, L., Lehéricy, S., Henry, C., Bourgeois, M., Larroque, C., Sainte-Rose, C., ... & Hertz-Pannier, L. (2004). Learning to read without a left occipital lobe: Right-hemispheric shift of visual word form area. *Annals of Neurology, 56*(6), 890-894. doi: 10.1002/ana.20326

Coulson, S., & Wu, Y. C. (2005). Right hemisphere activation of joke-related information: An event-related brain potential study. *Journal of cognitive neuroscience, 17*(3), 494-506. doi: 10.1162/0898929053279568

Danilova, N. N. (2006a). The Role of High-frequency Electrical Brain Activity in the Realization of Psychological Processes. Psychology. *Journal of Higher School of Economics, 3*(2), 62-72. Retrieved from https://psy-journal.hse.ru/data/2011/04/26/1210584340/62-72.pdf (in Russian)

Danilova, N. N. (2006b). Frequency specificity of gamma-rhythm oscillators. *Russian Psychological Journal Bulletin cognitive neuroscience, 3*(2), 35-60. Retrieved from http://www.psy.msu.ru/people/danilova/danilova2006b.pdf (in Russian)

Danilova, N. N. (2008). Frequency-selective gamma generators in processing of auditory stimuli. *Psychology in Russia, 1*(1), 299-308. doi: 10.11621 / pir.2008.0019

Danilova, N. N. (2010). Brain activity and its investigation in the E.N. Sokolov psychophysiological school. *Moscow University Psychology Bulletin cognitive neuroscience, 4*, 79-109. Retrieved from http://msupsyj.ru/pdf/vestnik_2010_4/79-109_vestnik_14_2010-4.pdf (in Russian)

D'Anselmo, A., Reiterer, S., Zuccarini, F., Tommasi, L., & Brancucci, A. (2013). Hemispheric asymmetries in bilinguals: Tongue similarity affects lateralization of second language. *Neuropsychologia, 51*(7), 1187-1194. doi: 10.1016/j.neuropsychologia.2013.03.016

Davidson, D. J., & Indefrey, P. (2007). An inverse relation between event-related and time–frequency violation responses in sentence processing. *Brain Research, 1158,* 81-92. doi: 10.1016/j.brainres.2007.04.082

Decker, S., Fillmore, P. T., & Roberts, A. (2017). Coherence: The measurement and application of brain connectivity. *NeuroRegulation, 4*(1), 3-13. doi: 10.15540/nr.4.1.3

Dehghani, M., Boghrati, R., Man, K., Hoover, J., Gimbel, S., Vaswani, A., ... & Kaplan, J. (2017). Decoding the Neural Representation of Story Meanings across Languages. Human Brain Mapping Retrieved from psyarxiv.com/qrpp3

Démonet, J. F., Thierry, G., & Cardebat, D. (2005). Renewal of the neurophysiology of language: functional neuroimaging. *Physiological reviews*, 85(1), 49-95. doi: 10.1152/physrev.00049.2003

Federmeier, K. D., & Kutas, M. (1999). Right words and left words: Electrophysiological evidence for hemispheric differences in meaning processing. *Cognitive Brain Research*, 8(3), 373-392. doi: 10.1016/S0926-6410(99)00036-1

Fedzechkina, M., Chu, B., & Florian, J. T. (2017). Human Information Processing Shapes Language Change. *Psychological science*, 956797617728726. doi: 10.1177/0956797617728726

Fellner MC., & Hanslmayr S. (2017). Brain Oscillations, Semantic Processing, and Episodic Memory. In: Mody M. (eds) *Neural Mechanisms of Language. Innovations in Cognitive Neuroscience* (pp. 63-80). Springer, Boston, MA doi: 10.1007/978-1-4939-7325-5_4

Elmer, S., & Kühnis, J. (2016). Functional connectivity in the left dorsal stream facilitates simultaneous language translation: an EEG study. *Frontiers in human neuroscience*, 10: 60. doi: 10.3389/fnhum.2016.00060

Gandour, J., Tong, Y., Talavage, T., Wong, D., Dzemidzic, M., Xu, Y., ... & Lowe, M. (2007). Neural basis of first and second language processing of sentence-level linguistic prosody. *Human Brain Mapping*, *28*(2), 94-108. doi: 10.1002/hbm.20255

Grabner, R. H., Brunner, C., Leeb, R., Neuper, C., & Pfurtscheller, G. (2007). Event-related EEG theta and alpha band oscillatory responses during language translation. *Brain research bulletin*, 72(1), 57-65. doi: 10.1016/j.brainresbull.2007.01.001

Hartzell, J. F., Davis, B., Melcher, D., Miceli, G., Jovicich, J., Nath, T., ... & Hasson, U. (2016). Brains of verbal memory specialists show anatomical differences in language, memory and visual systems. *Neuroimage*, 131, 181-192. doi: 10.1016/j.neuroimage.2015.07.027

Henderson, J. M., Choi, W., Lowder, M. W., & Ferreira, F. (2016). Language structure in the brain: A fixation-related fMRI study of syntactic surprisal in reading. *NeuroImage*, 132, 293-300. doi: 10.1016/j.neuroimage.2016.02.050

Herrmann, C. S., Fründ, I., & Lenz, D. (2010). Human gamma-band activity: a review on cognitive and behavioral correlates and network models. *Neuroscience & Biobehavioral Reviews*, *34*(7), 981-992. doi: 10.1016/j.neubiorev.2009.09.001

Jung-Beeman, M. (2005). Bilateral brain processes for comprehending natural language. *Trends in cognitive sciences*, 9(11), 512-518. doi: https://doi.org/10.1016/j.tics.2005.09.009

Kepinska, O., de Rover, M., Caspers, J., & Schiller, N. O. (2017). Whole-brain functional connectivity during acquisition of novel grammar: Distinct functional networks depend on language learning abilities. *Behavioural brain research*, 320, 333-346. doi: 10.1016/j.bbr.2016.12.015

Kircher, T. T., Brammer, M., Andreu, N. T., Williams, S. C., & McGuire, P. K. (2001). Engagement of right temporal cortex during processing of linguistic context. *Neuropsychologia*, 39(8), 798-809. doi: 10.1016/S0028-3932(01)00014-8

Knutson, K. M., Wood, J. N., & Grafman, J. (2004). Brain activation in processing temporal sequence: an fMRI study. *Neuroimage*, 23(4), 1299-1307. doi: 10.1016/j.neuroimage.2004.08.012

Krishnan, S., Watkins, K. E., & Bishop, D. V. (2016). Neurobiological basis of language learning difficulties. *Trends in cognitive sciences*, 20(9), 701-714. doi: 10.1016/j.tics.2016.06.012

Lopopolo, A., Frank, S. L., Van den Bosch, A., & Willems, R. M. (2017). Using stochastic language models (SLM) to map lexical, syntactic, and phonological information processing in the brain. *PloS one*, 12(5), e0177794. doi: 10.1371/journal.pone.0177794

Mason, R. A., & Just, M. A. (2004). How the brain processes causal inferences in text: A theoretical account of generation and integration component processes utilizing both cerebral hemispheres. *Psychological Science*, 15(1), 1-7. doi: 10.1111/j.0963-7214.2004.01501001.x

Nenert, R., Allendorfer, J. B., Martin, A. M., Banks, C., Vannest, J., Holland, S. K., & Szaflarski, J. P. (2017). Age-related language lateralization assessed by fMRI: The effects of sex and handedness. *Brain Research*, 1674, 20-35. doi: 10.1016/j.brainres.2017.08.021

Nyhus, E., & Curran, T. (2010). Functional role of gamma and theta oscillations in episodic memory. *Neuroscience & Biobehavioral Reviews*, *34*(7), 1023-1035. doi: 10.1016/j.neubiorev.2009.12.014

Peña, M., & Melloni, L. (2012). Brain oscillations during spoken sentence processing. *Journal of cognitive neuroscience*, 24(5), 1149-1164. doi: 10.1162/jocn_a_00144

Peterson, D. A., & Thaut, M. H. (2007). Music increases frontal EEG coherence during verbal learning. *Neuroscience letters*, 412(3), 217-221. doi: 10.1016/j.neulet.2006.10.057

Petsche, H., Etlinger, S. C., & Filz, O. (1993). Brain electrical mechanisms of bilingual speech management: an initial investigation. *Electroencephalography and Clinical Neurophysiology*, 86(6), 385-394. doi: 10.1016/0013-4694(93)90134-H

Plakhotnyk, N., Tukaiev, S., Zyma, I., Bas-Kononenko, O., & Dudnyk, Z. (2015). Verbal ethnic symbols as an indicator of language perception by bilinguals. *Austrian J. of Humanities and Social Sciences.*7-8, 29-31. doi: 10.20534/AJH-15-7.8-29-31

Rämä, P., Martinkauppi, S., Linnankoski, I., Koivisto, J., Aronen, H. J., & Carlson, S. (2001). Working memory of identification of emotional vocal expressions: an fMRI study. *Neuroimage,* 13(6), 1090-1101. doi: 10.1006/nimg.2001.0777

Rommers, J., Dijkstra, T., & Bastiaansen, M. (2013). Context-dependent semantic processing in the human brain: Evidence from idiom comprehension. *Journal of Cognitive Neuroscience*, 25(5), 762-776. doi: 10.1162/jocn_a_00337

Roswandowitz, C., Kappes, C., Obrig, H., & von Kriegstein, K. (2017). Obligatory and facultative brain regions for voice-identity recognition. *Brain*. awx313, PMID: 29228111, doi: 10.1093/brain/awx313

Shibata, M., Abe, J. I., Terao, A., & Miyamoto, T. (2007). Neural mechanisms involved in the comprehension of metaphoric and literal sentences: An fMRI study. *Brain Research*, 1166, 92-102. doi: 10.1016/j.brainres.2007.06.040

Sotillo, M., Carretié, L., Hinojosa, J. A., Tapia, M., Mercado, F., López-Martín, S., & Albert, J. (2004). Neural activity associated with metaphor comprehension: spatial analysis. *Neuroscience letters*, 373(1), 5-9. doi: 10.1016/j.neulet.2004.09.071

St George, M., Kutas, M., Martinez, A., & Sereno, M. I. (1999). Semantic integration in reading: engagement of the right hemisphere during discourse processing. *Brain,* 122(7), 1317-1325. PMID: 10388797 doi: 10.1093/brain/122.7.1317

Steinmann, S., Leicht, G., Ertl, M., Andreou, C., Polomac, N., Westerhausen, R., ... & Mulert, C. (2014). Conscious auditory perception related to long-range synchrony of gamma oscillations. *Neuroimage*, 100, 435-443. doi: 10.1016/j.neuroimage.2014.06.012

Vigneau, M., Beaucousin, V., Herve, P. Y., Duffau, H., Crivello, F., Houde, O., ... & Tzourio-Mazoyer, N. (2006). Meta-analyzing left hemisphere language areas: phonology, semantics, and sentence processing. *Neuroimage*, 30(4), 1414-1432. doi: 10.1016/j.neuroimage.2005.11.002

Vigneau, M., Beaucousin, V., Hervé, P. Y., Jobard, G., Petit, L., Crivello, F., ... & Tzourio-Mazoyer, N. (2011). What is right-hemisphere contribution to phonological, lexico-semantic, and sentence processing?: Insights from a meta-analysis. *Neuroimage*, 54(1), 577-593. doi: 10.1016/j.neuroimage.2010.07.036

Weiss, S., & Mueller, H. M. (2003). The contribution of EEG coherence to the investigation of language. *Brain and language*, *85*(2), 325-343. doi: 10.1016/S0093-934X(03)00067-1

Weiss, S., & Rappelsberger, P. (1996). EEG coherence within the 13–18 Hz band as a correlate of a distinct lexical organisation of concrete and abstract nouns in humans. *Neuroscience letters*, 209(1), 17-20. doi: 10.1016/0304-3940(96)12581-7

Weiss, S., & Rappelsberger, P. (1998). Left frontal EEG coherence reflects modality independent language processes. *Brain Topography*, 11(1), 33-42. doi: 10.1023/A:1022266419488

Weiss, S., & Rappelsberger, P. (2000). Long-range EEG synchronization during word encoding correlates with successful memory performance. *Cognitive Brain Research*, 9(3), 299-312. doi: 10.1016/S0926-6410(00)00011-2

Wierzbicka, A. (1992). *Semantics, culture, and cognition: Universal human concepts in culture-specific configurations*. New York-Oxford: Oxford University Press.

Wierzbicka, A. (2003). *Cross-cultural pragmatics: The semantics of human interaction*. Berlin: Walter de Gruyter.

Xu, J., Kemeny, S., Park, G., Frattali, C., & Braun, A. (2005). Language in context: emergent features of word, sentence, and narrative comprehension. *Neuroimage*, 25(3), 1002-1015. doi: 10.1016/j.neuroimage.2004.12.013

Submitted 15.02.2020