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THE NEURODYNAMICS OF α EEG BAND UPON MENTAL ARITHMETIC TASK PERFORMANCE BEFORE AND DURING THE FULLSCALE RUSSIAN INVASION OF UKRAINE

Background. *Living in war-affected zones has been found to significantly impact cognitive functions, mental health, and overall well-being in children, adolescents, and adults. Stress perception plays a role in this impact, with the psychological burden of war impairing cognitive development and functioning in youth and adults. Neurodynamics associated with managing the cognitive workload and stress is well-reflected in the EEG data, as chronic stress exposure significantly affects cognitive performance. The α EEG band has been widely investigated as a biomarker for assessing cognitive performance, mental fatigue, and the effects of interventions to enhance cognitive function. However, there is not enough data regarding the α band dynamics under the impact of long-term stressors, such as living in a war-torn country, especially during cognitive load. The study aimed to compare the α EEG band neurodynamics associated with the mental arithmetic tasks before and during the outbreak of Russia's full-scale invasion of Ukraine.*

Methods. *Fifty-seven volunteer subjects participated in the study; twenty-eight were enrolled before the full-scale invasion, and twenty-nine after the invasion outbreak. The EEG data were recorded during the sequential subtraction performance, with further subband selection, viz α1 [7.5, 9.5] Hz, α2 [9.6, 11] Hz, α3 [11.1, 12.9] Hz.*

Results. *In the α1 subband, the female group exhibited an increased number of coherent neural connections during the full-scale invasion. In the α2 subband, a topographical redistribution of connections was noted for the male group, namely the decrease of connection number and shift towards the frontal areas of the cortex. In the α3 subband, the female group showed a wide network of connections, compared to the male group, where a distinct parietal-predominated hub of connections was observed during the full-scale invasion.*

Conclusions. *It was discovered that female subjects showed higher degrees of behavioral inhibition during full-scale invasion, which could be interpreted as a covert indicator of elevated background anxiety. The male group demonstrated difficulties focusing their attention on the internal task. Lastly, volunteers in both groups showed an overall decline in the efficacy of top-down control over the task execution.*

Keywords: *neurodynamics, electroencephalography (EEG), magnitude-squared coherence (MSC), stress, cognitive load.*

Background

The influence of living in a war-affected zone on cognitive functions has been extensively studied, revealing significant negative impacts on cognitive development, mental health, and overall well-being. The findings in the research indicated that exposure to war events significantly affects cognitive functions in children (Vindevogel et al., 2013), adolescents (Aguirre, Rojas, & Torres, 2023), and veterans (Bovin et al., 2023), with stress perception acting as a moderator. We need a contextualized approach to understanding how individual experiences of war influence cognitive outcomes, suggesting that the psychological burden of war can impair cognitive development and functioning in youth and adults.

Recent research has investigated EEG markers during mental arithmetic task performance under normal and stressful conditions. This synthesis of findings from various studies highlights the relationship between EEG activity and cognitive workload, particularly in the context of mental arithmetic tasks.

One of the primary EEG markers associated with mental arithmetic is the modulation of beta oscillations. Balconi (2023) found that increased beta activity over left temporoparietal sites correlates with higher cognitive workload and effective strategy adaptation during task performance. This aligns with findings from Maghsoudi and Shalbaf (2021), who reported that specific frequency components in the theta, alpha, and beta bands are sensitive to changes in cognitive workload during mental arithmetic tasks. The authors emphasized that these frequency bands reflect the brain's electrophysiological activity, crucial for recognizing mental arithmetic tasks.

Moreover, the impact of stress on cognitive performance, particularly in mental arithmetic, has been extensively documented. Gärtner et al. (2015) demonstrated that acute stress negatively affects prefrontal cortex function, essential for executing complex cognitive tasks like mental arithmetic. They observed decreased frontal midline theta oscillations under stress, indicating impaired cognitive control. This is further supported by Al-Shargie et al. (2017), who reported that mental stress leads to reduced cortical activation in the PFC during mental arithmetic tasks, highlighting the detrimental effects of stress on cognitive performance.

In addition to the effects of stress, the relationship between perceived mental effort and EEG markers has

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been explored. Howells et al. (2010) found that perceived mental effort correlates with tonic changes in cortical arousal, as indicated by left parietal beta band power.

Furthermore, the interaction between different EEG frequency bands has been shown to facilitate cognitive performance. Rodriguez-Larios and Alaerts (2019) found that harmonic relationships between theta and alpha peaks are associated with improved performance in cognitive tasks, including arithmetic. This suggests that synchronizing these frequency bands may enhance cognitive processing during mental arithmetic tasks. EEG markers such as beta oscillations, frontal midline theta activity, and the interaction between theta and alpha rhythms play crucial roles in mental arithmetic task performance, particularly under stress. The findings indicate that cognitive workload and stress significantly influence EEG activity, which affects cognitive performance.

In recent years, increasing attention has been directed towards investigating specific sub-bands of the EEG alpha rhythm as markers of cognitive load, fatigue, and performance efficiency in computational tasks. The findings indicate that alpha coherence can serve as a valuable biomarker for assessing cognitive performance, mental fatigue, and the effects of interventions to enhance cognitive function. Li et al. (2019) discussed the impact of mental fatigue on brain activity, noting that alpha rhythm can change as the brain transitions from a normal state to fatigue. Maghsoudi and Shalbaf (2021) highlighted that alpha band coherence is sensitive to changes in cognitive workload during mental arithmetic tasks. Notably, magnitude-squared coherence (MSC) is a promising measure for assessing the efficiency of neural communication required for executing complex cognitive tasks. However, this approach has yet to be applied to evaluate the impact of long-term stressors, such as living in a war-torn country, on cognitive load.

Therefore, ***our study aimed*** to compare coherence in distinct alpha sub-bands during mental mathematical computations under normal conditions and during a full-scale invasion, specifically focusing on sex differences.

Methods

The study subjects were volunteer students of Taras Shevchenko National University of Kyiv, $n_{tot} = 57$, aged 18 to 24 years. Twenty-eight participants ("control group") were enrolled in the years 2010–2012, before the COVID-19 pandemic, hybrid and full-scale russian invasion of Ukraine ($n_{fem} = 15$, $n_m = 13$), and twenty-nine subjects took part in the examination during the full-scale invasion ($n_{fem} = 18$, $n_m = 11$) and formed "war group." Participants were informed about the content of the stimulation program; written informed consent was obtained from each subject following 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).

A routine EEG was recorded using the Neurocom hardware and software complex (KhAI Medica, Kharkiv, Ukraine). The electrodes were placed according to the international "10–20" electrode placement system. The resting state with eyes closed EEG was recorded before and after the task execution (60 s). The subjects were instructed to perform sequential subtraction. Each trial started with the oral communication of the 4-digit (minuend) and 2-digit (subtrahend) numbers (e.g., 4753 and 17, 3141 and 42, etc.) with their eyes closed. Mental arithmetic performance is a standardized stress-inducing experimental protocol (Jatoi, Kyvelou, & Feely, 2014; Finlay et al., 2016). Serial subtraction for 15 min is considered psychosocial stress (Noto et al., 2005). In this way, our study design required intensive cognitive activity from the subjects. The intensive mental load is accompanied by a change in the emotional background when the subject makes an additional effort to resolve tasks so that one can talk about evoked emotions in this case.

The obtained data were subdivided into subbands and further processed using the EEGLAB software package (Delorne, 2018(Delorme, & Makeig, 2004) based on the MATLAB software environment. The main algorithm used for data analysis was magnitude-squared coherence. Magnitude-squared coherence (MSC) is an objective frequency-domain response detection method that Dobie and Wilson (1993) introduced for analyzing evoked potentials. These researchers found that the technique can provide important results in the field of research on the cortical response of the human brain.

$$\mathrm{Coh}^2 = \frac{|Pxy|^2}{PxxPyy}. \qquad (1)$$

Magnitude-squared coherence (MSC) has been used in many areas of signal processing, for example, (Bortel, & Sovka, 2006) to measure the coherence between two realized complex signals. The MSC measure in human EEG is a real number between 0 and 1 in each band and subband. If MSC is 0 for all frequencies, the two signals are not linearly dependent; if MSC is 1 for all frequencies, the two signals are connected via a linear time-invariant (LTI) system. In other words, MSC is a measure that evaluates the degree to which one signal is predicted by another signal using a linear model and is implemented to analyze linear systems (Malekpour, Gubner, & Sethares, 2018). MSC can also be considered as a measure of the similarity of the frequency content of two signals (Malekpour, 2018). The MSC is characterized by symmetry, which means that the MSC between two signals, $x(t)$ and $y(t)$, is the same as the MSC between $y(t)$ and $x(t)$.

Results

The study aimed to focus attention primarily on the α EEG band and its subbands α1 [7.5, 9.5] Hz, α2 [9.6, 11] Hz, α3 [11.1, 12.9] Hz. In the α1 subband activity, the control female group (Fig. 1, A) was characterized by the formation of connections primarily in the caudal regions of the cortex, namely within the occipital areas and central areas (central, parietal areas) with relative right lateralization. On the other hand, the data obtained during the full-scale invasion were characterized by the shift of strong connection localization to the anterior areas of the cortex. Thus, the connections were bilaterally located mainly in the prefrontal, frontal, and posterior frontal regions of the cortex. However, in the male group (Fig. 1, B), such a clearly expressed reorganization of connections was not observed. It can be noted that in the state before the onset of the full-scale invasion, many connections could be observed both in the frontal and central-parietal areas of the cortex. At the same time, during the full-scale invasion, most connections were concentrated in the frontal, central, and anterior temporal regions of the cortex.

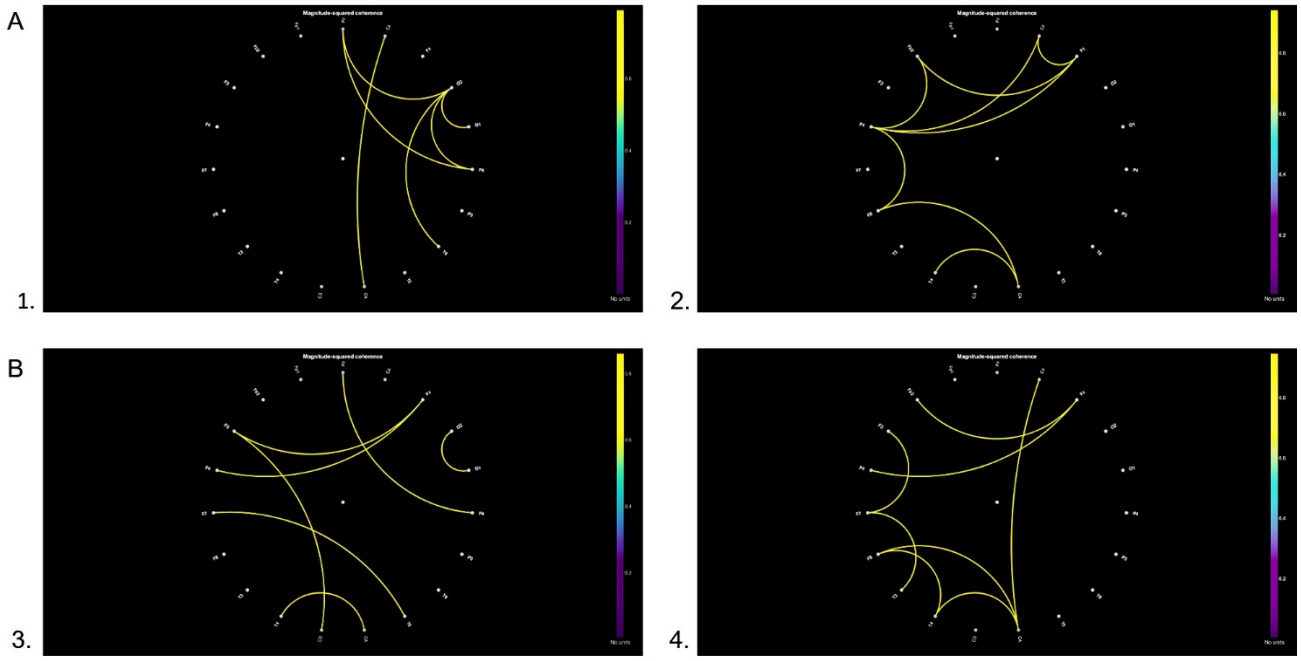

Fig. 1. Topographical distribution of connections (magnitude squared coherence) upon mental arithmetic task performance in α1 EEG subband in (A) female group before (1) and during (2) the fullscale russian invasion and in (B) male group before (3) and during (4) the fullscale russian invasion of Ukraine. Names of the EEG leads, abbreviated according to the international "10–20 %" system, are presented as a circle diagram. The color bar in the right corner represents the coherence levels

In the case of the α2 subband of activity, a distinct pattern of the cortical coherent connections' distribution could be observed. Thus, in the female group (Fig. 2, A), it was possible to observe an extensive network of connections, with small hubs in the central frontal and central regions. However, the number of connections in these hubs increased in the data obtained after the outbreak of the full-scale invasion. In addition, the number of local connections between closely located electrodes in the prefrontal and frontal regions of the cortex increased. It is also possible to note the establishment of connections in the occipital cortical areas.

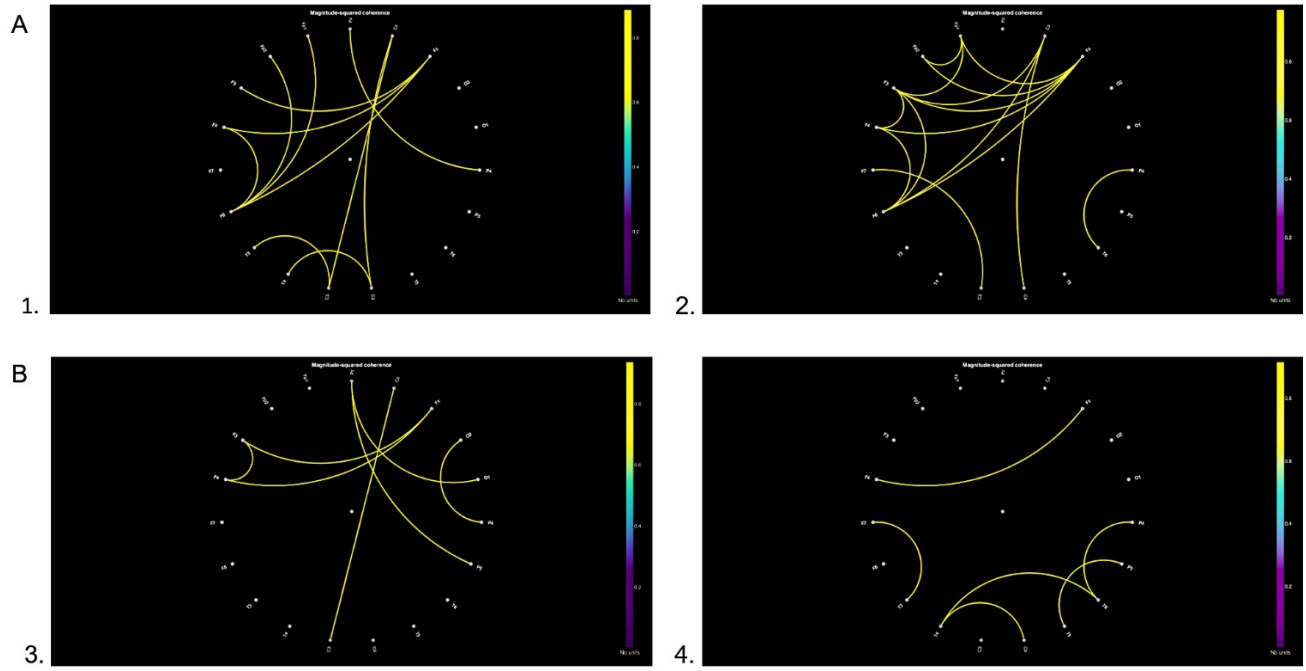

Fig. 2. Topographical distribution of connections (magnitude squared coherence) upon mental arithmetic task performance in α2 EEG subband in (A) female group before (1) and during (2) the fullscale russian invasion and in (B) male group before (3) and during (4) the fullscale russian invasion. Names of the EEG leads, abbreviated according to the international "10–20 %" system, are presented as a circle diagram. The color bar in the right corner represents the coherence levels

A distinct topographical distribution of connections was observed in the male group (Fig. 2, B). Thus, in the control group, EEG data demonstrated the formation of an extensive communication network without clearly defined hubs. These networks included bilateral connections within the cortex's frontal, central, and occipital regions. At the same time, a sharp drop in the number of connections could be observed during the calculations in the "war group". In these data, persistent connections between the central frontal and frontal regions of the right hemisphere cortex; between the parietal and posterior temporal areas within the left and right hemispheres, respectively; between the left posterior frontal and anterior temporal regions; between the central and anterior temporal regions of the cortex of the right hemisphere could be seen.

Lastly, we want to draw attention to the signal's behavior in the α3 subrange of bioelectric oscillations. In this case, similar dynamics can be noted for both groups during the full-scale invasion despite the differences in the structure of coherent connections in the "pre-war" control group. In the control group of females (Fig. 3, A), an extensive network of connections could be observed generally in the cortex without well-defined hubs. At the same time, the establishment of individual groups of connections was evident within the frontal areas of the right hemisphere cortex, in the parietal regions between the central and lateral areas of the cortex bilaterally, between the precentral regions of the cortex of both hemispheres, as well as between the central and anterior temporal areas of the cortex within both hemispheres. At the same time, in the male group (Fig. 3, B), it was possible to observe the formation of a connection hub in the left central parietal cortex, spreading to the occipital region bilaterally and the left parietal region. In addition, the results suggested a connection between the occipital and parietal areas of the cortex and between the cortex's central frontal and frontal regions in the right hemisphere.

At the same time, the similarity of the connectivity distribution in the full-scale invasion groups in the male and female groups was evident. In the female group, the analysis confirmed the local connection between the prefrontal areas, the anterior temporal and central areas of the cortex in the left hemisphere, and the posterior temporal and parietal areas of the cortex of the right hemisphere (Fig. 3, A, 2). In the male group, connections were observed between the frontal, temporal, and parietal areas of the right hemisphere's cortex and between the central frontal and the frontal regions of the left hemisphere cortex.

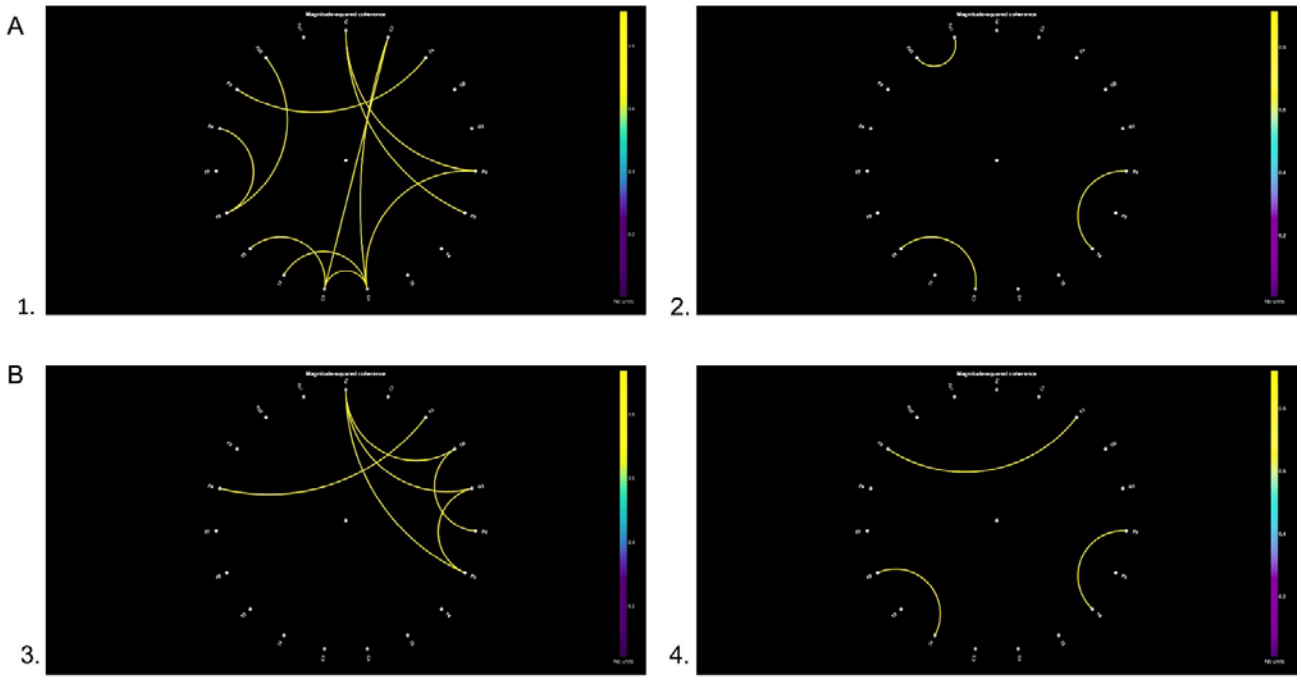

Fig. 3. Topographical distribution of connections (magnitude squared coherence) upon mental arithmetic task performance in α3 EEG subband in (A) female group before (1) and during (2) the fullscale russian invasion and in (B) male group before (3) and during (4) the fullscale russian invasion. Names of the EEG leads, abbreviated according to the international "10–20 %" system, are presented as a circle diagram. The color bar in the right corner represents the coherence levels

Discussion and conclusions

The phase of α-oscillations correlates with the cyclic modulation of neuronal excitability, which affects the neuronal and behavioral response to sensory stimuli. A large body of existing data indicates that α-oscillations have a major functional role in changes in attention, influencing timing in local neuronal networks and interregional phase interactions (Palva, S., & Palva, J., 2007). So far, there is data on the involvement of α-oscillations in suppressing cognitive processes unrelated to the task, strengthening task-conditioned processes, and the executive control of the behavioral response (Palva, S., & Palva, J., 2011). It is also believed that α-oscillations correspond to the semantic component of perception and are involved in its top-down control component (Palva, S., & Palva, J., 2012). Synchronization in the α-band in certain cortex regions is correlated with the so-called "idling" reaction, spatial and temporal anticipation of stimulus, and scanning of the surrounding environment.

Moreover, it has been reported that, in particular, the lower α1-frequency desynchronizes in response to the presented warning stimulus. The authors suggest that the

reactions of this lowest alpha subband probably reflect brain processes related to phasic alertness and α-rhythm modulation in the frontal areas of the cortex, which may act as correlates of changes in individual affective states (Kim et al., 2019).

First, we would like to note that in the case of the α1 subband of activity, a significant increase in the expressiveness of coherent connections could be observed in the female group during the full-scale invasion. This phenomenon during the performance of mental calculation can be associated with a higher level of behavioral inhibition and, in turn, can be considered as an indicator of the background anxiety increase (van Diepen, Foxe, & Mazaheri, 2019). Behavioral inhibition is an active inhibitory mechanism that allows us to withhold unwanted or prepotent responses triggered by internal or external stimuli (Iemi, & Busch, 2018). Behavioral inhibition is associated with decision-making, error correction, response inhibition, and ordinary life without danger (van Diepen et al., 2016). Furthermore, Jensen and Mazaheri (2011) suggested that the α1 power would be positively related to behavioral inhibition as a function and personality trait.

In the case of the α2 subband, the topographical reorganization of coherent connections in the male group can be noted, compared to a relatively stable topography of connections in the female group both before and during the full-scale invasion. Thus, taking into account the decrease in the number of coherent connections, as well as the topographic narrowing of the connectivity network to the anterior areas of the cortex (frontal-central-parietal), it can be assumed that the male group experienced more difficulties with concentrating attention on the task performance during the full-scale invasion, as compared to pre-invasion rates. According to existing data (Lozano-Soldevilla, & VanRullen, 2019), 10 Hz alpha drives attention toward an internally oriented brain state, creating an unfavorable neural environment for the surrounding sensory stimuli while reflecting a cortico-cortical attention loop.

Lastly, in the α3 subband, the female group was characterized by a wide network of connections, compared to the male group, where a clear focus of connections with parietal predominance was formed. In addition, a sharp decrease in strong coherent connections in both groups, with a general convergence of their topography, was revealed. The α3 subband in the context of the α-oscillations function is generally associated with active memory performance (Sadaghiani, & Kleinschmidt, 2016), downstream control over neural excitability, and information flow in large-scale cognitive control neural networks (Clark et al., 2004). Thus, a significant decrease in the number strong coherent connections within the α3 subband may reflect a considerable complication when performing mental calculations and operating with large numbers.

Unfortunately, the work has certain limitations, particularly due to the lack of quality control of mental calculations for data obtained before the outbreak of a full-scale invasion. However, in future works, this aspect will be taken into account, particularly to assess the long-term impact of chronic stress caused by a full-scale russian invasion of Ukraine.

Chronic stress conditions caused by the full-scale russian invasion of Ukraine for two full years significantly affected the brain's ability to cope with the cognitive workload, in particular from the point of view of changes in the functioning of the attention and memory systems. In particular, it was found that female subjects under the full-scale invasion condition demonstrated higher levels of behavioral inhibition, which may be seen as an indirect sign of increased anxiety. At the same time, the subjects from the male group experienced difficulties with concentrating attention on the internal task. Ultimately, subjects from both groups were characterized by a general drop in top-down control over the current task performance. The obtained data make it possible to assess the destructive effect of chronic stress on the cognitive abilities of the Ukrainian civilian population. They can also serve as a basis for choosing the most effective and developing new therapeutic approaches.

Authors' contribution: Mariia Chernykh – conceptualization, methodology, software, data curation, validation, formal analysis, writing – original draft preparation. Viktoriia Kravchenko – writing – literature review and editing. Yevdokiia Reshetnik – conceptualization, data curation. Ihor Zyma – conceptualization, writing – review and editing, supervision.

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НЕЙРОДИНАМІКА α-ДІАПАЗОНУ ЕЕГ ПРИ ВИКОНАННІ МЕНТАЛЬНИХ АРИФМЕТИЧНИХ ВПРАВ ДО ТА ПІД ЧАС ПОВНОМАСШТАБНОГО ВТОРГНЕННЯ РОСІЇ В УКРАЇНУ

Вступ. ***Життя в зонах, уражених війною, суттєво впливає на когнітивні функції, психічне здоров'я та загальне самопочуття дітей, підлітків і дорослих. Сприйняття стресу відіграє певну роль у цьому впливі, оскільки психологічний тягар війни погіршує когнітивний розвиток і функціонування молоді та дорослих. Нейродинаміка, пов'язана з керуванням когнітивним навантаженням і стресом, добре відображена в даних ЕЕГ, оскільки хронічний стрес значно впливає на когнітивні показники. Діапазон альфа-ритму ЕЕГ широко досліджувався як біомаркер для оцінювання когнітивної діяльності, розумової втоми та наслідків втручань для покращення когнітивних функцій. Однак даних щодо динаміки α-діапазону під впливом тривалих стресових факторів, таких як проживання в охопленій війною країні, особливо під час когнітивного навантаження, недостатньо. Мета дослідження – порівняти нейродинаміку альфа-діапазону ЕЕГ, пов'язану із завданнями ментальної арифметики до та під час початку повномасштабного вторгнення росії в Україну.***

Методи. ***У дослідженні брали участь 57 добровольців обох статей; 28 проходили обстеження до повномасштабного вторгнення та 29 після початку вторгнення. Дані ЕЕГ записували під час виконання арифметичного рахунку подумки з подальшим виділенням піддіапазонів, а саме: α1 [7,5, 9,5] Гц, α2 [9,6, 11] Гц, α3 [11,1, 12,9] Гц.***

Результати. ***У α1-піддіапазоні можна було спостерігати збільшену кількість когерентних зв'язків у групі жінок, що здійснювали обчислення під час війни. У піддіапазоні α2 у чоловічій групі спостерігався топографічний перерозподіл зв'язків, а саме, зменшення кількості зв'язків та зсув у бік фронтальних ділянок кори. Нарешті, у піддіапазоні α3 жіноча група продемонструвала широку мережу зв'язків порівняно з чоловічою групою, де під час повномасштабного вторгнення спостерігався виразний центр зв'язків у тім'яній зоні кори великих півкуль.***

Висновки. ***Було виявлено, що під час повномасштабного вторгнення суб'єкти жіночої статі демонстрували вищий ступінь поведінкового гальмування, що можна інтерпретувати як прихований показник підвищеної фонової тривожності. Чоловіча група продемонструвала труднощі зосередження уваги на внутрішньому завданні. Нарешті, добровольці в обох групах продемонстрували загальне зниження рівня низхідного контролю над виконанням завдання.***

Ключові слова: ***нейродинаміка, електроенцефалографія (ЕЕГ), квадратична когерентність (MSC), стрес, когнітивне навантаження.***

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