Regulatory Mechanisms in Biosystems

ISSN 2519-8521 (Print)
ISSN 2520-2588 (Online)
Regul. Mech. Biosyst.

Impact of chronic stress on alpha band spectral power and the potential of digital correction of cognitive functions

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Article info

Received 11.04.2025
Received in revised form 19.05.2025
Accepted 28.06.2025

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Shkabara, A. V., Ushakova, G. O., & Severynovska, O. V. (2025). Impact of chronic stress on alpha band spectral power and the potential of digital correction of cognitive functions. Regulatory Mechanisms in Biosystems, 16(3), e25099. doi:10.15421/0225099

Chronic stress causes hormonal and neurochemical changes, disrupting the balance of excitation and inhibition processes in the brain, which affects the rhythmic activity of neural networks, particularly in terms of power spectral density (PSD) in the alpha frequency range. Also, stress negatively affects cognitive functions, including memory, attention, and executive control. This study examined the relationship between PSD in the alpha band and performance of visual memory tasks in students with different levels of perceived stress living near the front line of a military conflict. The study included resting-state electroencephalogram (EEG) recordings and cognitive tests before and after a month of training on the CogniFit platform. The results showed that increased alpha-band power in frontal regions was positively associated with visual memory performance in individuals with low stress levels. Decreased alpha activity in parietal-occipital regions predicted improved task performance. Men with low stress showed dominant activation in the right frontal area (Fp2), while women demonstrated more balanced bilateral prefrontal activity. The regression analysis revealed weaker associations between alpha activity and memory performance in the moderate stress group, which may reflect reduced neural efficiency and higher interindividual variability. After cognitive training, both groups showed increased alpha activity in the frontal cortex and decreased alpha power in parietal-occipital regions, reflecting cognitive improvement. This was associated with process automatization and a shift in activity to posterior brain regions in men. In women, prefrontal control increased, indicating more deliberate cognitive regulation. Although the cognitive training effectively improves short-term visual memory, sex-specific neural patterns were observed after training, reflecting differences in stress levels and brain organization. The results highlight individual differences in brain neuroplasticity, which should be considered when developing cognitive training programs.

Keywords: cognitive training; electroencephalography (EEG); frontal cortex; neuroplasticity; perceived stress; sex-differences; spectral power density (PSD); visual memory.

Introduction

In the context of military aggression in Ukraine, studying the psychological state and cognitive functions of young people, especially in front-line areas, becomes especially important. The impact of war on adolescents' mental health has been documented in recent research (Osokina et al., 2023). Memory is an essential cognitive function that affects adaptation to stress, academic performance, and professional development (Almarzouki, 2024). However, anxiety, sleep problems, emotional exhaustion, and stress can negatively affect visual working memory performance (Gong et al., 2024). Chronic stress, by causing changes in the neurophysiology of the brain (through the hypothalamic-pituitary-adrenal (HPA) axis, cortisol (Sherman et al., 2023) and neurotransmitter imbalance), can alter the bioelectrical activity of the brain, particularly the alpha rhythm, which can lead to problems with memory, attention, and executive functions (Schwabe et al., 2022, Dronse et al., 2023; Schwabe, 2025). Studies (Marshall et al., 2018; Pei et al., 2024) have shown a connection between prolonged stress and changes in alpha oscillations. In this regard, cognitive training is considered a promising way to correct negative changes in the brain caused by stress.

Mental and acute stress reduce the activity of the alpha band in the brain while increasing the activity of the beta components of the EEG. Gert Vanhollebeke and co-authors (Vanhollebeke et al., 2022) showed that psychosocial stressors reduce alpha activity. The decrease in alpha wave power is manifested in different phases of the stress response and is accompanied by a parallel increase in beta activity (Pei et al., 2024). This phenomenon is observed in people with anxiety disorders, who work in a noisy environment, or who are under prolonged exposure to psychosocial stress (Alyan et al., 2021).

Typically, alpha rhythms are enhanced in relaxed states and reduced during cognitive load, especially in the frontal regions (Pei et al., 2024). Alpha suppression reflects the transition of the brain to a state of increased alertness and attention, high arousal, which can be caused by motivation or stress. A prolonged decrease in the alpha band's power spectral density (PSD) can serve as a neurophysiological marker of chronic stress that persists over time and does not spontaneously normalize. Neurobiological mechanisms may explain the disappearance of alpha oscillations during stress. Prolonged stress activates the hypothalamic-pituitary-adrenal axis, leading to increased levels of glucocorticoids such as cortisol, which affect the brain. The latter induces neurochemical and structural changes, particularly in areas that generate or regulate alpha rhythms. Studies show that prolonged exposure to cortisol damages the hippocampus and neocortex – brain regions critical for memory and executive functioning. These effects are mediated by factors like reduced glucose uptake, neuronal atrophy, and decreased neurogenesis (Marshall et al., 2018). Stress-induced changes can disrupt the excitation-inhibition balance necessary for sustained alpha oscillations. In addition, stress increases the noradrenergic and sympathetic tone, contributing to cortical hyperactivation (reflected by increased beta and decreased alpha power) (Pei et al., 2024).

Chronic stress "keeps" the brain in a constant "fight or flight" mode, suppressing the calm alpha band. Over time, this neural state can exhaust regulatory circuits and impair the brain's ability to generate stable alpha activity. The reduction in alpha power is more pronounced during cognitively demanding or uncontrollable stressors (Pei et al., 2024). Some studies under stress have noted frontal alpha asymmetry (Alyan et al., 2021).

There is a strong link between alpha activity levels and cognitive function. When stress suppresses alpha power, it can impair these functions through several mechanisms. Alpha oscillations are thought to play a role in sensory information processing and attention maintenance. Higher alpha power, particularly in areas not involved in the task, is consistent with functional inhibition of distracting inputs, which aids focus (Alyan et al., 2021). During stress, widespread suppression of alpha power may indicate a loss of this inhibitory filtering. For example, a study (Marshall et al., 2018) showed that older adults with high cumulative life stress showed reduced occipital alpha activity during a working memory task, which correlated with poorer attentional control. People with high stress tended to suppress task-irrelevant brain activity, as evidenced by weaker alpha synchronization, which reduced concentration. Stress-related alpha deficits can manifest as difficulty concentrating, increased distractibility, and impaired selective attention. Low alpha power has also been associated with increased anxiety and hypervigilance (Attar, 2022), which inherently diverts attentional resources from goal-directed tasks. Alpha oscillations are closely involved in memory processes. During working memory storage, the brain often increases alpha power to protect stored information (Marshall et al., 2018). If stress blunts this alpha response, working memory performance suffers. This suggests that stress disrupts the mechanisms that support memory encoding and maintenance. Brain stimulation studies support the causal relationship between alpha rhythm and memory. Alpha brain stimulation that is out of phase with natural rhythms (i.e., disrupting the internal synchronization of alpha waves) during information retention in working memory leads to a significant decrease in parietal alpha activity and accuracy in working memory tasks. This suggests an essential role for alpha rhythm in maintaining cognitive function (Chen et al., 2023). Conversely, synphasic alpha stimulation preserves alpha activity and memory performance.

Thus, a regulated alpha rhythm is critical for working memory, and stress-induced alpha suppression can lead to memory deficits. In addition to short-term memory, chronic stress is known to impair hippocampal-dependent learning and long-term memory consolidation, partly through the effects of cortisol (Marshall et al., 2018). Decreased alpha power associated with high cortisol and anxiety may be a biomarker for these memory impairments, as low alpha has been observed with short-term memory problems (Attar, 2022). Thus, decreased alpha activity during stress correlates with poor memory retention and learning performance. Alpha rhythms in the frontal and parietal areas contribute to executive processes such as inhibition, cognitive flexibility, and decision-making (de Ramón et al., 2022). Practical executive function often requires short-term increases in alpha power to avoid distractions or to switch between tasks. Under conditions of prolonged stress, people usually exhibit executive dysfunction, for example, impaired inhibitory control and impulsive decision-making. Altered alpha activity may be one contributing factor. Studies have found that low resting alpha power is associated with executive function deficits, as well as with conditions such as depression and post-traumatic stress disorder when stress is chronic (Attar, 2022). Conversely, when alpha power is abnormally high in states of inattention, as observed in some cases of attention deficit disorder, it reflects insufficient arousal and poor executive function (de Ramón et al., 2022). Both extremes indicate that proper alpha modulation is necessary for optimal executive function. In stressed individuals with low alpha power, one would expect the frontal cortex to be over-engaged in emotional or stress-related processing, leaving fewer neural resources for executive control. Taken together, alpha oscillatory changes serve as an index of the balance between a calm, well-regulated cognitive state and excessive arousal. Insufficient alpha power (along with the accompanying excess high-frequency activity) during chronic stress may compromise the neuronal efficiency required for attentional focus, memory retention, and executive function regulation.

Neurofeedback is a technique in which people learn to increase or decrease specific brainwave frequencies using real-time EEG feedback. Numerous studies have shown that training people to increase alpha power leads to cognitive benefits. For example, in a memory study (Zoefel et al., 2011), the authors showed that just five sessions of neurofeedback training to increase the amplitude of the alpha component of the EEG led to improved spatial memory performance. A comprehensive study (Jacques et al., 2024) found that increasing alpha oscillations through neurofeedback improved working memory and attention in healthy adults. This approach strengthens the brain's capacity to generate alpha waves, potentially counteracting stress-related reductions in alpha power. In the military context, alpha neurofeedback has been proposed to preserve cognitive function during operational stress.

Empirical evidence indicates that alpha neurofeedback can reduce anxiety and symptoms of post-traumatic stress disorder. Nicholson et al. (2020) reported that individuals undergoing correction of alpha rhythm by neurofeedback experienced a decrease in PTSD symptom severity, suggesting that this approach may help restore cognitive-emotional balance in individuals exposed to prolonged stress. Some protocols train individuals to suppress excessive frontal alpha activity when it is maladaptively high. Overall, neurofeedback offers a direct mechanism for correcting alpha abnormalities, and studies suggest that it can thus improve attention, memory, and resilience to stress.

Traditional cognitive training, such as repetitive tasks targeting memory, attention, or other skills, can also affect alpha activity and stress-related cognitive abilities. A recent study by Loock & Schwabe (2024) provides striking evidence that six weeks of intensive training completely prevented stress-induced working memory deficits in healthy adults. Participants who underwent daily adaptive memory training were resilient to acute stress, performing significantly better on a memory test after stress than an untrained control group. This occurred even though both groups had similar hormonal and subjective responses to stress, suggesting that the training enhanced cognitive function even under stressful conditions. Although EEG was not measured in this study, cognitive protection suggests that training improved the functional capacity of brain regions, likely through plasticity. Indeed, prolonged training was associated with structural changes in the prefrontal cortex and hippocampus that could support brain bioelectrical activity (including alpha) during stress. The authors (de Ramón et al., 2022) reported that a 12-week digital cognitive stimulation program for children with attention-deficit/hyperactivity disorder (ADHD) resulted in significant increases in posterior alpha power compared to a sham training group. The increase in power in the alpha band was accompanied by improvements in attention, working memory, and cognitive flexibility. Interestingly, the degree of alpha enhancement correlated with a reduction in ADHD-related inattention symptoms. Although this study focused on ADHD, the results demonstrate how cognitive training can normalize abnormal alpha activity, moving it in the direction seen in healthy peers.

Furthermore, cognitive training may help restore alpha activity and related cognitive functions in individuals with chronic stress who exhibit reduced EEG alpha power. Combined lifestyle interventions show promise: in Parkinson's disease patients with cognitive impairment, a regimen of physical activity and cognitive training resulted in improved executive function, which correlated with increases in frontal theta and alpha power after the intervention (Trenado et al., 2023). This supports the idea that increased brain plasticity through training may be reflected in EEG biomarkers such as alpha, which serve as indicators of cognitive recovery. Among various mental training techniques, mindfulness meditation – often facilitated through digital platforms – has also been explored for its impact on stress regulation and neural oscillatory patterns. Meditation practices induce a relaxed but focused state, and EEG studies have shown increases in alpha power with regular meditation. A review by Lee et al. (2018) reported that during mindfulness and open-ended monitoring meditation, practitioners showed increased alpha activity in the posterior regions of the brain compared to non-meditators. Some meditation styles have also been shown to increase alpha oscillations bilaterally (Soriano et al., 2024). Increased power in the alpha band through meditation is consistent with subjective reductions in stress and anxiety. In essence, meditation can counteract the effects of stress by creating an alpha-rich state, similar to deep relaxation. Experimental studies have shown that even beginners can learn self-regulation and increase alpha power through guided meditation and neurofeedback. Such mindfulness-based interventions have been associated with improvements in attention and emotional regulation, which are typically impaired by chronic stress (Lee et al., 2018, Lee et al., 2025).

By naturally training the brain to shift into an alpha state, meditation can restore the balance between excitation and inhibition necessary for optimal cognitive function. In the context of prolonged stress (e.g., in military personnel on the front lines or in individuals with high levels of anxiety), the use of mindfulness training has shown benefits in both reducing perceived stress and normalizing biomarkers (Li et al., 2024). While more research is needed on EEG outcomes in chronically stressed populations, the available evidence strongly suggests that cognitive training and mindfulness training can induce neuroplastic changes that lead to healthier alpha activity and improved cognitive function during stress.

Thus, prolonged stress affects the brain, reducing alpha power density and leaving signs of increased arousal in EEG profiles (Vanhollebeke et al., 2022). In essence, when the brain's alpha oscillations are disrupted by chronic stress, the mind's ability to filter information, maintain working memory, and exercise top-down control is also disrupted.

Encouragingly, research over the past decade has highlighted the potential of cognitive training as a digital correction for these effects. Those who have been or are experiencing stress can benefit from various methods to improve their cognitive function and increase alpha power, including neurofeedback that targets the alpha range, structured cognitive activities, and mindfulness meditation. Such training influences neuroplasticity to restore a more balanced bioelectrical state of the brain, mitigating the effects of stress. Studies have shown improved working memory performance during acute stress (Loock & Schwabe, 2024) and increased resting alpha power after training. These interventions target the same neural circuitry disrupted by stress, promoting functional recovery. Thus, chronic stress and EEG alpha activity are inversely related, with stress attenuating alpha rhythms and impairing cognitive performance. However, targeted cognitive training can reverse or reduce these neural and cognitive changes. By enhancing alpha oscillations and, consequently, the brain networks they represent, training interventions offer a promising way to improve cognitive resilience to prolonged stress. Future research should continue to refine these digital therapeutics, explore personalized protocols (e.g., neurofeedback) for people under chronic stress, and test the long-term efficacy of alpha interventions on stress-related cognitive decline. Integrating stress neuroscience with cognitive training has great potential for creating effective techniques to enhance brain health and cognitive function in today's demanding society, where stress is becoming an increasingly prevalent burden.

The study aims to investigate the effects of stress and cognitive training on the neurophysiological functioning of visual memory by analyzing power spectral density in the alpha range and coefficients of determination across different brain regions.

Materials and methods

Formation of study groups. Before the study, each participant was familiarized with the study design and signed an informed consent. The study was approved by the Bioethics Commission of Oles Honchar Dnipro National University (protocol No. 1, dated 17 October 2023). The Declaration of Helsinki, the UNESCO Declaration of Principles on Tolerance, and the Convention for the Protection of Human Rights in Biology and Medicine conducted it.

Volunteers from among the students who signed an informed consent to participate in the study were selected based on stable physical and mental health and the absence of mental, neurological, or cognitive problems. Subsequently, individuals were selected from those who had high positive and low negative affect on the emotional well-being scale (PANAS), slept at least 7 hours in the last 5 days, and had general cognitive functional status (according to the Mini-Mental State Examination method) within normal limits, a level of memory and attention assessed by the CogniFit Memory Test, at computerized cognitive assessment tool (CogniFit Inc., San Francisco, California, USA) at not lower than average, and an average or high level of emotional resilience (Connor-Davidson Resilience Scale). All were right-handed, as determined by a battery of generally accepted tests, with normal or corrected-to-normal vision. Participants with a history of serious eye diseases that could affect visual function were excluded. To ensure that the results reflected real cognitive processes, a balance was found between experimental control and environmental validity.

In the first stress test, 1200 students participated in the test of the Perceived Stress Scale (PSS-10) (Cohen, 1983). For the main study, 160 students aged 18–24 years were selected who voluntarily agreed to participate. This age range was chosen because it corresponds to the period of intensive cognitive function development. For further analysis, participants were divided into groups with low and medium levels of perceived stress, each consisting of forty women and men, to investigate sex differences in their visual memory.

The women were tested during the follicular phase of the menstrual cycle (days 5–10) to reduce hormonal influences on cognitive function. The menstrual cycle phase was determined using the calendar method. In one of the five individuals, hormone levels (luteinizing hormone, estradiol, and progesterone) were analyzed, which allowed us to minimize errors associated with individual variations in cycle length.

Procedure for collecting and analyzing electrophysiological data. The Neurocom complex (KHAI Medyka, Ukraine) was used to record the brain's bioelectrical activity. To minimize external influences, participants were placed in a separate noise-insulated chamber. Signal recording was carried out using silver chloride electrodes located according to the international system "10–20%." Conductive gel improved the contact between the electrodes and the skin, and the resistance did not exceed 5 kOhm. Recording was carried out at a sampling frequency of 500 Hz.

After obtaining the sketch, artifacts were removed automatically and, if necessary, manually. The entire recording was divided into 10-s periods for analysis.

The study participants were asked to relax and avoid active thinking to reduce the impact of stress factors before the start of the study. All data were stored in the Neurocom Professional database for further analysis, real-time signal monitoring was performed, and settings were adjusted if necessary.

The study was carried out in the following stages: EEG at rest (eyes closed, 1 min); EEG at rest (eyes open, 1 min); EEG during a visual memory task (CogniFit); EEG after training for one month (CogniFit).

Visual memory study. To evaluate short-term visual memory, we employed the CogniFit platform (USA) using the WOM-REST Recognition Test. This assessment is derived from classical cognitive paradigms, including the Symbol Search subtest of the WAIS, the Wisconsin Card Sorting Test (Heaton, 1981), and Raven's Progressive Matrices. During the task, participants were asked to memorize a series of visual stimuli and subsequently identify them among distractor images (www.cognifit.com, USA).

Statistical processing of the obtained data. The study used stratified randomization to balance the distribution of participants by gender and stress level. Using a computer-generated random number, students were randomly assigned to four experimental groups, each consisting of 40 students. This method ensured an even distribution between the groups and reduced the likelihood of confounding. The experimenter who analyzed the EEG data and cognitive performance did not have access to information about the participants' stress level or their distribution into groups. This reduced the risk of subjective influence when analyzing the results. The sample size (40 participants in each group) was determined based on the principles of statistical power. Considering the expected effect size, the level of statistical significance ($\alpha = 0.05$), and the required power of the test ($1-\beta = 0.80$), preliminary calculations using G*Power showed that such a sample is sufficient to obtain reliable conclusions. For each group, the mean value of performance and standard error (SE) were calculated to assess the variability of the results within the group. To determine the changes in task performance in each group between the first test and the retest one month later, a one-way analysis of variance (ANOVA) was used, performed in the RStudio 2023.12.1 environment. Before performing the ANOVA, the normality of the residuals' distribution was checked using the Shapiro-Wilk test. The homogeneity of variances assumption was verified using Levene's test. Post-hoc analyses were conducted using the Bonferroni correction ($P < 0.05$) in cases of statistically significant effects. To assess the relationship between the power spectral density (PSD) in different EEG bands (in this example, in the alpha band) and the performance of visual memory tasks, linear regression analysis was used in the same RStudio 2023 12.1 environment. This analysis was limited to data previously identified as statistically significant. Before conducting the analysis, the linearity of the relationship was checked using the residual plot and the Ramsey test; the normality of the residuals was assessed using the Shapiro-Wilk test; and the homoscedasticity of the residuals was checked using the Breusch-Pagan test (bp test). Regression graphs and heat maps were constructed to visualize the data.

Results

Perceived stress level among students in the frontline zone. At the beginning of the study, we conducted a psychometric survey of 1,200 students in the frontline zone using the Perceived Stress Scale (PSS). The purpose of the study was to assess the level of psychoemotional state of each participant and identify groups with different levels of stress sensitivity.

All respondents were divided into three groups according to their subjective perception of difficult life situations and ability to adapt to stress. 22% of students showed a low level of stress, which indicates their emotional stability and ability to self-regulate. 62% had an average level of stress, which corresponds to standard reactions to learning and life stress. 16% had a high level of stress, which indicates significant psychological stress and the need for additional adaptation methods (Fig. 1). For further study, groups of men and women (n = 40 in each group) were selected who had a low or moderate level of perceived stress.

Comparison of visual memory test performance in men and women with different levels of perceived stress before and after training on the CogniFit platform. In men with a low level of perceived stress (hereinafter referred to as low stress for brevity), a repeated-measures ANOVA followed by a post hoc Bonferroni correction revealed a statistically significant improvement in task performance after cognitive training, $F_{1,78} = 260.67$, $P = 5.07 \times 10^{-17}$ (Fig. 2a).

The mean percentage of correctly completed tasks increased from M = 76.06, SD = 3.15 before training to M = 89.4, SD = 4 after training. A similar trend was observed in women: $F_{1,39} = 107.41$, $P = 1.67 \times 10^{-14}$ (Fig. 2b); the mean percentage of correctly completed tasks increased from M = 78.20, SD = 2.00 before training to M = 93.05, SD = 5.98 after training.

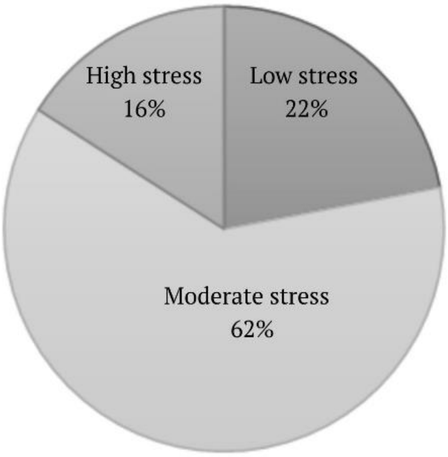

Fig. 1. Distribution of students (n = 1200, 2024) by level of perceived stress (according to PSS-10)

Performance in men with medium levels of perceived stress (mean stress level) was $F_{1,79} = 42.19$, $P = 8.10 \times 10^{-11}$ (Fig. 2c); the mean percentage of correctly completed tasks increased from M = 67.47, SD = 8.16 before training to M = 81.72, SD = 8.64 after training. A similar trend was found in women: the mean before training was $F_{1,38} = 12.95$, $P = 7.61 \times 10^{-4}$ (Fig. 2d). The mean percentage of correctly completed tasks increased from M = 75.13, SD = 13.95, before training to M = 83.88, SD = 6.83 after training. This indicates that digital exercises were practical in improving short-term visual memory for people with different levels of stress.

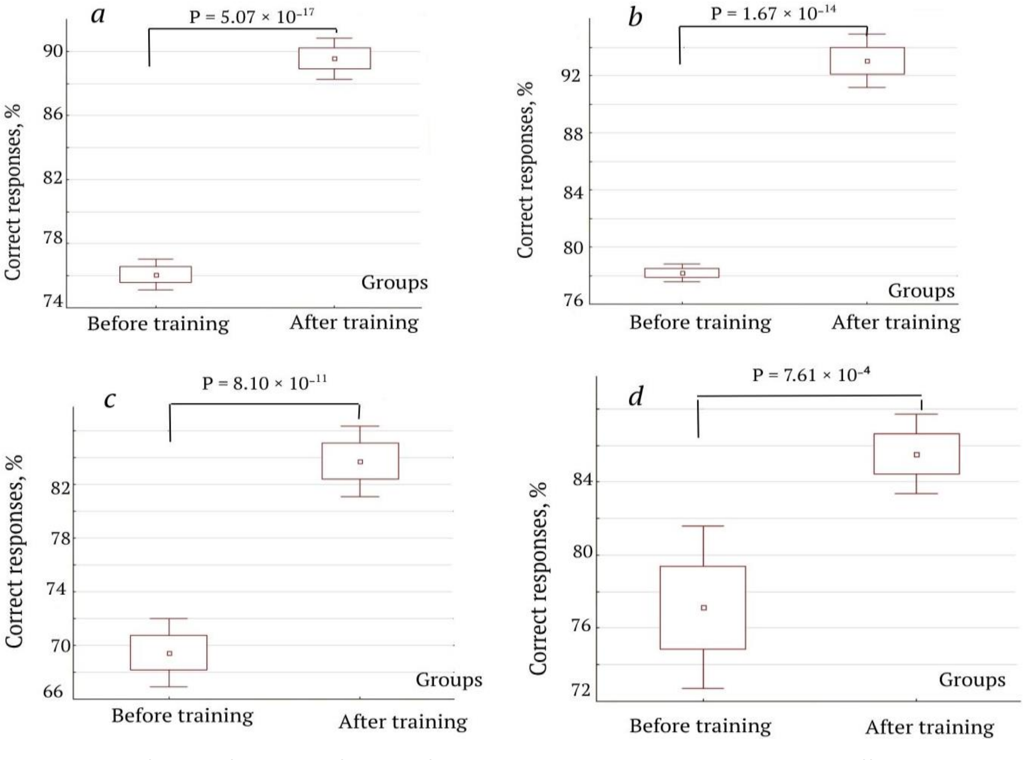

Fig. 2. Comparison of task performance before and after cognitive training in men and women with different perceived stress: boxplots show the percentage of correctly completed tasks before and after the cognitive training; small squares represent the mean values (M), and vertical lines (whiskers) represent the standard deviation (SD); boxes indicate the interquartile range (IQR): *a* – men with low perceived stress; *b* – women with low perceived stress; *c* – men with medium perceived stress; *d* – women with medium perceived stress

Analysis of the relationship between neurophysiological indicators and visual memory performance at the first test. In the second stage, we conducted a regression analysis to study the relationship between the power spectral density (PSD) in the alpha-band of the EEG, recorded during the first visual memory test, and the performance of the task, which allowed us to determine to what extent neurophysiological indicators of brain activity can predict the effectiveness of cognitive activity, especially visual memory. The results obtained for men with low stress levels are presented in the graph (Fig. 3), demonstrating the relationship between PSD in prefrontal brain areas and performance in visual memory tasks. A significant positive regression coefficient was found at Fp1 between PSD and the number of correct responses ($\beta = 14.62$, 95% CI [5.46, 23.78], $P = 2.56 \times 10^{-3}$, $R^2 = 0.22$). According to the beta-independent regression coefficient (β), the number of correct responses increases by 14.62 on average when the PSD increases by one unit (V^2/Hz). The 95% confidence interval for the β coefficient is denoted as the CI. The coefficient of determination R^2 shows that changes in the PSD at Fp1 can explain 21.5% of the variation in correct responses. Other factors that were not considered in this model account for 78.5% of the variation.

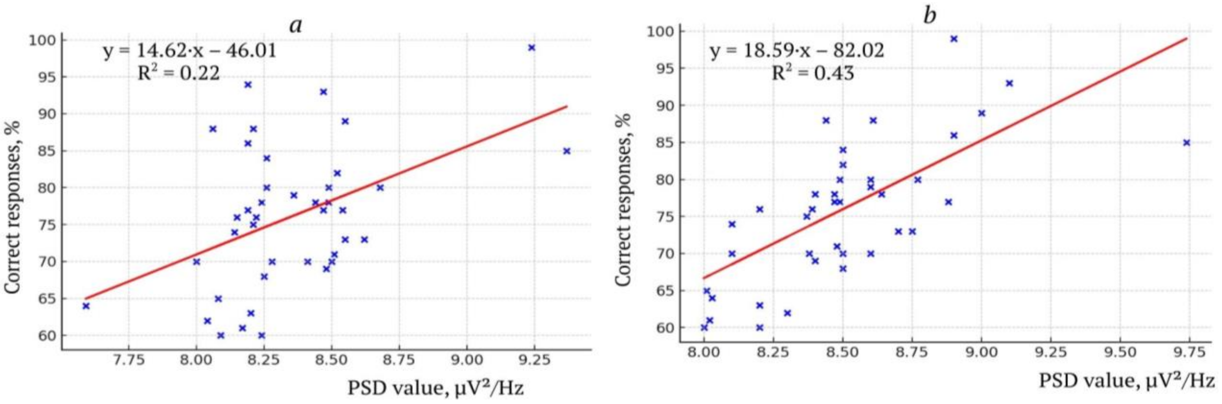

Fig. 3. Regression analysis graphs between the power spectral density at points Fp1 (*a*) and Fp2 (*b*) (alpha-band) and the performance of the visual memory task in men with low stress levels (first test): horizontal axis (X) is the PSD value (μV²/Hz) in the alpha-band; vertical axis (Y) is the percentage of correctly completed visual memory tasks

Thus, this model shows a moderate relationship between activity in the left prefrontal region and visual memory performance. This means that although the left prefrontal cortex in this part of the left hemisphere influences task performance, it is not the only factor that determines the outcome.

At Fp2, a significant relationship was also found between the left prefrontal cortex and performance ($\beta = 18.59$, 95% CI: [11.53; 25.64], $P = 4.66 \times 10^{-6}$, $R^2 = 0.43$). The model explains 42.8% of the variation in the results, indicating that the right prefrontal cortex has a stronger connection with visual memory than the left and is the leading one in regulating cognitive processes related to memorizing visual information.

The following key statistical data for each EEG lead demonstrate a relationship between power spectral density (PSD) at other EEG points and visual memory task performance, presented in a generalized form (Table 1).

Regression analysis showed statistically significant inverse relationships between visual memory task performance in most studied brain areas and SPD in the alpha band in men. The strongest relationships were found in the occipital-parietal areas (Oz, P3, P4, Pz). The coefficients of determination (R^2) ranged between 0.68 and 0.71 ($P < 0.001$). These results show that reduced electrical activity in the mentioned areas has a positive effect on visual memory performance. The coefficient of determination in central regions reached up to 0.67 ($P < 0.001$). The results indicate that the reduction in alpha SPD in the central areas of the cerebral cortex largely explains the variation in cognitive performance, with the most significant effect observed at point C4. Regression analysis showed statistically significant inverse relationships between the PSD in the alpha band and task performance in most of the studied brain areas (except the frontal regions) in stress-resistant women during the first visual memory test. Frontal alpha enhancement (Fp1, Fp2) was associated with better task performance and moderate effect sizes ($R^2 \approx 0.30$; $P < 0.001$). A probable ($P < 0.001$) inverse effect is observed in the central, parietal, and occipital areas. A decrease in alpha activity improves task performance. This may be because low alpha activity in these areas reflects increased cortical excitability, enhancing spatial, visual, and sensorimotor data processing. The most significant effects ($P < 0.001$) were observed in women (in the occipital Oz ($R^2 = 0.55$) and central C3 ($R^2 = 0.65$) areas. This emphasizes their essential role in visuospatial processing and motor integration. For other EEG points, the regression coefficients were not statistically significant ($P > 0.05$), indicating no reliable relationship.

Table 1

The regression analysis of results between the PSD in the alpha-band and the performance of the visual memory task in men and women (first test), n = 40

Participant group	EEG channels	β	95% CI	Level of statistical significance, P	R^2
Men with low stress levels	C3	–6.00	–7.83; –4.17	7.77×10^{-8}	0.54
	C4	–9.44	–11.59; –7.28	8.55×10^{-11}	0.68
	Cz	–5.91	–7.91; –3.9	5.69×10^{-7}	0.49
	P3	–29.34	–35.65; –23.03	1.81×10^{-11}	0.70
	P4	–24.89	–30.55; –19.24	7.55×10^{-11}	0.68
	Pz	–27.01	–32.91; –21.10	1.84×10^{-11}	0.69
	Oz	–22.91	–27.68; –18.15	7.12×10^{-12}	0.71
Men with moderate stress levels	C3	–6.46	–10.38; –2.54	1.93×10^{-3}	0.23
	Pz	–10.55	–20.72; –0.38	4.24×10^{-2}	0.11
Women with low stress levels	Fp1	6.78	3.39; 10.16	1.44×10^{-4}	0.30
	Fp2	7.10	3.70; 10.51	2.40×10^{-4}	0.32
	C3	–14.87	–8.49; –11.25	4.45×10^{-10}	0.65
	C4	–4.67	–8.40; –0.94	1.56×10^{-2}	0.14
	Cz	–4.79	–7.69; –1.89	1.85×10^{-3}	0.23
	P3	–6.24	–8.73; –3.75	1.07×10^{-5}	0.40
	P4	–5.42	–7.13; –3.70	1.65×10^{-7}	0.52
	Pz	–5.35	–7.26; –3.43	1.81×10^{-6}	0.46
	Oz	–6.74	–8.73; –4.75	3.84×10^{-8}	0.56
Women with moderate stress levels	C3	–7.99	–12.96; –3.03	2.36×10^{-3}	0.22

The number of relationships between the PSD in the alpha band and performance on the association task is limited in students with a moderate stress level. A statistically significant inverse relationship ($P < 0.001$) was found at point C3 in both men and women, explaining approximately 23% of the variance in performance. A similar, though weaker, negative association was observed at Pz in men ($R^2 = 0.11$). At other EEG sites, the relationships were not statistically significant.

Analysis of the relationship between neurophysiological indicators and visual memory performance after training in the CogniFit program. To assess the impact of cognitive training on brain activity and memory efficiency, the relationship between neurophysiological indicators and visual memory performance after training on the CogniFit platform was investigated. The study allows us to determine the neurophysiological changes that occur after training and how these changes are related to task performance. The results of the regression analysis, indicating essential indicators that are associated with the improvement or deterioration of visual memory, are presented below.

In men with low-stress levels after a month of training, significant ($P < 0.001$) relationships were found between the PSD and task performance in the frontal sites: Fp1, $R^2 = 0.590$, and Fp2, $R^2 = 0.963$ (Table 2). The right prefrontal area is a key region with the highest coefficient of determination, playing a crucial role in cognitive adaptations following training. In central areas, an inverse probable relationship of varying strength is observed between the PSD level and performance. An increase in PSD alpha band EEG in these regions is associated with a decrease in task accuracy, which may indicate an increase in cognitive load or ineffective compensatory mechanisms. C4 has the most significant influence ($R^2 = 0.96$), which means it makes an essential contribution to the control of cognitive processes. The strong negative regression coefficient between PSD and task performance in the parietal regions suggests that performance becomes less efficient when neural activity in these areas increases. The coefficient of determination values range from 0.734 to 0.890 ($P < 0.001$). In women, similar to men, higher alpha PSD in the frontal regions positively predicted memory performance, according to the regression analysis. The Fp1 model explained 78% of the variation, and the Fp2 model explained 70% of the variation. The central regions showed an average level of performance. C3 ($R^2 = 0.65$) has the most significant effect, as a decrease in PSD is accompanied by the most significant increase in performance. A strong inverse association between alpha power and task performance was observed in the parietal (P3, P4) and occipital (Oz) regions ($p < 0.001$), explaining up to 84% of the variance. This suggests that reduced alpha activity facilitates better cognitive and visual memory performance.

After a month of training in men with an average stress level, significant regression relationships between the PSD and performance of visual memory tasks were found in the central and parieto-occipital areas. A significant inverse relationship between PSD and performance was seen in C3, C4, and Pz, with explained variance ranging from 48% to 60%. The most pronounced effects were observed in C4, P4, and Oz, each accounting for over 70% of the variability, suggesting their central role in post-training cognitive improvements. The negative connection implies that a drop in PSD in these areas leads to improved performance results, suggesting better cognitive integration following training. Other EEG areas showed no notable associations. In women with an average stress level after training, significant inverse relationships were found between power spectral density and task performance in the central, parietal, and occipital areas ($P < 0.001$), with explained variance reaching up to 74%. The most substantial effects were found in P4 and Oz, highlighting their key role in cognitive and visual memory processes. No statistically significant relationship was found between spectral power density and task performance in other EEG channels.

Table 2
The regression analysis of results between the PSD
in the alpha-band and the performance of the visual memory task
in men and women (after training), n = 40

Participant group	EEG channels	β	95% CI	Level of statistical significance	R²
Men with low stress levels	Fp1	2.56	1.87; 3.25	8.60×10^{-21}	0.59
	Fp2	10.40	9.73; 11.08	1.91×10^{-21}	0.96
	C3	–15.99	–19.08; –12.89	1.32×10^{-5}	0.74
	C4	–4.62	–4.92; –4.31	1.31×10^{-5}	0.96
	Cz	–4.21	5.76; –2.66	2.66×10^{-6}	0.44
	P3	–5.20	–5.79; –4.61	5.42×10^{-20}	0.89
	P4	–5.25	–5.91; –4.60	1.12×10^{-18}	0.87
	Pz	–4.50	–5.39; –3.61	4.21×10^{-21}	0.73
	Oz	–4.87	–5.67; –4.07	6.34×10^{-21}	0.79
Men with moderate stress levels	C3	–4.69	–6.27; –3.10	6.10×10^{-7}	0.49
	C4	–5.56	–7.16; –3.95	2.44×10^{-8}	0.56
	P3	–5.60	–6.72; –4.48	1.80×10^{-11}	0.73
	P4	–6.80	–8.18; –5.42	2.11×10^{-10}	0.72
	Pz	–12.64	–16.07; –9.22	5.79×10^{-11}	0.59
	Oz	–18.65	–22.17; –15.13	2.78×10^{-9}	0.75
Women with low stress levels	Fp1	5.81	4.83; 6.79	$8{,}90 \times 10^{-14}$	0.78
	Fp2	6.97	5.49; 8.45	1.72×10^{-11}	0.70
	C3	–6.63	–8.24; –5.02	4.33×10^{-10}	0.65
	C4	–5.55	–6.96; –4.14	1.20×10^{-9}	0.63
	Cz	–5.36	–6.82; –3.91	2.49×10^{-9}	0.59
	P3	–7.05	–8.07; –6.04	2.6×10^{-20}	0.84
	P4	–6.88	–7.97; –5.79	1.13×10^{-20}	0.81
	Oz	–5.29	–6.37; –4.20	5.43×10^{-12}	0.72
Women with moderate stress levels	C3	–4.20	–5.43; –2.97	3.22×10^{-8}	0.56
	C4	–3.90	–5.08; –2.73	5.89×10^{-8}	0.54
	Cz	–5.08	–6.46; –3.70	6.10×10^{-9}	0.59
	P3	–5.99	–7.46; –4.51	1.21×10^{-9}	0.63
	P4	–6.54	–7.80; –5.28	8.87×10^{-13}	0.73
	Pz	–4.86	–6.05; –3.66	6.06×10^{-10}	0.64
	Oz	–5.27	–6.31; –4.25	1.01×10^{-12}	0.74

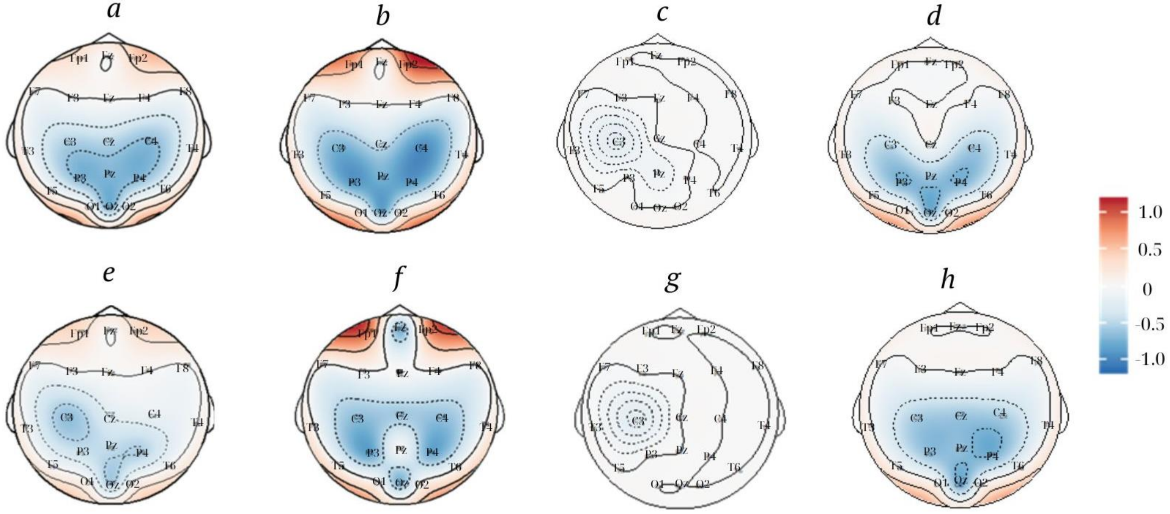

Fig. 4. Topographic heatmaps illustrating the results of the regression analysis between spectral power density in the alpha band (8–12 Hz) and visual memory scores in men and women with different levels of stress tolerance: *a* – men with high stress tolerance during the first test; *b* – men with high stress tolerance after training; *c* – men with moderate stress tolerance during the first test; *d* – men with moderate stress tolerance after training; *e* – women with high stress tolerance during the first test; *f* – women with high stress tolerance after training; *g* – women with moderate stress tolerance during the first test; *h* – women with moderate stress tolerance after training; the color scale represents beta coefficients: blue areas indicate negative values, and red areas indicate positive values; the color intensity corresponds to the coefficient of determination (R²) – the higher the R², the stronger the color

To visualize and interpret the obtained data, we used heat maps that display the value of the coefficient of determination (R^2) and the direction of the regression coefficient (β). This method allowed us to clearly show the strength and path of the interaction between spectral power and task performance.

During the first task, low-stress men showed slightly increased regression and determination coefficients in the prefrontal point Fp2, indicating the dominance of right-hemisphere neural mechanisms in spatial processing and memorization. Women showed a more balanced prefrontal cortex involvement, indicating an even distribution of neural activity between the hemispheres during the visual memory tasks. Overall, the coefficients of determination suggest that higher alpha power in the frontal cortex predicts better cognitive performance.

At the same time, for men with low-stress levels during the first attempt at a cognitive visual test, a decrease in PSD in the alpha band in the posterior regions of the brain (parietal-parietal-occipital) was also an essential factor in improving performance. In women, this relationship is less pronounced, although a negative association between alpha activity and performance is observed in the posterior brain regions. Men and women with moderate stress levels performed lower in the first visual memory test than those with low stress levels. This is confirmed by the smaller number of significant ties (C3 and C4 in men and C3 in women) and low R^2 values. The values obtained suggest a weaker association between brain activity and performance. Our data shows instability or irregularity in neural patterns, indicating problems with cognitive information processing in people under stress.

Motor control, sensorimotor integration, and cognitive flexibility are associated with central cortical areas, specifically C3 and C4. The low regression connectivity values in these areas in men and women with moderate stress may indicate less effective interaction between sensory and cognitive processes, which makes it challenging to perform visual memory tasks effectively. In addition, the central left hemisphere (C3) is more associated with language functions, and the fact that it was less critical in the group of students with moderate stress may indicate a different cognitive strategy for completing the tasks. After training, stress-resistant men showed an increased coefficient of determination (R^2) in frontal areas, with dominance at Fp2. Women demonstrated a similar performance dependence on the increase in PSD in the alpha band of the frontal brain regions. Still, they involved both hemispheres during the task, which is confirmed by high R^2 values in Fp1 and Fp2. As a result, decreased spectral power density in the alpha band at points C3, C4, Cz, P3, and P4 improved task performance. This trend was similar in men; there was also a dependence on PSD in the alpha band at point Pz.

After training in the CogniFit program, values in the parieto-occipital cortex of the brain decreased in people with a moderate level of stress: the regression coefficient β decreased, indicating an improvement in cognitive processes, and the coefficient of determination R^2 increased, indicating a stronger relationship between brain activity and mental performance. We can talk about improved results after training, but they remained lower than in individuals with a low stress level.

In summarizing the results, it is worth noting that in stress-resilient men, after training, meaningful brain activity shifts from the frontal zones to the parieto-occipital regions, indicating the automation of these processes. That is, task performance became more mechanical and less energy-consuming. In women, cognitive control was increased after training due to the activation of the frontal zones (Fp1, Fp2).

Thus, an increase in positive associations in the frontal areas and a decrease in alpha activity in other cortical regions (particularly in the parietal and occipital zones) indicate the optimization of cognitive control and a more efficient use of brain resources. In general, all groups demonstrated improved neural activity, which means they involved adaptive mechanisms of brain plasticity in response to digital training.

Discussion

Group disparities in cognitive and EEG activity. Substantial variability in cognitive performance and EEG spectral characteristics across different groups, influenced by factors such as gender, stress, and baseline cognitive functioning, highlights the importance of subgroup analyses for optimizing cognitive training interventions and understanding brain – behavior associations. Recognizing these group-specific variations is crucial for identifying individuals who are most likely to benefit from mental training and for elucidating the relationship between brain activity and task performance within each subgroup.

Men and women often exhibit different EEG activity profiles during cognitive tasks. For example, men typically exhibit higher beta power, while women exhibit higher alpha power during cognitive tasks (Corsi-Cabrera et al., 1993).

Despite similar task performance, women's and men's brains may function differently. For example, Ghazi et al. (2021) found that women have greater modulation of peak alpha frequency, although working memory performance is similar to that of men.

There are also differences in connectivity: women show higher interhemispheric (interparietal) EEG coherence than men when performing cognitive tasks (Corsi-Cabrera et al., 1993). These data are consistent with our findings on gender-specific variations in PSD in the alpha-band EEG, indicating that the dynamics of neural oscillations during memory tasks may vary by gender, even when task performance is the same.

Stress is known to negatively affect cognitive abilities, particularly memory and attention (Cocenas-Silva et al, 2019). A meta-analysis of the psychosocial consequences of stress showed that stress consistently reduces alpha activity and tends to increase beta activity (Vanhollebeke et al., 2022, Saffari et al., 2023). Such differences show that stress can affect brain bioelectrical activity and cognitive test results, meaning it needs to be controlled for maximum cognitive learning effectiveness.

Also, a person's initial cognitive abilities can influence EEG activity and learning outcomes. Studies show that people with superior memory and cognitive skills often have distinct neural signatures, for example, higher peak alpha frequency or stronger alpha power. Peak EEG alpha frequency distinguishes high-performing individuals from low-performing individuals (Angelakis et al., 2004). This means that the brain's basic oscillatory properties reflect its cognitive potential. Cognitive learning studies show that basic EEG parameters can be associated with individual differences in learning ability. It has been found (Juras et al., 2025) that higher levels of alpha activity in the parietal zone at rest are associated with significant improvements in working memory training.

Our findings are consistent with these observations: participants with higher initial performance levels and corresponding alpha-activity profiles – demonstrated distinct neurophysiological mechanisms during and after visual-memory training. Since individual cognitive baselines and neural dynamics can shape the effectiveness of mental training, accounting for such group differences is essential when developing personalized cognitive-training approaches (Jaiswal et al., 2019; Marakushyn et al., 2024).

Effects of cognitive training on attention, memory, and brain bioelectric activity in the alpha-band. Brain games, working memory tasks, and neurofeedback techniques are effective in improving cognitive function while simultaneously inducing changes in EEG spectral characteristics, particularly in the alpha rhythm. Our results demonstrate an increase in visual memory task performance after a month of training on the CogniFit platform, which is consistent with numerous studies that confirm cognitive function improvements in response to mental training.

Memory and related skills can be significantly improved through cognitive training. For example, older adults who underwent working memory training showed moderate to significant improvements in performance on memory-related tasks (Spironelli & Borella., 2021). In our study, both men and women improved their visual short-term memory after training, with a ~17–19% increase in task performance, consistent with the literature. Meta-analytic studies confirm that regular performance on working memory tasks significantly improves performance (Spironelli & Borella., 2021). Performance changes are most noticeable on tasks that resemble the training tasks (near-transfer effects), but in some cases, the effect may extend to untrained aspects of memory.

In addition to memory, cognitive training can improve attention and executive function. Many memory training programs improve attention and reduce distraction as the brain learns to filter out relevant information. In the example above (Spironelli & Borella., 2021), training increased memory capacity and reduced errors through inhibitory control. This suggests an improved ability to maintain attention and reduce the impact of external distractors on a task. Research shows that working memory training improves sustained attention and task-switching efficiency, even in individuals with attentional control problems (Salminen et al., 2012; Luo et al., 2017). Thus, our finding of improved task performance, with increased speed and reduced errors after training, is consistent with the broader evidence that cognitive training promotes attention and memory.

Cognitive training is accompanied by changes in brain activity, especially in the alpha frequency range (8–12 Hz), which is associated with a state of relaxed alertness and information processing. In many cases, alpha power modulations reflect increased neural efficiency. As shown in studies of alpha neurofeedback (Zhou et al., 2022a, 2022b), participants who learned to increase alpha activity performed better on cognitive tasks. In addition, it was found that people with the highest levels of alpha band activity showed the most significant performance gains. Our participants also showed post-training changes in alpha spectral power that included increases in the prefrontal region and decreases in the parieto-occipital areas. These patterns are consistent with the idea that training induces a rebalancing of bioelectrical activity – some brain regions exhibit higher alpha activity to conserve resources and attention retention, while areas most activated during the task demonstrate suppression of the PSD alpha component to engage more actively. A study of elderly participants who underwent working memory training (Spironelli & Borella., 2021) found an increased beta/alpha ratio in frontal brain regions, indicating increased cortical activity. According to our data, the alpha power spectrum during visual memory tasks shifts after training, reflecting some neurophysiological adaptation. Taken together, these results support the idea that cognitive training improves behavioral performance and tunes brain bioelectrical activity, especially alpha components, in a way that promotes mental performance.

Mechanisms of brain plasticity underlying EEG changes following training. Functional and plastic changes in key neural networks accompany the cognitive improvements related to training. Our findings suggest that the prefrontal, parietal, and occipital cortices play essential roles in developing training-induced neuroplasticity. Training may improve attention and memory performance by enhancing frontal-mediated cognitive control and optimizing alpha activity in the brain's posterior regions, specifically the parieto-occipital areas.

The prefrontal cortex plays a crucial role in executive functions, including attentional control, strategic thinking, and organizing working memory. Our study showed that after training, alpha activity in the prefrontal cortex, specifically at the Fp2 site, was positively associated with accuracy on visual memory tasks, indicating that frontal regions predict cognitive success. These findings are consistent with previous data indicating the involvement of frontal mechanisms during mental training.

Increased coherence between the frontal and parietal cortices demonstrates improved top-down regulation. As a result, after training, the prefrontal cortex has better control over the activity of posterior regions. Neurofeedback studies support the idea that targeted modulation of frontal cortex alpha activity can improve cognitive function and strengthen functional connections between the parietal and frontal cortices (Zhou et al., 2022). The results show that training enhances the prefrontal cortex's ability to coordinate cognitive processes more effectively. Maintaining optimal levels of frontal alpha activity, which promotes focus, helps achieve cognitive performance. In other words, training improves task control and regulates neural rhythms (such as alpha or beta) according to the needs of cognitive performance. The parietal regions of the brain play a crucial role in visuospatial processing and storing information in working memory. Our study showed that after training, alpha spectral power in areas P3 and P4 was inversely proportional to memory performance; that is, lower levels of alpha band power were associated with better cognitive performance. This suggests that the most effective participants had more pronounced alpha desynchronization in parietal areas during memory tasks, which led to better neural processing. It is known that alpha desynchronization in the parietal cortex is an indicator of active engagement of neural networks and improved information processing efficiency (Strzelczyk & Langer, 2024). When a person memorizes visual information, the alpha rhythm in the parietal and occipital regions decreases, facilitating cognitive processing. Studies show that the level of parietal alpha desynchronization during information encoding is directly correlated with memory quality. According to simultaneous EEG and fMRI studies, it was found that a decrease in alpha activity in the parietal zone is accompanied by increased frontoparietal communication and activation of the occipital cortex, which indicates the effective involvement of executive regions of the brain in controlling memory processes (Strzelczyk & Langer, 2024).

Our results show that participants who exhibited reduced parietal alpha activity (indicating activation of the parietal cortex) performed better on a visual memory test after training. This suggests cognitive training improves memory and concentration by improving coordination between the parietal cortex and frontal areas.

Our work provides evidence that a post-training reduction in occipital PSD alpha band is linked to improved memory performance, thereby confirming its relevance in cognitive processes. These findings support the idea that high occipital alpha activity may signal the exclusion of visual information flow and that its decline shows active involvement in visual data processing. The frontal cortex exerts top-down regulation by reducing occipital alpha activity, which improves visual processing (Lenartowicz et al., 2016).

During training on the CogniFit platform, students likely improved their ability to regulate occipital alpha power: they learned to reduce the alpha rhythm at critical moments to optimize the visual cortex's function. This, in turn, could improve the connection between the occipital and parietal areas (responsible for storing images) and between the occipital and the frontal regions, which helps filter and control attention more effectively. Studies (Ericson et al., 2024) confirm that after intensive training in visuospatial working memory, synchronization of alpha waves occurs between different brain areas, including the occipital and parietal regions. These improvements contribute to better performance not only in tasks participants have already learned but also in those they encounter for the first time.

Changes that occur at the level of neural networks indicate that the occipital cortex becomes more integrated into the memory system, which contributes to the improvement of visual information retention and processing. Our data, which demonstrates an inverse relationship between occipital alpha power spectral density (PSD) and memory accuracy, suggests that training activates the occipital cortex more effectively. This may be due to reduced alpha inhibition, which improves visual attention and encoding. Thus, during cognitive training, coordinated changes in brain function occur. The frontal cortex controls alpha rhythms to optimize cognitive processes, while the parietal and occipital cortices show adaptive dynamics of alpha activity: desynchronization during concentration and synchronization during rest periods or when resisting distractions. The mechanism of these changes is likely related to the modulation of alpha oscillations in the posterior brain by regulatory signals from the prefrontal cortex, which is consistent with the concept of impulse inhibition (Zhou et al., 2022a, 2022b). Regular training helps to strengthen this mechanism, increasing the coherence and efficiency of neural connections. Importantly, these changes can be transferred to other cognitive processes. The study demonstrated that a gradual increase in alpha synchronization between key frontal-parietal-occipital connections is accompanied by the transfer of improvements in visuospatial working memory to new tasks (Ericson et al., 2024). This supports the hypothesis that alpha oscillations act as a regulatory mechanism of neural plasticity, contributing to more efficient functional interaction between brain regions.

Our results are crucial for grasping the physiological foundation of cognitive development in light of the current studies. EEG spectral power, particularly in the alpha band, is a primary biomarker in cognitive function and its improvement. In practice, this means that initial EEG parameters can help predict individual response to training, as there is evidence that certain alpha rhythms can predict training success (Juras et al., 2025). This may open opportunities for the development of personalized cognitive training programs. First, individuals with initially low alpha power or high stress can undergo relaxation or neurofeedback sessions beforehand, which will help them better adapt to the training program. Second, the differences related to gender and stress factors confirm the need for an individualized approach – adapting training to the characteristics of different groups can significantly improve results. Third, the neurophysiological mechanisms identified (frontal control and posterior alpha activity plasticity) highlight the flexibility of neural networks, and that targeted cognitive training can alter functional interactions between the prefrontal, parietal, and occipital cortices. This neuroplasticity has significant potential, which means that cognitive functions such as memory and attention can be improved in individuals with initial cognitive deficits.

Our findings support the idea that cognitive training improves cognitive skills and promotes adaptive changes in brain rhythms and interregional interactions, which are the basis for overall cognitive resilience (Zhou et al., 2022a; Juras et al., 2025).

CogniFit is a popular platform for cognitive assessment and training in clinical and research settings. It has a proven scientific methodology, allows you to analyze more than 20 cognitive functions, and offers practical methods for improving them. Its importance in cognitive neuroscience is confirmed by its widespread use in more than 580 scientific institutions. Using the platform for studying cognitive disorders and insomnia, doctors and researchers have digital tools for assessing and correcting cognitive disorders (Preiss et al., 2013; Haimov et al., 2013). It can also be used for comprehensive cognitive screening of individuals, which makes it a valuable tool not only in clinical diagnostics and treatment but also in education (Peretz, 2011; Shatil, 2013). Our studies indicate that cognitive performance and neurophysiological processes can be improved using tasks from the CogniFit platform. Alterations in alpha spectral power show neuroplasticity mechanisms following training. This means the training can improve memory and reduce the effects of stress.

Conclusion

This study's results confirm that perceived stress significantly influences the neurophysiological mechanisms of visual memory. This influence is reflected in the spectral power density in the alpha frequency range and the coefficients of determination across various cortical areas.

Stress affects emotional and physiological states and deeply regulates cognitive and neurophysiological processes. Low-stressed males demonstrated dominant proper frontal activation (Fp2), suggesting hemispheric specialization. At the same time, females displayed a more symmetrical prefrontal activation pattern, suggesting a more integrative or distributed approach to neural resource utilization.

Following cognitive training, functional brain changes became evident in stress-resilient individuals: men demonstrated a shift in activity from frontal to parietal-occipital regions, indicating increased process automatization and reduced cognitive load; women retained high prefrontal activity and bilateral engagement, suggesting enhanced executive control and efficient adaptation strategies.

Participants with moderate stress levels exhibited reduced baseline neural efficiency and showed limited gains following cognitive training, pointing to stress-induced barriers in neuroplastic adaptation.

Stress influences cognition on multiple levels, affecting cortical activity and neural resource strategies. Although cognitive training encourages adaptive physiological neuroplasticity, its effectiveness depends on how well people handle stress and how their brains are structured. These results highlight the need for tailored strategies in cognitive improvement initiatives.

The authors express their sincere gratitude to CogniFit Inc. (San Francisco, California, USA) for supporting this study through a bilateral agreement, which provided free access to their cognitive training platform for research purposes from 2024 to 2026.

The research was conducted within the framework of the scientific initiative topic "Molecular mechanisms of adaptation to stress and the search for natural adaptogens" of the Department of Biochemistry and Physiology of the Oles Honchar Dnipro National University of the Ministry of Education and Science of Ukraine (State registration number: 0122U001457).

The authors declare no conflict of interest.

References

Almarzouki, A. F. (2024). Stress, working memory, and academic performance: A neuroscience perspective. Stress, 27(2), 153–166.

Alyan, E., Saad, N. M., Kamel, N., Yusoff, M. Z., Zakariya, M. A., Rahman, M. A., Guillet, C., & Merienne, F. (2021). Frontal electroencephalogram alpha asymmetry during mental stress related to workplace noise. Sensors, 21(6), 1968.

Angelakis, E., Lubar, J. F., & Stathopoulou, S. (2004). Electroencephalographic peak alpha frequency correlates of cognitive traits. Neuroscience Letters, 371(1), 60–63.

Attar, E. T. (2022). Review of electroencephalography signals approaches for mental stress assessment. Neurosciences Journal, 27(4), 209–215.

Chen, X., Ma, R., Zhang, W., Zeng, G. Q., Wu, Q., Yimiti, A., Xia, X., Cui, J., Liu, Q., Meng, X., Bu, J., Chen, Q., Pan, Y., Yu, N. X., Wang, S., Deng, Z.-D., Sack, A. T., Mc Laughlin, M., & Zhang, X. (2023). Alpha oscillatory activity is causally linked to working memory retention. PLoS Biology, 21(2), e3001999.

Cocenas-Silva, R., Droit-Volet, S., & Gherardi Donato, E. C. S. (2019). Chronic stress impairs temporal memory. Timing and Time Perception, 7(2), 108–130.

Cohen, S., Kamarck, T., & Mermelstein, R. (1983). A global measure of perceived stress. Journal of Health and Social Behavior, 24(4), 385–396.

Corsi-Cabrera, M., Ramos, J., Guevara, M. A., Arce, C., & Gutierrez, S. (1993). Gender differencesm in the eeg during cognitive activity. International Journal of Neuroscience, 72(3–4), 257–264.

De Ramón, I., Pacios, J., Medina, R., Bouhaben, J., Cuesta, P., Antón-Toro, L., Quintero, J., Ramos Quiroga, A., & Maestú, F. (2022). Alpha-band power increases in posterior brain regions in attention deficit hyperactivity disorder after digital cognitive stimulation treatment: Randomized controlled study. Brain Communications, 4(2), fcac038.

Dronse, J., Ohndorf, A., Richter, N., Bischof, G. N., Fassbender, R., Behfar, Q., Gramespacher, H., Dillen, K., Jacobs, H. I. L., Kukolja, J., Fink, G. R., & Onur, O. A. (2023). Serum cortisol is negatively related to hippocampal volume, brain structure, and memory performance in healthy aging and Alzheimer's disease. Frontiers in Aging Neuroscience, 15, 1154112.

Ericson, J., Palva, S., Palva, M., & Klingberg, T. (2024). Strengthening of alpha synchronization is a neural correlate of cognitive transfer. Cerebral Cortex, 34(2), bhad527.

Ghazi, T. R., Blacker, K. J., Hinault, T. T., & Courtney, S. M. (2021). Modulation of peak alpha frequency oscillations during working memory is greater in females than males. Frontiers in Human Neuroscience, 15, 626406.

Gong, L., Liu, T., Zhou, Y., & Zhang, R. (2024). The impact of sleep quality on visual working memory varied with the duration of maintenance. Frontiers in Psychology, 15, 1404989.

Haimov, I., & Shatil, E. (2013). Cognitive training improves sleep quality and cognitive function among older adults with insomnia. PLoS One, 8(4), e61390.

Heaton, R. K. (1981). Wisconsin Card Sorting Test (WCST). Psychological Assessment Resources, Odessa.

Jacques, C., Quiquempoix, M., Sauvet, F., Le Van Quyen, M., Gomez-Merino, D., & Chennaoui, M. (2024). Interest of neurofeedback training for cognitive performance and risk of brain disorders in the military context. Frontiers in Psychology, 15, 1412289.

Jaiswal, S., Tsai, S.-Y., Juan, C.-H., Muggleton, N. G., & Liang, W.-K. (2019). Low delta and high alpha power are associated with better conflict control and working memory in high mindfulness, low anxiety individuals. Social Cognitive and Affective Neuroscience, 14(6), 645–655.

Juras, L., Hromatko, I., & Vranic, A. (2025). Parietal alpha and theta power predict cognitive training gains in middle-aged adults. Frontiers in Aging Neuroscience, 17, 1530147.

Lee, D. J., Kulubya, E., Goldin, P., Goodarzi, A., & Girgis, F. (2018). Review of the neural oscillations underlying meditation. Frontiers in Neuroscience, 12, 178.

Lee, S., Kim, J. H., Kim, H., Kim, S. H., Park, S. S., Hong, C. W., Kwon, K. T., Lee, S. H., Kim, K. S., Choi, H., Kim, J. B., & Kim, D.-J. (2025). Investigating the effect of mindfulness training for stress management in military training: The relationship between the autonomic nervous system and emotional regulation. BMC Psychology, 13, 13.

Lenartowicz, A., Lu, S., Rodriguez, C., Lau, E. P., Walshaw, P. D., McCracken, J. T., Cohen, M. S., & Loo, S. K. (2016). Alpha desynchronization and fronto-parietal connectivity during spatial working memory encoding deficits in ADHD: A simultaneous EEG-fMRI study. NeuroImage: Clinical, 11, 210–223.

Li, W. W., Nannestad, J., Leow, T., & Heward, C. (2024). The effectiveness of mindfulness-based stress reduction (MBSR) on depression, PTSD, and mindfulness among military veterans: A systematic review and meta-analysis. Health Psychology Open, 11, 20551029241302969.

Loock, K., & Schwabe, L. (2024). Cognitive training prevents stress-induced working memory deficits. Biological Psychiatry: Cognitive Neuroscience and Neuroimaging, 9(10), 1039–1047.

Luo, X., Zhang, L., & Wang, J. (2017). The benefits of working memory capacity on attentional control under pressure. Frontiers in Psychology, 8, 1105.

Marakushyn, D., Bulynina, O., Isaieva, I., Karmazina, I., & Maslova, N. (2024). Impact of stress on emotional health and cognitive function. Medical Science of Ukraine, 20(2), 136–142.

Marshall, A. C., Cooper, N., Rosu, L., & Kennett, S. (2018). Stress-related deficits of older adults' spatial working memory: An EEG investigation of occipital alpha and frontal-midline theta activities. Neurobiology of Aging, 69, 239–248.

Nicholson, A. A., Ros, T., Densmore, M., Frewen, P. A., Neufeld, R. W. J., Théberge, J., Jetly, R., & Lanius, R. A. (2020). A randomized, controlled trial of alpha-rhythm EEG neurofeedback in posttraumatic stress disorder: A preliminary investigation showing evidence of decreased PTSD symptoms and restored default mode and salience network connectivity using fMRI. NeuroImage: Clinical, 28, 102490.

Osokina, O., Silwal, S., Bohdanova, T., Hodes, M., Sourander, A., & Skokauskas, N. (2023). Impact of the Russian invasion on mental health of adolescents in Ukraine. Journal of the American Academy of Child and Adolescent Psychiatry, 62(3), 335–343.

Pei, D., Tirumala, S., Tun, K. T., Ajendla, A., & Vinjamuri, R. (2024). Identifying neurophysiological correlates of stress. Frontiers in Medical Engineering, 2, 1434753.

Peretz, C., Korczyn, A. D., Shatil, E., Aharonson, V., Birnboim, S., & Giladi, N. (2011). Computer-based, personalized cognitive training versus classical computer games: A randomized double-blind prospective trial of cognitive stimulation. Neuroepidemiology, 36(2), 91–99.

Preiss, M., Shatil, E., Čermáková, R., Cimermanová, D., & Ram, I. (2013). Personalized cognitive training in unipolar and bipolar disorder: A study of cognitive functioning. Frontiers in Human Neuroscience, 7, 108.

Saffari, F., Norouzi, K., Bruni, L. E., Zarei, S., & Ramsøy, T. Z. (2023). Impact of varying levels of mental stress on phase information of EEG signals: A study on the frontal, central, and parietal regions. Biomedical Signal Processing and Control, 86(B), 105236.

Salminen, T., Strobach, T., & Schubert, T. (2012). On the impacts of working memory training on executive functioning. Frontiers in Human Neuroscience, 6, 166.

Schwabe, L. (2025). Memory under stress: From adaptation to disorder. Biological Psychiatry, 97(4), 339–348.

Schwabe, L., Hermans, E. J., Joëls, M., & Roozendaal, B. (2022). Mechanisms of memory under stress. Neuron, 110(9), 1450–1467.

Shatil, E. (2013). Does combined cognitive training and physical activity training enhance cognitive abilities more than either alone? A four-condition randomized controlled trial among healthy older adults. Frontiers in Aging Neuroscience, 5, 8.

Sherman, B. E., Harris, B. B., Turk-Browne, N. B., Sinha, R., & Goldfarb, E. V. (2023). Hippocampal mechanisms support cortisol-induced memory enhancements. Journal of Neuroscience, 43(43), 7198–7212.

Soriano, J. R., Bracho Montes de Oca, E., Karaiskou, A.-I., De Vuyst, H.-J., Rodriguez-Larios, J., Feng, N., Varon, C., & Alaerts, K. (2024). Bidirectional alpha power EEG neurofeedback during a focused attention meditation practice in novices. NeuroRegulation, 11(3), 230–241.

Spironelli, C., & Borella, E. (2021). Working memory training and cortical arousal in healthy older adults: A resting-state EEG pilot study. Frontiers in Aging Neuroscience, 13, 718965.

Strzelczyk, D., & Langer, N. (2024). Pre-stimulus activity mediates event-related theta synchronization and alpha desynchronization during memory formation in healthy aging. Imaging Neuroscience, 2, 1–22.

Trenado, C., Trauberg, P., Elben, S., Dimenshteyn, K., Folkerts, A.-K., Witt, K., Weiss, D., Liepelt-Scarfone, I., Kalbe, E., & Wojtecki, L. (2023). Resting state EEG as biomarker of cognitive training and physical activity's joint effect in Parkinson's patients with mild cognitive impairment. Neurological Research and Practice, 5, 46.

Vanhollebeke, G., De Smet, S., De Raedt, R., Baeken, C., van Mierlo, P., & Vanderhasselt, M.-A. (2022). The neural correlates of psychosocial stress: A systematic review and meta-analysis of spectral analysis EEG studies. Neurobiology of Stress, 18, 100452.

Zhou, Q., Cheng, R., Yao, L., Ye, X., & Xu, K. (2022a). Neurofeedback training of alpha relative power improves the performance of motor imagery brain–computer interface. Frontiers in Human Neuroscience, 16, 831995.

Zhou, Q., Cheng, R., Yao, L., Ye, X., & Xu, K. (2022b). Corrigendum: Neurofeedback training of alpha relative power improves the performance of motor imagery brain–computer interface. Frontiers in Human Neuroscience, 16, 977387.

Zoefel, B., Huster, R. J., & Herrmann, C. S. (2011). Neurofeedback training of the upper alpha frequency band in EEG improves cognitive performance. NeuroImage, 54(2), 1427–1431.