CLOSED-LOOP METHODS OF NON-INVASIVE BRAIN STIMULATION IN THE DIAGNOSIS AND CORRECTION OF COGNITIVE IMPAIRMENTS

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Abstract. Cognitive impairments are among the most common types of neurological disorders that require the creation of reliable diagnostic and correction tools. Along with the development of effective drugs, in recent years a line of research has been actively developing, in which various methods of non-invasive brain stimulation with feedback from the current physiological parameters of a person, and primarily from the rhythmic components of the electroencephalogram (EEG), are successfully used to diagnose and correct cognitive impairments. The purpose of the presented work is to analyze recent publications, consider the achievements of this line of research and highlight the most promising directions for its further development. Studies using transcranial magnetic and electrical stimulation, as well as sensory types of stimulation - acoustic, photic and audiovisual stimulations, in which non-invasive stimulation is carried out on the basis of feedback signals from the patient's own bioelectrical processes, are considered. The advantages of EEG-guided light-music stimulation, developed by the authors for the correction of various cognitive disorders, are demonstrated.

Keywords: cognitive impairment, correction, non-invasive brain stimulation, transcranial magnetic and electrical stimulation, sensory stimulation, feedback, electroencephalogram (EEG), EEG-guided light-music stimulation.

List of Abbreviations
EEG – electroencephalogram
LED – light-emitting diode

The development and adequate use of reliable diagnostic and correction tools for cognitive impairment is a relevant area of modern neurological research. Its significance and relevance are determined by the following circumstances. Cognitive impairment is one of the most common types of neurological disorders encountered in the practice of both neurologists and doctors of other specialties (Lokshina *et al.*, 2023). Cognitive deficit has a negative impact on the quality of life of the patient and his environment, largely hindering the possibility of returning to full social and professional recovery (Bogolepova & Levin, 2020). Therefore, early detection and treatment of diseases of the nervous system accompanied by cognitive impairment are among the most significant tasks of modern clinical neurology (Emelin, 2020).

When considering the basic principles of therapy for cognitive impairment, an unambiguous conclusion is made that it should be comprehensive and include not only drug-based methods of improving cognitive functions, but also non-drug-based methods - cognitive training, cognitive stimulation and cognitive rehabilitation (Parfenov, 2023). In this regard, of interest is the line of research that has been actively developing in recent years (Polevaya *et al.*, 2024), in which various methods of non-invasive brain stimulation with feedback from a person's current physiological parameters, which control stimulation in real time, are used to diagnose and correct cognitive impairment (Farkhondeh *et al.*, 2022). Such interventions take into account the individual dynamics of micro- and macrostates of the brain (Khanna *et al.*, 2015; Dick & Nozdrachev, 2020) and achieve high personalization and effectiveness, acquiring the character of physiologically informed adaptive neuromodulation (Wendt *et*

al., 2022). Among the most popular types of non-invasive stimulation are transcranial electrical and magnetic stimulation, as well as sensory types of stimulation - acoustic, light and audiovisual interventions (Polevaya *et al.*, 2024). The basic mechanism of action of the stimulation procedures used is considered to be the activation of neuroplasticity processes (Piradov *et al.*, 2018), due to which impaired cognitive functions such as perception, memory, attention, speech and others are restored (Kalantarova *et al.*, 2020).

The analysis of literature shows that the number of publications on this topic has been exponentially increasing in recent years, as has the range of conditions for the successful use of different types of noninvasive brain stimulation with feedback in the diagnosis and correction of cognitive disorders. The purpose of this paper is to analyze recent publications, review the achievements of this line of research, and identify the most promising areas for its further development. The paper reviews studies using transcranial magnetic and electrical stimulation, as well as sensory types of stimulation-acoustic, light, and audiovisual interventions, in which noninvasive stimulation is carried out based on feedback signals from the patient's own bioelectric processes. The paper demonstrates the advantages of EEG-guided light and music stimulation developed by the authors to correct various cognitive disorders.

Transcranial magnetic and electrical stimulation in the correction of cognitive functions

Transcranial magnetic and electrical stimulations are widely used in cognitive neuroscience. This is due to their ability to modulate the activity of the stimulated area of the brain and neural networks through neuroplasticity mechanisms to clarify the role of individual areas of the cerebral cortex in ensuring perception, memory, attention, speech and other cognitive functions (Bakulin *et al.*, 2020).

The most popular and actively developing methods of adaptive neurostimulation are those using feedback from the patient's EEG. This is due to the advantages of EEG such as ease of use, non-invasiveness, high temporal resolution, and the ability to extract data in real time (Koenig *et al.*, 2020).

A number of studies have shown that non-invasive sensory stimulation synchronized with certain current EEG parameters can improve sleep quality, enhance cognitive functions, and memory consolidation processes (Choi *et al.*, 2020; Barnes *et al.*, 2023). For example, after a session of transcranial electrical stimulation controlled by slow-wave EEG components, a significant increase in memory consolidation was recorded, which manifested itself in improved processes of recognition and reproduction of information (Ketz *et al.*, 2018). High efficiency has also been demonstrated for transcranial magnetic stimulation synchronized with certain phases of EEG oscillations (Ding *et al.*, 2022).

It is also known that rhythmic transcranial magnetic stimulation under the EEG control is a highly effective treatment for cognitive disorders (Poydasheva *et al.*, 2021). It is emphasized that oscillations induced in the cerebral cortex by rhythmic stimulation in older people help restore natural frequencies of neural activity to those frequency characteristic of a younger and healthier brain (Qiao *et al.*, 2022).

EEG-controlled sensory stimulation in the correction of cognitive functions

Recent studies have demonstrated the possibility of significantly improving sleep quality and memory consolidation processes using acoustic stimulation controlled by feedback signals from slow-wave EEG components (Ruch *et al.*, 2022) or sleep EEG spindles (Ngo *et al.*, 2019). Successful elimination of anxiety and depression states was observed with audiovisual stimulation automatically controlled by feedback signals from narrow-band spectral components of the EEG (Pino, 2022).

Another option for non-invasive brain stimulation with feedback is the computer transformation of current EEG parameters into therapeutic sensory stimulation. For example, pronounced positive effects in the correction of cognitive functions have been recorded with

rhythmic photic stimuli automatically generated in real time based on the digitized values of the native EEG (Fedotchev, 2019). Also worthy of attention is the bioacoustic correction method, which consists in presenting a person with acoustic signals obtained by computer transformation of the current EEG (Konstantinov *et al.*, 2014). The method allows person to "hear" the work of the brain in real time and has been successfully used to restore such cognitive functions as executive functions, perception, reading and mental arithmetic in patients with focal brain lesions (Tereshin *et al.*, 2019) and in the cognitive rehabilitation of patients with the consequences of transient cerebrovascular disorders (Shchegolkov *et al.*, 2022).

EEG-controlled acoustic stimulation is also effectively used in a number of clinical applications. Thus, the presentation of acoustic stimuli generated in real time by software-controlled transformation of the subject's dominant EEG rhythms into a sound sequence causes a clinically significant reduction in post-traumatic stress symptoms and an improvement in cognitive functions (Tegeler *et al.*, 2017; Shaltout *et al.*, 2018; Tegeler *et al.*, 2023). According to the authors, the on-line updating of one's own EEG patterns and the resonance between audible acoustic signals and oscillatory brain networks provide the body with the opportunity for autocalibration, relaxation, and overcoming stable pathological conditions (Tegeler *et al.*, 2020).

EEG-guided light-music stimulation in the correction of cognitive impairments

Computer transformation of current EEG parameters into therapeutic sensory stimuli was also used in our studies. A musical neural interface was developed in which the current values of the dominant spectral EEG components (EEG oscillators) of the subject are transformed into music-like signals, reminiscent of flute sounds in timbre, smoothly varying in pitch and intensity. This neural interface was successfully used in the correction of stress-induced disturbances (Fedotchev *et al.*, 2018) and in the cognitive rehabilitation of the elderly (Fedotchev *et al.*, 2020). The described method of EEG-guided musical stimulation was improved by adding a second feedback loop, in which rhythmic light stimuli formed on the basis of the patient's native EEG are presented simultaneously with music-like stimulation (Fedotchev *et al.*, 2019; Fedotchev *et al.*, 2022). The created method of light-music stimulation with double feedback from EEG was successfully applied to eliminate the risks of reliability of high-tech specialists (Fedotchev, 2022), as well as for cognitive rehabilitation of patients with stroke (Mukhina *et al.*, 2021).

Our studies also outlined a promising approach to increasing the effectiveness of EEG-guided sensory stimulation. This approach involves the use of resonance scanning, or LED rhythmic photostimulation with a gradually increasing frequency in the range of the main EEG rhythms (Savchuk *et al.*, 2022). It has been experimentally shown that resonance scanning can serve as a kind of preliminary tuning of the brain, causing the activation of potential resonators in the EEG spectrum and increasing the brain's response to subsequent EEG-controlled adaptive neurostimulation (Fedotchev *et al.*, 2023). It is important to emphasize that the possibility of enhancing cognitive activity and improving well-being in general through the interaction of endogenous and exogenous oscillations has been proven in model studies (Nuidel *et al.*, 2019). When combining resonance scanning with EEG-controlled adaptive neurostimulation, significant positive effects in the treatment of patients with post-COVID syndrome were recorded after just one combined exposure (Polevaya *et al.*, 2022).

The data reviewed are summarized taking into account the conditions, type of stimulation and feedback parameter (Table 1).

The data in the table show that the range of conditions for the successful use of non-invasive brain stimulation in the correction of cognitive impairments is quite wide, as are the specific characteristics of the applied therapeutic stimulation. In addition, the arrangement of publications in chronological order allows one to note the annual increase in their number, which indicates the prospects of this area of research.

Table 1

Dynamics of studies successfully using non-invasive brain stimulation with feedback in the correction of cognitive impairments

Purpose/condition of the study	Type of stimulation	Feedback parameter	Reference
Bioacoustic correction of the functional state	EEG-controlled acoustic stimulation	Frontal and occipital EEG	Konstantinov *et al.*, 2014
Enhancing of cognitive control under stress	Acoustic stimulation	Dominant EEG rhythms	Tegeler *et al.*, 2017
Elimination of stress-induced cognitive impairments	Music-acoustic stimulation	Narrow-band EEG oscillators	Fedotchev *et al.*, 2018
Enhancing of memory consolidation	Transcranial electrical stimulation	Slow wave EEG components	Ketz *et al.*, 2018
Optimization of cognitive functions	Acoustic stimulation	Dominant EEG rhythms	Shaltout *et al.*, 2018
Enhancing of cognitive control under stress	Rhythmic light stimulation	Digitized native EEG	Fedotchev, 2019
Strengthening of memory consolidation	Acoustic stimulation	Sleep spindles on EEG	Ngo *et al.*, 2019
Restoration of cognitive functions	EEG-controlled acoustic stimulation	Frontal and occipital EEG	Tereshin *et al.*, 2019
Enhancing of cognitive control	Acoustic stimulation	Dominant EEG rhythms	Tegeler *et al.*, 2020
Cognitive rehabilitation of the elderly	Music-like stimulation	Alpha EEG oscillators	Fedotchev *et al.*, 2020
Therapy for cognitive disorders	Transcranial magnetic stimulation	Total EEG	Poydasheva *et al.*, 2021
Cognitive rehabilitation of stroke patients	EEG-guided light-music stimulation	Alpha EEG oscillators + native EEG	Mukhina *et al.*, 2021
Correction of psychogenic cognitive disturbances	Audiovisual stimulation	Spectral EEG components	Pino, 2022
Cognitive rehabilitation in post-covid syndrome	EEG-guided light-music stimulation	Alpha EEG oscillators + native EEG	Polevaya *et al.*, 2022
Restoration of cognitive functions	EEG-controlled acoustic stimulation	Frontal and occipital EEG	Shchegolkov *et al.*, 2022
Enhancing of memory consolidation	Acoustic stimulation	Slow wave EEG components	Ruch *et al.*, 2022
Cognitive rehabilitation of high tech specialists	EEG-guided light-music stimulation	Alpha EEG oscillators + native EEG	Fedotchev, 2022
Improving sleepy, activation of cognitive functions	Acoustic stimulation	Dominant EEG rhythms	Tegeler *et al.*, 2023
Cognitive rehabilitation of university students	EEG-guided light-music stimulation	Alpha EEG oscillators + native EEG	Fedotchev *et al.*, 2023

Conclusions

The presented data allow one to conclude that the development and improvement of approaches to the correction of cognitive impairments using non-invasive brain stimulation with feedback is an actively developing and promising area of neurophysiology. Judging by the publications reviewed, the greatest development and efficiency are demonstrated by technologies using automatic modulation of non-in-

vasive sensory stimulation by feedback signals from rhythmic components of the EEG. Feedback from these components ensures the involvement of the mechanisms of multisensory integration, neuroplasticity and resonance mechanisms of the brain in the processes of correction of cognitive impairments. Due to the use of control signals from the EEG, such non-invasive stimulation, by taking into account the dynamics of brain microstates, achieves high personalization and efficiency of therapeutic procedures. Automatic control of therapeutic sensory stimulation makes it possible to use these technologies in conditions that do not require conscious efforts of the subjects, which is especially important when conducting therapeutic sessions with children and with patients who are characterized by altered mental states or drug therapy is contraindicated.

The above advantages of the considered technologies open up prospects for their application in rehabilitation activities of a wide profile, in military and sports medicine, disaster medicine, and scientific research.

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