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THE BRAIN-COMPUTER INTERFACE NEUROPHYSIOLOGICAL ASPECTS

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Abstract. *The brain-computer interface (BCI) is a device that allows to control external technical systems specifically with brain signals. In the last two decades, the development of BCI has been rapidly developing: the areas of its implementation are expanding, new types of sensors for recording brain signals are being proposed, the quality of their recognition is improving, and methods for training subjects to control BCI are being improved. The review describes the history of BCI development and neurophysiological background.*

Key words: *BCI , mental activity , Parkinson's disease, electrical stimulation , neurorehabilitation*

Аннотация. *Интерфейс мозг-компьютер (ИМК) — это устройство, позволяющее управлять внешними техническими системами именно сигналами мозга. В последние два десятилетия развитие ИМК стремительно развивается: расширяются области его реализации, предлагаются новые типы датчиков для регистрации сигналов мозга, улучшается качество их распознавания, методы обучения испытуемых управлению ИМК совершенствуются. В обзоре описаны история развития ИМК и нейрофизиологические предпосылки.*

Ключевые слова: *ИМК, психическая деятельность, болезнь Паркинсона, электростимуляция, нейрореабилитация.*

Izoh. *Miya-kompyuter interfeysi (MKI) tashqi texnik tizimlarni miya signallari bilan aniq boshqarish imkonini beruvchi qurilma. So'nggi yigirma yil ichida MKI rivojlanishi jadal sur'atlar bilan rivojlanmoqda: uni amalga oshirish sohalari kengaymoqda, miya signallarini yozib olish uchun sensorlarning yangi turlari taklif qilinmoqda, ularni tanib olish sifati yaxshilanmoqda va fanlarni o'qitish usullari MKI nazorati takomillashtirilmoqda. Ushbu sharh MKI rivojlanish tarixi va neyrofiziologik imkoniyatlarni tavsiflaydi.*

Kalit so'zlar: *BCI, aqliy faoliyat, Parkinson kasalligi, elektr stimulyatsiyasi, neyroreabilitatsiya.*

1. Introduction. All forms of mental activity are ultimately realized in the form of muscle contractions, which allow us to interact with the outside world and communicate with each other: muscles control the movements of the lips and eyes, facial expression and the formation of speech. Muscle contractions are an integral part of sensory functions, for example, tactile and kinesthetic sensations, which require hand movements, and vision, which is carried out by moving eyes. Our body movements are tracked by a large number of sensory receptors. The incoming stream of sensory and motor signals is processed at different levels of the nervous system, including the higher parts of the brain. The details of the processing of incoming signals tend to pass our minds, and we take it for granted that we manage to perform very complex tasks: walk upright, maintain balance, move our fingers, speak, and much more. Unfortunately, the ability to move and sense can be impaired as a result of damage to the nervous system. Millions of people around the world suffer from sensory and motor disorders caused by spinal fractures, stroke, Parkinson's disease, amyotrophic lateral sclerosis and other pathologies. Often the higher parts of the brain still retain their functionality, but are cut off from the muscles, and as a result the patient cannot move, speak or feel. There are no effective treatments for many motor and sensory disorders. Patients are confined to beds or wheelchairs for the rest of their lives. The development of effective rehabilitation methods or devices that compensate for the missing functions is one of the most important tasks of modern medicine. Artificial parts for the nervous system brain-computer interface (BCI) is a promising tool for the treatment of many neurological pathologies. It is based on the principle of creating connections between intact areas of the brain and auxiliary devices that are able to compensate for motor and sensory functions. [1, 14].

History of BCI based Steady State Evoked Potentials

Since the mid-1960s, Steady State Evoked Potentials (SEPs) have been used as a monitoring tool during neurosurgical procedures or spinal surgery [4]. For example, by stimulating the posterior tibial nerve and by monitoring the SEPs in the somatosensory cortex during spinal surgery, early surgery-related damages to the motor capacity of the patient can be detected [3]. Experiments were carried out on monkeys implanted with multielectrode matrices for recording cortical potentials and electrical stimulation [10, 12]. It was shown that the sensorimotor cortex was activated when the monkeys made movements, and electrical stimulation of the cortex, on the contrary, caused muscle contraction. In 1963, Walter carried out an experiment in which the first BCI in the sense that we understand it now [9] was realized. For medical reasons, the patients were implanted with electrodes in various areas of the cerebral cortex. They were asked to switch projector slides by pressing a button. Finding the region of the cortex responsible for reproducing this muscle pattern, the researcher connected it directly to the projector. Patients pressed the disconnected button, but the slides continued to switch: control was carried out directly by the brain, and even faster than the person had time to press the button. An idea similar to the idea of modern BCIs was formulated in the late 1960s. scientists from the US National Institute of Health (National Institute of Health), who stated that the main direction of their research will be the development of principles and methods for controlling external devices using brain signals [7]. The researchers implanted electrodes in the motor cortex of monkeys, which recorded the action potentials of several neurons while the animals moved their hand [2]. The recorded discharges of neurons were transformed into the trajectory of hand movement using linear regression. It took another ten years of research to implement such a transformation in real time: monkey learned to control the cursor on the screen by activating neurons in the motor cortex [11]. A similar study was led at the same time by Fetz [8], but the emphasis was on studying biofeedback, and the scientists were faced with the question: can a monkey control the discharges of its neurons arbitrarily? It turned out that arbitrary control of the activity of the neurons responsible for the movements is possible even without making movements. This result is important for understanding the work of "mirror neurons" and neurons involved in the mechanism of empathy. Simultaneously with the development of motor BCIs, researchers created sensory interfaces [13]. In 1957 the French scientists Djourno and Eyriès succeeded at the of the help of a single-channel electrode, which stimulated the auditory nerve, to cause sound sensations in the deaf. In 1964, Simmons introduced a multi-channel version of the invention. In the 1970s House and Urban have named the device, which consists of a transducer and a multi-channel electrode, a cochlear implant. The development was approved by the US Food and Drug Administration. After further improvements, the cochlear implant has been successfully introduced into clinical practice. In the 1980s began research aimed at restoring vision with the help of BCI. Completely blind people were implanted with an electrode matrix in the visual cortex. The resulting visual sensations - a kind of neuroelectrophotopixels - were called phosphenes. For a long time or never seen the light, people have learned to recognize simple patterns of phosphenes [6, 5]. Currently, electro simulation vision is being introduced into clinical practice: a rather complex image from a video camera (one or more) is transmitted to neuroimplants in the eye or visual cortex. A stormy leap in BCI research took place in the 1990s–2000s. Nicolelis and Chapin designed a BCI that controlled mechanical limbs [2]. The activity of the cortex and basal ganglia recorded in rats in the waking state was transmitted to a robot that delivered water to the animal. Nicolelis then continued his research on primates. This line of research has been implemented in a number of projects: a robotic arm controlled by cortical ensembles [11], BCI for artificial tactile feedback [7], BCI for recognizing leg movements [8], BCI for bimanual movements [19], and others. In the same years, experiments began on the implantation of electrodes in the human brain. Kennedy (in 2015 he implanted electrodes on himself) was working with a patient with amyotrophic lateral syndrome. An electrode was placed in the patient's cortex, injecting myelin growth factors through a special tip. The implant allowed the patient to generate a binary command signal [3]. In the early 2000s several laboratories began to compete with each other in the development of invasive BCIs. Donoghue's team has worked with monkeys and humans, including implanting multielectrode arrays into the human motor cortex, allowing paralyzed humans to control a cursor [8] and robotic arms [9]. Schwartz and colleagues studied the control of movements in three-dimensional space on monkeys [13]. In an experiment involving humans, they managed to achieve maximum control in the control of an anthropomorphic robotic arm [7] - perhaps this is still the most advanced technology in this area. In the process of developing the BCI, Andersen, Shenoy and Vaadia, who studied various areas of the cortex as signal sources for BCI, created new original algorithms for decoding brain signals. At the same time, studies were also carried out on non-invasive neurointerfaces, which were based on EEG recording, infrared oximetry of the brain, and functional electrical stimulation. Practical solutions have been proposed for wheelchair control (Birbaumer, Pfurtscheller, Walpaw, Müller, Schalk, Neuper, Kübler, Millan and other researchers) and restoration of limb mobility after injuries and strokes [12]. Neuronal decoding, How do motor BCIs determine the parameters (properties) of movement by excitation of neurons? Many neurophysiological studies have shown that the action potential of isolated neurons corresponds to specific behavioral manifestations. For example, the firing of neurons in the motor cortex determines the position, acceleration, and angle of rotation of the hand. Developers use such correspondences to decode neural signals. The coding of various movement parameters by neurons began to be studied in the 1950s and 1960s: using needle electrodes, the extracellular activity of single neurons in different areas of the brain was recorded. These were studies of the somatosensory [14], motor [6], and visual [5] systems. It became clear that even single neurons exhibit stable patterns of activity encoding a range of sensory and motor manifestations. The methodology for recording single neuronal activity has subsequently been used in many studies. Wise et al. discovered that cortical neurons fire a few seconds before a movement is made. In their experiments, the monkeys knew what movement they should make, but were trained not to do so until the trigger was fired [6]. Kalaska et al. used the recording of single neural activity and delayed movement task to study the effect of visual stimuli on the direction of movement [7]. These experiments showed that neuron discharges contain information about both real movements and those that are planned by the brain but are not carried out. Georgopoulos and colleagues studied the patterns of single motor cortical neurons during hand movement in different directions [5]. It turned out that there is a relationship between the signal strength and the direction of movement and is described by the cosine function, i.e., the neuron discharge frequency was maximum for any direction, and then decreased as we moved away from it. To explain how neuronal discharges are transformed in the movement of the hand in a certain direction, Georgopoulos proposed the concept of a population vector. Such a vector is a vector sum of signals from a set of neurons (neuronal population), which changes when a movement is made and reflects its direction. It is interesting that even the mental representation of movement without doing it by hand, for example, the imagination of rotation in space by 90°, was well described by the population vector [13]. Thus, it became clear that excitations of individual neurons carry information about behavioral manifestations and their parameters and can be decoded. SSSEP have also been used in different clinical applications, for instance to measure the tactile acuity of amputees [7] or as a marker for monitoring cortical processes resulting from a nociceptive and non-nociceptive somatosensory input [11].

Methods of SEPs.

Historically, in most studies aiming to study SEPs, the latter were elicited by electrical stimulation of peripheral nerves [8, 10, 6]. For instance, a correctly adjusted current flowing between two electrodes placed over the median nerve near the wrist can elicit an SEP. Indeed, the intensity of current pulses is increased until they produce tiny twitches of the thenar muscle, located on the hand palm at the base of the thumb, and simultaneously elicit SEPs [8]. Beside electrophysiological studies, this method of stimulation offers great tools to clinicians for monitoring patient state, for example during delicate spinal cord surgery [10]. However, electrical stimulation of peripheral nerves is reported as unpleasant and elicits SEPs with low amplitude [1, 2]. Therefore, efforts have been made to switch to mechanical stimulation, especially in the context of brain-computer interfacing where the system must be as comfortable to use as possible during long periods.

Neuroplasticity associated with the use of BCI

Many studies have convincingly shown that learning to work with BCI increases the plasticity of the brain of the subject. It was suggested that due to this, artificial limbs can eventually be built into the body model and perceived by the brain as their own [1, 2]. Controlling external devices with a BCI has much in common with using tools. Thus, in a well-known experiment on the study of neuroplasticity in monkeys trained to use a rake to pull up distant objects [1], it wasfound that the neurons of the posterior parietal cortex, which respond to objects in the zone of direct access to the hand, began to respond to objects located within the reach of the rake. In other words, the brain “built” the rake into the body schema. Long-term use of BCIs can lead to similar changes in the brain. For example, neurons involved in BCI control change activity patterns [11]. The connections of neurons with each other also change [8, 11], and their sensitivity to the direction of movement also changes [9].

Non-invasive BCIs an important requirement for BCIs is safety. The safest are non-invasive BCIs, i.e., those that do not use penetration into biological tissues to record neuronal activity. Many non-invasive BCIs have been developed, primarily for wheelchair control and restoration of communicative function using speech synthesizers [12]. EEG recording is the most common method used in the development of non-invasive BCIs. According to the method of brain activation, the method can be independent (endogenous activation - imagination of movement) and dependent (exogenous activation - demonstration of movement on the screen). In the first case, slow cortical potentials, mu (8–12 Hz), beta (18–30 Hz), and gamma rhythms (30–70 Hz) are used for control [4]. The efficiency of the method can be improved by using adaptive decoding algorithms [9]. In the second case, focusing attention on an external visual stimulus results in a well-defined response of the visual cortex in comparison with the response to a stimulus left without attention, and the patient's intentions are deciphered based on a pre-recorded difference in reactions to noticed and ignored stimuli. For example, when training a BCI based on stationary induced visual potentials, a response to periodically appearing stimuli is recorded [10]. Several objects are shown on the screen, each of which appears and disappears at its own frequency. The subject focuses in turn on each of them. P300 potentials can be used similarly [7]. A significant problem of EEG-BCIs is EEG recording artifacts, which can be mistaken for neural activity and even serve as control signals. Dependent BCIs are less sensitive to artifacts. Better signal quality compared to EEG, better temporal and spatial resolution, and less sensitivity to artifacts are demonstrated by electrocorticographic BCIs, but they are invasive. In addition to EEG, magnetoencephalography (MEG) is used [12]. To register weak magnetic fields generated by the brain, a very high sensitivity of the method is required, which is provided by superconducting quantum magnetometers. As a result, MEG recording requires special equipment and conditions (first of all, magnetic shielding), but MEG provides better temporal and spatial resolution than EEG. Another method for recording brain activity is monitoring the concentration of oxyhemoglobin and deoxyhemoglobin in the cerebral circulation using near infrared spectroscopy (NIR) with a time resolution of 100 ms and a spatial resolution of 1 cm. The main drawback of the technology is a significant signal delay, up to several seconds. Nevertheless, BCIs based on it are gaining popularity [13]. Functional magnetic resonance imaging is a powerful tool for monitoring changes in blood supply to the brain. Its temporal resolution is limited to 1–2 s, the signal delay is several seconds, but the method differs from all non-invasive techniques in its unsurpassed spatial resolution, which makes it possible to track the activity of any part of the brain [3]. Sensory BCIs Sensory BCIs can be used to restore hearing, vision, taste, smell, tactile and proprioceptive sensitivity, and a sense of balance. Violations of the functions of the sense organs can occur both due to damage to the peripheral parts of the nervous system, causing a complete loss of feelings (blindness, deafness), and due to damage to the organs of processing sensory information of a higher level (thalamus, cerebellum, subcortical nodes, cerebral cortex) , which, however, do not lead to a complete loss of sensitivity.

Conclusion.

BCI, in our opinion, is a progressive way of organizing a link between the possibility of patients' mobility in contact with the external environment, since their pathologies are often accompanied by a decrease or absence of muscle activity. Analyzing EEG patterns in stroke patients, it is possible to build their rehabilitation programs based on the use of non-invasive BCIs. One of the complex systems that combines a variety of technical solutions is the brain-computer interface, as it is based on biological prerequisites and in-depth research by scientists. The main directions for research in this area are the minimization of the device, the simplification of the structure for consumption by a wider range of users, the creation of device software for domestic use.

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