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Neuroboundaries

Brain research is enabling us to stretch the very limits of human cognition. However, exploring the mysteries of the brain has limits of its own, many of which we are still struggling to overcome.

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The fundamental limits of the study of the human brain were described at least half a century ago in the frequently quoted statement by Emerson Pugh: "If the human brain were so simple that we could understand it, we would be so simple that we couldn't." In recent years, however, there has been more and more talk about "mind uploading" and "mind reading." In the modern-day world, where every piece of information is encoded as a string of zeros and ones, we forget all too easily that to read something, we must first know and understand the code. Otherwise, we will not even know how to copy information – we need to know which voltage and magnetization levels in the logic gates and memories of our electronic devices correspond to specific states. The way information is encoded in the brain, however, is incomparably more complicated.

Reading information is yet another layer of abstraction, on top of the string of zeros and ones. In the brain, these strings are replaced by potentials and neurotransmitter storms around neurons. Even if this code were as simple as the code created by humans for computers, we would still need to know the format. But unfortunately, we simply do not. On the other hand, neuroscience is one of the fastest growing disciplines that can boast plenty of spectacular successes, which gives rise to many misunderstandings. Clarifying them is the goal of the first part of this article.

The brain and classical brain-computer interfaces

● The brain of a human versus the brain of a worm

The human brain has nearly 100 billion neurons, many of which form tens of thousands of links to other neurons. Every human brain is differently formed, as is evident even to the naked eye: in the process of neurogenesis, characteristic folds are formed in human brains as they mature, and so are the constantly changing connections between specific neurons. Contrary to what was a dogma not so long ago, we know that neurons not only die, but can also be newly formed in an adult, already formed brain. Thus, we know the neural patterns in the human brain only in the statistical sense. This explains the basic problems faced by neuroscience: it is not easy to study a structure if each of its instantiations is different and changes dynamically over time.

For this reason, basic research usually focuses on much simpler organisms, the best known of which is the nematode named *Caenorhabditis elegans*. Its body contains 959 cells, 302 of which are neurons. Most importantly, we know the exact pattern of connections between these neurons. It remains unchanged throughout the life of each individual, and it is the same in all of them! Understanding the inner workings of this "brain" is therefore unimaginably easier than understanding how the human brain operates.

But then, what does "understanding" mean here? In the European culture, when we understand something, we can usually describe it using our own words. In science, this is the language of equations, which means that we can create a mathematical model. Once we create a complete model of the nervous system of *C. elegans*, we will be able to "copy" it into a computer and accurately recreate its reactions and behavior, such as its characteristic wriggling movement. In the case of *C. elegans*, the exact structure of the connections between neurons (called connectome) was reconstructed 35 years ago. The only thing left now is to transfer it to computer memory and run the artificial worm. Many teams of prominent scientists have been working continuously to achieve this goal, but so far without success. Their efforts can be followed at such websites as http://openworm.org.

● Brain-computer interfaces

Now that we've had a bucket of cold water thrown on our enthusiasm, let's soberly turn our attention to the successes of modern neuroscience. Of course, it is impossible to cover the entire body of knowledge of such a broad discipline in one short article, so we will focus on one of the most popular examples, namely brain-computer interfaces (BCIs). Back in the early days of this discipline, we talked about brain-machine interfaces (BMIs). Soon, however, it turned out that there must be a computer between the brain and the machine, and connecting a computer to a machine is quite simple. For this reason, a brain-computer interface was classically defined as a system allowing communication with a computer without involving muscles. If we removed this condition, BCIs would also include a mouse and a keyboard, which undoubtedly enable communication with a computer by transmitting the intentions generated in the brain.

The most common way to put this idea into effect involves a system based on the reading of brain waves, in other words the good old electroencephalography (EEG). Its discovery has been ascribed to the Polish researcher Adolf Beck. As part of the research he conducted for his doctoral dissertation "The Determination of Localizations in the Brain and the Spinal Cord With the Aid of Electrical Phenomena" (which he defended in 1891), he studied the potentials associated with movement and stimuli in the cerebral cortex of experimental animals (essentially the same thing is made possible by today's Neuralink devices, but they are smaller, wireless, and can be implanted under the skull). During his research, Beck discovered and described an "active independent current," which in effect meant EEG. After his discovery was published in the international journal *Centralblatt für Physiologie*, it turned out that a mention of the same phenomenon (albeit without such a detailed study as Beck's) had earlier appeared in a short sentence in a report on a grant-funded project authored by Richard Caton, who was then credited as the discoverer.

But let's get back to modern EEG-based BCIs. They can be based on the EEG readings of signals of the focus of attention on flashing symbols (which have meanings attributed to them), reflected in what are referred to as evoked potentials (EPs), or on motor imagery (MI) data, which means the imagined movements of limbs. In the latter case, unfortunately, this is not a direct representation of the movement being imagined, but only 1–2 bits resulting from the differentiation of which limb the imagined movement pertains to. A more detailed explanation would take us well beyond the scope of this article, so readers interested in this topic should watch the popular-science presentations and animations prepared by BrainTech in connection with project POIR.01.01.01-00-0573/15 "Brain-computer interface" and posted on https://braintech.pl/bci.

BCIs in Poland

BCIs have been under worldwide development for decades. In Poland, the symbolic beginning of such research came with the first public demonstration of

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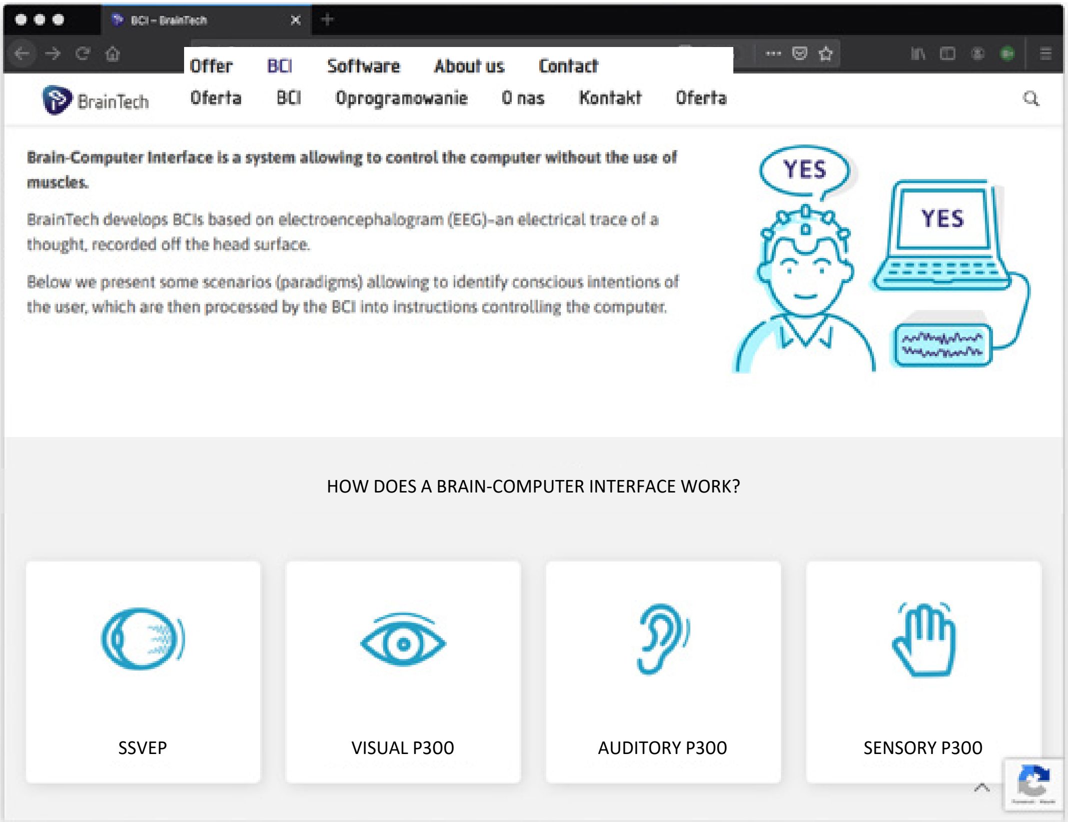
a BCI at the University of Warsaw's Faculty of Physics in June 2008. Since then, Polish scientists have joined the world's leaders in this field, and the most advanced technologies from this group have become available in Poland thanks to the activity of such companies as BrainTech. It is one of the world's few providers of complete BCI solutions (hardware and software) created from scratch for industry, education, and researchers. The company also offers a globally unique device that makes it possible to detect the focus of attention on selected fragments of the screen based on steady-state visually evoked potentials (SSVEPs). Most importantly, world-class specialists are educated as part of the world's first program of studies in neuroinformatics, offered by the University of Warsaw since 2009.

Examples of the use of BCIs outside the formal framework of the field include the study of disorders of consciousness carried out at the University of Warsaw in collaboration with the "Alarm Clock" Clinic in Warsaw (a hospital for children with severe brain damage) and the Światło Foundation (which supports patients requiring long-term and specialist care and people with disabilities) from Toruń. Here, we can also talk about going beyond the limits of modern medicine, which is based on a feedback loop centering around the assessment of the progress of treatment. For fractures or open wounds, we can assess the progress of healing relatively objectively. In conditions related to the functioning of the brain, it is necessary to communicate with the patient. In the case of states of disordered consciousness (colloquially referred to as coma), such communication is impaired or "switched off," at least in its classic form, which involves speech and gestures. Here is where the BCIs created at BrainTech can step in.

Which way forward for BCIs?

The above description pertains to the classical understanding of BCI. As scientists, we initially focused on trying to improve the speed of information transfer, but we quickly reached our limit. In this case, the actual limit of communication speed in currently available interfaces is hundreds of bits per minute, which is a lot slower than the typical ways of communicating with computers. We keep pushing this limit, but this is unfortunately a very slow process. For the past decade or so, we have seen little progress in solutions that stand a chance of finding practical applications. Therefore, instead of moving forward, the discipline began to develop sideways. First, we witnessed the emergence of the concept of hybrid BCIs, or communication systems in which the reading of brainwaves is supported by an additional muscle channel, such as eye or head movements. This was sometimes necessary for the use of a BCI in situations requiring a fast and sure reaction. Simultaneously, "passive BCIs" emerged, which



Popular-science explanation of how BCIs work can be found at https://braintech.pl/bci/?lang=en read behavioral states (such as fatigue, concentration, and so on) from the EEG signals. These are simply based on the good old EEG technology, but the new name translates into better recognition and clout. As such, the popularity of BCIs has contributed to a renaissance of interest in electroencephalography, not only in its classical form, but also in many innovative and interesting applications. Moreover, the technology (both hardware and software) used in these fields is very similar to classical BCIs. Therefore, the classic description presented above should be complemented by the voice of the young generation of neurohackers, fascinated by neurotechnology applications.

KRYSTIAN DEREZIŃSKI

Growing interest in neurotechnology has led to the emergence of portable, easy-to-use, and affordable systems for monitoring neural activity. This photo shows a student testing a device that records EEG signals

New applications – the future of BCIs is now

● Neurohacking and future applications
The limitations of BCIs mentioned earlier apply to standard, proven methods that use non-invasive EEG readings from the scalp. But as a result of the growing popularity of this field and the multitude of ongoing research and projects, we could cite many isolated yet very optimistic examples that point us towards possible advancements in the future.

● Writing in the mind's eye
Last year, a team of researchers from Stanford University presented a system based on an intracortical BCI. The researchers managed to decode imagined attempts at handwriting from the motor cortex and translate them into text in real time. The sole participant in the study was able to type at a speed of 90 characters per minute, which is comparable to the typical smartphone typing speed of healthy individuals (115 characters per minute). Here, we should mention that the project presented in the article involved only one participant, the procedure of installing the electrodes was invasive (requiring open-brain surgery), the participant underwent long training, so this is generally not a plug-and-play technology. Nevertheless, the project has met with considerable recognition in the neurotechnology sector and is still considered very impressive, as demonstrated by the first place it won in the prestigious Annual BCI Award competition in 2020.

● An exoskeleton connected to the brain
In another project, a team from the University of Grenoble developed a BCI system allowing the user to control an exoskeleton (a portable bionic skeleton designed for gait rehabilitation, among other things). Here, the research was likewise based on an invasive BCI, with electrodes being implanted under the skull. On the Internet, we can find videos showing tests in which a man paralyzed from the neck down walks on his own and touches selected points with his hand. Of course, this is a great solution for quadriplegic patients, but it would not be a stretch to imagine many other applications in the near future.

● Neural prostheses in Parkinson's disease
In aging societies, the number of people suffering from neurodegenerative diseases continues to rise. One example is Parkinson's disease, a neurodegenerative disorder that affects the extrapyramidal system, which is responsible for body movements. In the late stages of the disease, gait and balance deficits respond poorly to such commonly available therapies as sensory cuing, dopamine replacement strategies, and deep brain stimulation (DBS). In 2020, the Swiss center NeuroRestore, headed by Prof. Grégoire Courtine, presented a neuroprosthesis that acquired neural signals from the motor cortex, processed them, inferred the intended movements, and then sent out wireless commands to the spinal cord stimulation system in a way that reinforced intended movements, thus significantly alleviating gait and balance deficits in the model of Parkinson's disease in non-human primates. The Swiss center's work gives hope to many people affected by the disease and their loved ones.

What happens next?

We can cautiously assume that we will witness the development of many new solutions in neurotechnology in the near future. Progressive miniaturization of electronic devices, a steady increase in the computing power of computers, new artificial intelligence algorithms, and ever-faster and more widespread access to the Internet allow us to expect further growth of interest in BCIs and their rapid development. Of course, we should be aware of not only the limitations of such systems, but also the opportunities they offer. They may still surprise us on more than one occasion. ■

Further reading:

https://braintech.pl/?lang=en

https://www.klinikabudzik.pl/en