Brain-computer interface: A reciprocal self-regulated neuromodulation

Efthymios Angelakis PhD, Athanasios Hatzis PhD

Contact: Efthymios Angelakis, Ph.D., Masters Program in Applied Psychology, The American College of Greece, 6 Gravias Str., 15342 Aghia Paraskevi, Athens, Greece. Phone/fax: +30-210-600-9192. E-mail: angelakis@acgmail.gr

Abstract

Brain-computer interface (BCI) is a system that records brain activity and process it through a computer, allowing the individual whose activity is recorded to monitor this activity at the same time. Applications of BCIs include assistive modules for severely paralyzed patients to help them control external devices or to communicate, as well as brain biofeedback to self regulate brain activity for treating epilepsy, Attention-Deficit Hyperactivity Disorder, anxiety, and other psychiatric conditions, or to enhance cognitive performance in healthy individuals. The vast majority of BCIs utilizes non-invasive scalp recorded electroencephalographic (EEG) signals, but other techniques like invasive intracortical EEG, or near-infrared spectroscopy measuring brain blood oxygenation are tried experimentally.

Key words: brain-computer interface, neurofeedback, EEG, near-infrared spectroscopy, ADHD, seizures, paralysis, TTD.

Introduction

Human brain activity has fascinated science fiction novelists and cinematographers as well as neuroscientists. The former two typically fulfill the human fantasy to control others' minds or extend one's own mind capacity, whereas the latter typically try to understand how the mind really works. *Applied neuroscience* is a field that merges the wish to extend our mind's capacity with the knowledge we have already acquired on how the brain works. Brain-computer interfaces (BCIs) are two such applications that attempt to improve paralyzed individuals' capacity to communicate and to control external devices, as well as to help individuals with or without pathology to exercise control on their own brains.

BCIs take advantage of technology to record brain activity directly from the brain. During the first international meeting for BCI technology that took place in June of 1999 at the Rensellaerville Institute near Albany, New York, BCI was defined as "…*a communication system that does not depend on the brain's normal output pathways of peripheral nerves and muscles*." (29). Two major functional signals are recorded from the brain, electrical activity and metabolism or blood flow. Electrical activity can be recorded either invasively with implanted electrodes from single neurons (intracellular) and multiple neurons (extracellular), or non-invasively from the scalp, via electroencephalography (EEG). Metabolism and blood flow can be recorded with various techniques, including positron emission tomography (PET), single-photon emission tomography (SPECT), functional magnetic resonance imaging (fMRI), and near-infrared spectroscopy (nIRS), with various degrees of invasiveness. A major restriction of BCIs is that the technology used must record and analyze brain signals fast enough for reasonable speed of communication or control. Other restrictions include cost, size, invasiveness, and mobility of the equipment used.

Neuromodulation

Neuromodulation is a general term that refers to the alteration of activity in the central, peripheral, or autonomic nervous systems. A very close and relative term neurostimulation is most commonly used to emphasize the stimulation of nerves by injecting automated electrical control signals. Usually there is a one-way communication between devices based on this technology and the nervous system. On the contrary, BCI establishes a two-way communication with emphasis on the extraction, recording, and analysis of the signal from the nervous system. Depending on the kind of feedback that the system provides to the user the modification of the neural activity is usually done interactively, with the natural way.

Assistive applications for computer control in rehabilitation

1. Non-invasive EEG-controlled computer operations

Non-invasive EEG-controlled computer operations use scalp electrodes that record the summed activity of thousands of neurons. Signals are amplified and then digitized with analog-to-digital (A/D) converters. Scalp-recorded EEG signals vary in frequency from under 1 Hz to more than 50 Hz (19). With the use of analog filters or complex mathematical algorithms like the Fast-Fourier Transformation (FFT) for digital signals we can isolate the amplitudes or other characteristics of limited frequency bands that typically represent different brain functions (19). For example, the “alpha” EEG rhythm is recorded over the occipital cortex in the range of 8-12 Hz, and is usually seen when individuals close their eyes. It is presumed that this rhythm reflects temporary inactivity or idling of a cortical area that is ready to be active again.

Since the 1970’s, several published studies have shown the ability to learn, via operant conditioning, how to self-regulate the EEG in the alpha, theta, “sensorimotor” (SMR, 12-15 Hz), and “beta” (15-30 Hz) frequency bands, as well as direct current (DC) voltage below 1 Hz, called “slow cortical potentials (SCPs) (for a review, see 16). These observations have led to two different applications: brain self-regulation (EEG biofeedback, also neurofeedback, discussed later) (16), and non-invasive BCI for control and communication in patients with severe or total motor paralysis (“locked-in syndrome”) due to severe neuromuscular disorders, such as amyotrophic lateral sclerosis, brainstem stroke, and spinal cord injury (11).

The “Thought Translation Device” (TTD) is an EEG non-invasive BCI for communication via self-regulation of SCPs in severely paralyzed patients (11). Patients learn to control a cursor in a computer screen and this may be used to control external devices (e.g., turn lights on/off), or to communicate verbally with the Language Support Program (LSP) (21). Electrodes are placed on the scalp over the vertex (Cz in the International 10-20 system) and EEG is recorded against mastoid reference. The signal is digitally filtered and amplitude and polarity (positive vs. negative) of SCPs control the screen cursor. In the LSP, letters and symbols are presented in a dichotomous manner, in groups and subgroups, so the patient can select one of two. To increase typing speed, the software includes “smart” spelling by suggesting frequently used words form a dictionary. For the same reason, the TTD can also be used to select from a menu of standard expressions or commands.

These investigators have shown that patients with late-stage amyotrophic lateral sclerosis were able to learn control of this BCI after 3 – 8 weeks of training (12). Moreover, they showed that healthy individuals could control such BCIs with auditory feedback alone, although with less accuracy than with visual feedback (8). Still, this may be the only solution to paralysed patients with visual impairments. One problem with severely paralysed patients is the uncertainty regarding their cognitive awareness, since they may appear as being in a vegetative state. For this reason, Hinterberger and associates **(**9) incorporated in the TTD a diagnostic tool using evoked-response potentials (ERPs) of the EEG, and were able to classify two out of five severely brain-injured patients in persistent vegetative state (previously diagnosed as unresponsive) as trainable for the TTD.

Others have shown BCI control driven by different EEG frequencies. McFarland and associates (14) showed that trainees were able to control a BCI by manipulating amplitude of either alpha (or in this case "mu", since this 8-12 Hz activity is recorded over the sensorimotor cortex) or beta (18-25 Hz) frequency bands. Adding more variables to control, such as more frequency bands or more scalp areas, may increase the complexity of control possible in BCIs. Alternatively, combining more EEG variables in multivariate linear algorithms has been shown to improve BCI control accuracy (15).

2. Invasive EEG- controlled computer operations

Non-invasive recording of the EEG signal proved important for the initial development of BCIs but according to Donoghue it has several limitations. In particular "*it is impossible for these BMIs to obtain a direct readout of movement intent because neural spiking that carries this information is lost by averaging and filtering across the scalp* (5)". Most important, "*EEG as control signals are slow to engage or modulate (over 1 second), they require mental concentration to the exclusion of other activities and continuous control beyond 1 dimension is difficult to achieve* (23)". As an alternative technology, direct brain-machine interfaces are based on the implantation of intracortical electrode arrays. Such an array had been implanted in the motor cortex area in a Macaca mulatta monkey (30). In the first trial the monkey controlled the position of a cursor on a video monitor using its hand to track a continuously moving visual target. In subsequent trials hand control of the cursor was substituted with neural control to test the reconstruction of hand trajectory. The experiment showed that the neural output from the motor cortex can be used to control a computer cursor almost as effectively as a natural hand.

In June 2004 Cyberkinetics implanted a 4x4 mm, 100-channel sensor on the surface of the motor cortex, in the precentral gyrus immediately posterior to the superior frontal sulcus (18). The surgical procedure consisted of an incision and 3 cm diameter craniotomy located above the right primary motor cortex. The patient was a 25 year-old quadriplegic ventilator-dependent male who was unable to move either upper extremity due to a C4 spinal cord injury and is actively participating in a pilot study of BrainGate system at the Sargent Rehabilitation Center. Using the BrainGate system the participant gained control of a computer interface, with no special training, and managed to operate the cursor while performing other voluntary motor tasks e.g. the patient was able to have full control over a TV while having a discussion with a nearby attendant.

Therapeutic applications

Brain biofeedback

Neurofeedback (NF; also *EEG Biofeedback*) is a technique that helps individuals self-regulate their EEG activity based on operant-conditioning. It utilizes the same principles and technology that BCIs use to record and analyze cortical electrical activity, but instead of being used for communication or control of external utilities it feeds the analyzed information back to the individual, in order to control the very source that produced the signal. NF is based on the principle that brain function can be self-regulated and altered with appropriate exercise in a similar fashion that muscle exercise can reshape a muscle. Just like body-building uses mirrors to provide information about muscle activity, NF uses BCIs as brain mirrors to make individuals aware of specific brain functions and their direction.

NF was found and developed by independent researchers for the treatment of different disorders. Sterman and his colleagues are responsible for developing a NF protocol to treat epilepsy by increasing 12-15 Hz activity over their rolandic cortex (24), whereas Rockstroh and associates have developed an alternative protocol for the same purpose by suppressing negative SCPs (22). Lubar and colleagues have found a NF protocol to treat Attention Deficit Hyperactivity Disorder (ADHD) by suppressing theta activity and increasing SMR or low beta (13), whereas Heinrich and colleagues have recently developed an alternative ADHD protocol by augmenting negative SCPs (7). Peniston and Kulkosky (20) have shown amplitude increases in the alpha (8-13 Hz) and theta (4-7 Hz) frequency bands to assist in the treatment of alcoholism, whereas Hardt and Kamiya (6) illustrated the potential of increasing alpha amplitude to reduce anxiety. Other researchers have also shown the potential of NF to enhance cognitive performance in healthy adults (27).

NF is being used worldwide to either treat neurological and psychological disorders, or to expand the cognitive potential of healthy individuals. Routine conditions treated with NF include ADHD, anxiety, epilepsy, and addictive disorders, whereas traumatic brain injury (TBI), learning disabilities, depression, and schizophrenia are currently being investigated as potential candidates (see review by Monastra, 2003).

The rationale for the development of NF protocols has been based upon EEG and neuroimaging research on correlates of brain pathology (ADHD, depression, TBI); accidental discovery (epilepsy); or neurophysiological correlates of cognitive states (anxiety, substance abuse). Sometimes more than one NF protocols are found effective for the same syndrome (see above). Some propose the comparison of clients' EEG to normative EEG databases in order to individualize NF according to each client's abnormalities (25). This is partly based on the rationale that identical symptoms may be due to different underlying primary pathologies, like for example attentional problems being due to ADHD or depression. However, EEG abnormality does not equal pathology, just as normal EEG does not guarantee healthy brain function. Therefore, caution and experience must be applied in such decisions, just as with any other medical or psychological treatment. A combination of standardized protocol, EEG normative database comparison, experience, and expert consultation will maximize the probability of treatment success.

NF sessions last for approximately one hour, including preparation and cleaning, 20-40 minutes of NF, and are usually administered twice per week. The number of sessions needed for treatment varies substantially from individual case to case, depending among other things on the condition being treated, the client's learning success, and the severity of the condition. Sterman (24) reports having used 25 sessions to treat epileptic seizures, Lubar (13) suggests that 40-80 sessions are needed to treat ADHD, whereas improvement of patients with anxiety disorders have been reported with only 8 NF sessions (see 17, for a review).

Clinical efficacy of NF varies among studies, but epilepsy and ADHD seem to have the strongest experimental support, with anxiety and substance abuse following, and depression, schizophrenia, TBI, learning disabilities, Tourette's and chronic fatigue syndromes, and autism being under investigation (16). Long term-effects of NF have been reported after six-month and up to 10-year post-treatment follow-ups (16, 13). However, NF is not considered a panacea or sufficient treatment for all symptoms of the conditions treated, and other concurrent forms of care are recommended, including psychotherapy, family therapy, group support, and medication, whenever needed (13). The existing research suggests that NF is a promising technique to treat a number of disorders. However, there is need for more research to further support the specificity of NF versus placebo, as well as the specificity of EEG frequency and scalp location to maximize or even attain therapeutic results.

Lubar (13) reports more than 1200 organizations worldwide (including private clinics and research centers/laboratories) applying NF for ADHD alone, based on information from NF equipment manufactures. There are several professional organizations that promote education and research on NF, including the International Society for Neuronal Regulation and its chapters worldwide (iSNR, www.isnr.org), the Association for Applied Psychophysiology and Biofeedback (AAPB, www.aapb.org), the Electroencephalography and Clinical Neuroscience Society (ECNS, www.ecns.com), and the Biofeedback Society of California (BSC, www.biofeedbackcalifornia.org) based in the U.S., as well as the Society for Applied Neuroscience (SAN, www.applied-neuroscience.org) based on Europe. Additionally, the Biofeedback Certification Institute of America (BCIA, www.bcia.org) tests and certifies clinicians who provide NF services to the public.

Research applications

1. NIRI-driven BCIs & biofeedback

Recent attempts investigate the possibility to control BCIs via hemodynamic self-regulation. A non-invasive and inexpensive technology to measure cerebral blood flow (CBF) is using near-infra-red spectroscopy (nIRS) imaging, also referred to as *hemoencephalography* (HEG) (26). Developed in the late 1970's (10), this technique uses near-infra-red light transmitters and respective sensors placed on the scalp, and can record blood oxygenation changes approximately 1 to 1 ½ cm under the scalp (1). In contrast to light of different wavelengths, nIR light can pass through living tissue for short distances and be differentially absorbed and reflected back by different concentrations of oxy- and deoxy-hemoglobin. The rationale for using nIRS in BCIs is that nIRS self-regulation is faster to learn than EEG, and thus reduces patient frustration and possible withdrawal (3).

A few case studies have shown that HEG-biofeedback training to increase blood oxygenation in prefrontal cortex may improve sustained attention in children and adults with various pathologies including ADHD, stroke, depression, and TBI (26) or reduce migraines (2). However, since these were not controlled studies, more systematic research has to follow to illustrate the potential of this method.

2. fMRI biofeedback

Others have shown the possibility to feedback blood oxygen level-dependent (BOLD) response with fMRI, with a delay of less than 2 s from image acquisition. Weiskopf and associates successfully trained an individual to self-regulate BOLD of the rostral-ventral and dorsal part of the anterior cingulate cortex (ACC) (28). In a controlled study, deCharms and colleagues showed that volunteers who got fMRI feedback (but not others who did not get such feedback) were able to learn enhanced voluntary control over the somatomotor cortex (4).

Conclusions

BCIs show great potential in medical applications. Severely paralyzed “locked-in” patients can use BCIs to control their environment and communicate with others, a radical change in their life quality. Self-regulation of brain function with NF provides a very promising alternative for the treatment of psychiatric and neurological disorders such as epilepsy, ADHD, and anxiety, as well as the opportunity for healthy individuals to improve their cognitive performance. Researchers are currently investigating new applications for BCIs, such as treatment of depression or TBI, new technologies for BCIs like nIRS, implanted EEG electrodes, or even fMRI biofeedback, that will expand or improve current applications. Improved BCIs will provide better control accuracy, more complex communication, faster learning, and benefit for a broader patient range. However, it is a complex field that requires combined efforts and serious further research. As experts in this field note, “BCI development depends on close interdisciplinary cooperation between neuroscientists, engineers, psychologists, computer scientists, and rehabilitation specialists” (29).

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