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INTRODUCTION

Brain-Computer Interface: Current and Emerging Rehabilitation Applications

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Abstract

A formal definition of brain-computer interface (BCI) is as follows: a system that acquires brain signal activity and translates it into an output that can replace, restore, enhance, supplement, or improve the existing brain signal, which can, in turn, modify or change ongoing interactions between the brain and its internal or external environment. More simply, a BCI can be defined as a system that translates "brain signals into new kinds of outputs." After brain signal acquisition, the BCI evaluates the brain signal and extracts signal features that have proven useful for task performance. There are 2 broad categories of BCIs: implantable and noninvasive, distinguished by invasively and noninvasively acquired brain signals, respectively. For this supplement, we will focus on BCIs that use noninvasively acquired brain signals.

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A formal definition of brain-computer interface (BCI) is as follows: "a system that measures central nervous system (CNS) activity and converts it into artificial output that replaces, restores, enhances, supplements, [informs], or improves natural CNS output and thereby changes the ongoing interactions between the CNS and its external or internal environment."[1(p3)] More simply, a BCI can be defined as a system that translates "brain signals into new kinds of outputs."[1(p5)] There are 2 major ways in which BCIs can be used. The first is straightforward and has been studied for >25 years; in this case, the BCI system acquires a brain signal and allows the user, through feedback, to engage the BCI output for control of the environment (light switch, temperature control) or communication devices. A second and newly emerging BCI application involves using the system as a motor learning—assist device. In this case, the BCI may enhance motor control recovery by demanding more focused attention or guiding activation or deactivation of brain signals.[2]

BCI research has experienced a recent exponential growth, which can be attributed to a number of the following factors: availability of rapid, real-time sophisticated signal processing methods; a greater understanding of the characteristics and uses of brain signals; an appreciation of the phenomenon of activity-dependent brain plasticity; and a growing dissatisfaction with current rehabilitation methods and the need for improved methods for recovery of function for those with persistent motor impairment.[2]

Brain signals can be acquired in a number of forms, including electrical (eg, electroencephalography [EEG]) or magnetic fields (eg, functional magnetic resonance imaging [fMRI]) or functional near infrared spectroscopy (fNIRS).

It is important for those of us who are clinicians and clinician-scientists to be informed about the development and capability of BCIs because these systems have potential to enhance rehabilitation methods. Even more importantly, it is critical for us to participate in the design and development of these systems so that BCI system designs are grounded in the needs of patients, framed within feasible technical interfaces, and constructed for practical delivery in a clinical environment. To that end, we present this supplement: Brain-Computer Interface: Current and Emerging Rehabilitation Applications. Within this supplement, we are providing articles that arose from presentations at the 2013 International Brain-Computer Interface Meeting, which was held June 3 through June 7, 2013, at the Asilomar Conference Center in Pacific Grove, California.

The 2013 BCI meeting was the fifth in the international BCI meeting series, with past meetings in 1999, 2002, 2005, and 2010. The purpose of the international BCI meeting series is to bring

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together the diverse contributors to BCI research and development in a distinctive retreat-style meeting that encourages interaction, collaboration, and discussion. Therefore, the international BCI meeting series strives to push the BCI field forward, encouraging growth and translation of BCIs from the laboratory to the clinic. The 2013 meeting was supported by the National Institutes of Health and National Science Foundation and other governmental and private sponsors (further sponsor information available at http://bcimeeting.org/2013/sponsors.html). The meeting drew scientists from 29 countries, representing 165 research groups, with a total of 301 attendees, of whom 37% were students or postdoctoral fellows. There were >200 extended abstracts submitted for peer review, from which 25 were selected for oral presentation (individual index abstracts: http://bcimeeting.org/2013/researchsessions.html), and 181 were selected for poster presentation (individual index abstracts: http://bcimeeting.org/2013/posters.html). Accepted abstracts were published in open-access conference proceedings (http://castor.tugraz.at/doku/BCIMeeting2013/BCIMeeting2013_all.pdf). The retreat-style format featured 19 highly interactive workshops[3] and an exhibit hall with formal poster session and technology demonstrations.

The 2013 BCI meeting theme was Defining the Future. Compared with prior BCI conferences, attendance included an increased representation of clinicians, clinician-scientists, and people with disabilities. There were a number of firsts for the meeting series. First, the planning committee was composed of BCI researchers from around the world. Second, both the planning committee and conference participants included people with severe disabilities who need assistive technology for communication. A woman with amyotrophic lateral sclerosis (ALS) who uses assistive technology for communication served on the program committee (http://bcimeeting.org/2013/meetinginfo.html). She attended the meeting remotely; she participated in a panel discussion and provided a presentation at a virtual BCI user's forum. This forum provided a venue by which BCI users could speak directly to the conference attendees. A man with brainstem stroke attended the meeting with his caregivers, presenting both in a workshop and in the virtual user's forum. Both are coauthors on an article in this supplement[4] summarizing the experiences of BCI users with the current state of BCI technology. A third new development was that attendees at the 2013 BCI meeting voted to establish a Brain-Computer Interface Society, which will plan and oversee the 6th International BCI Meeting to be held in 2016. Fourth, there was an increase in the number of venues for dissemination of results. This supplement contains articles with a clinical or patient experience focus. A special section in the *Journal of Neural Engineering* published articles with an engineering focus.[5] A summary of the conference workshops was published in the newly established *Brain-Computer Interfaces* journal.[3]

The articles in this supplement provide examples of work conducted using a variety of BCI technology applications, including communication, leisure activities, and motor learning.

List of abbreviations:

AAC	**augmentative and alternative communication**
ALS	**amyotrophic lateral sclerosis**
BCI	**brain-computer interface**
CNS	**central nervous system**
EEG	**electroencephalography**
fMRI	**functional magnetic resonance imaging**
fNIRS	**functional near infrared spectroscopy**
tDCS	**transcranial direct current stimulation**
TMS	**transcranial magnetic stimulation**

Communication

Problem

Communication is an essential function for health care,[6,7] function, and quality of life.[8] For those with neuromuscular impairments and difficulty with writing or speaking, augmentative and alternative communication (AAC) devices can compensate and provide device-assisted communication.[6] Most currently available AAC devices are controlled by available physical movements, and in the presence of volitional movement, they work well for performing a simple task. However, there are limitations to currently available AAC devices. First, the capability of currently available AAC devices can be overwhelmed by task complexity or by the simultaneous task demands of a given function. Second, some individuals do not possess the required physical capability to control an AAC device, and others have progressive diseases which eventually preclude their use of any physical movement to control communication devices. Therefore, the inability of some people to operate AAC devices is of particular concern[6] and represents an area of vital need. A study on end-of-life decisions by people with ALS[7] quoted a participant as saying "as long as I can properly communicate with my voice, my eyes or a machine or whatever, I want to have a respirator…But as soon as I can no longer communicate, that's it! I don't want anything else to be done."(p210)

Role of BCIs in rehabilitation

In contrast with most available AAC devices, BCIs can be controlled through the direct use of brain signal, bypassing the need for volitional muscle activity as a control paradigm. For a number of years,[9,10] potential BCI users and caregivers have expressed the importance of BCIs for communication. In a focus group of potential BCI users with ALS and their caregivers, one caregiver described the promise of BCI as follows: "I just think it is wonderful that you can give someone a voice who is losing theirs."[11](p523)

BCIs have been developed and tested for use in controlling devices for communication. BCIs are most appropriate and most needed by people with few other options for control of assistive technology. These include people with late-stage ALS, people with disorders of consciousness who show signs of cognitive awareness but lack other means of communication, and other populations of people who cannot reliably operate physical interfaces or eye gaze systems to access assistive technology. In this supplement, Kübler et al[12] discuss a decision process for determining who should participate in in-home BCI research studies, considering participant characteristics, support structure, and environmental factors. To date, BCIs have primarily been used in the laboratory or in controlled research studies. However, one commercial BCI device is now available.[a] Therefore, as discussed by Hill et al[13] in this supplement, critical issues remain for the widespread adoption of BCIs as practical AAC devices for clinical use. Peters' article[4] describes both the promise and shortcomings of BCI as a communication device and compares BCI to conventional assistive technology solutions.

BCIs are increasingly being integrated with other commercial assistive technology on an experimental basis[14] and can form an interface that is based on brain signals and is incorporated within the framework of other existing assistive technology, increasing the accessibility of such devices.[15] There is a growing awareness that BCIs can be used in combination with physical input signals if the patient has such signals available, a concept described as a hybrid BCI design.[16] In this supplement, Schettini et al[17] investigate the