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The Wadsworth BCI Research and Development Program: At Home With BCI

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***Abstract*—The ultimate goal of brain–computer interface (BCI) technology is to provide communication and control capacities to people with severe motor disabilities. BCI research at the Wadsworth Center focuses primarily on noninvasive, electroencephalography (EEG)-based BCI methods. We have shown that people, including those with severe motor disabilities, can learn to use sensorimotor rhythms (SMRs) to move a cursor rapidly and accurately in one or two dimensions. We have also improved P300-based BCI operation. We are now translating this laboratory-proven BCI technology into a system that can be used by severely disabled people in their homes with minimal ongoing technical oversight. To accomplish this, we have: improved our general-purpose BCI software (BCI2000); improved online adaptation and feature translation for SMR-based BCI operation; improved the accuracy and bandwidth of P300-based BCI operation; reduced the complexity of system hardware and software and begun to evaluate home system use in appropriate users. These developments have resulted in prototype systems for every day use in people's homes.**

***Index Terms*—Augmentative communication, brain–computer interface (BCI), conditioning, electroencephalography (EEG), mu rhythm, P300, rehabilitation, sensorimotor cortex.**

I. Introduction

Conditions such as amyotrophic lateral sclerosis (ALS), brainstem stroke, and brain or spinal cord injury can impair the neural pathways that control muscles or the muscles themselves. People who are most severely affected may lose all or nearly all voluntary muscle control, even eye movements and respiration, and may be essentially "locked in" to their bodies, unable to communicate in any way or limited to slow unreliable single-switch methods. Studies of the past 20 years show that the scalp-recorded electroencephalogram (EEG) can be the basis for brain–computer interfaces (BCIs) [1]–[5] that restore communication and control to these severely disabled individuals.

Since 1986, the Wadsworth Center BCI Laboratory in Albany, New York, has shown that healthy and disabled people can learn to control the amplitude of mu and beta rhythms in the EEG recorded over sensorimotor cortex and that these rhythms can be used to control a cursor on a computer screen in one or two dimensions [5]–[7]. More recently, we have evaluated and refined P300-based BCI operation [8], [9], and also begun to explore BCI applications of electrocorticographic activity (ECoG) [10]. Our primary focus at present is to convert the

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current complex BCI system used in the laboratory into a practical user-friendly BCI system for unsupervised daily home use by people with severe disabilities who have found conventional assistive technology inadequate, and to show that this system is useful to those individuals in their daily lives. To accomplish this, we have: expanded and improved our general-purpose BCI software (BCI2000); optimized system parameters for sensorimotor rhythm (SMR)-based and P300-based BCI operation; begun to develop a set of menu-based applications; and begun to reduce the complexity of system software and hardware. We are seeking to determine: to what extent the system gets daily use; to what extent we can minimize the need for ongoing technical support; and to what extent the BCI system improves quality of life for its users and their families and caregivers.

II. Current Work

A. Software Development: BCI2000

An important first step in developing a versatile home system has been our development of BCI2000, a software platform that supports and facilitates all reasonable combinations of brain signals, recording methods, processing methods, and output devices [11].[1] The goals of the BCI2000 project are 1) to create a system that facilitates the implementation of any laboratory or home BCI system; 2) to incorporate into this system support for the most commonly used BCI methods; and 3) to disseminate the system and associated documentation to other laboratories. Currently, work is focused on facilitating the translation of advances achieved using the complex laboratory-system configurations into the reduced home-system configurations. In this way, BCI2000 facilitates progress in laboratory and clinical BCI research by reducing the time, effort, and expense of testing new BCI methods, by providing a standardized data format for offline analyses, and by allowing groups lacking high-level software expertise to engage in BCI research. In addition to the basic BCI functionality already incorporated in BCI2000, we are currently adding features that allow interfacing the system with off-the-shelf communication aids (such as predictive spelling programs). To date, BCI2000 has been adopted by more than 75 laboratories around the world that use the system for a variety of studies. With the versatility provided by its features, BCI2000 is currently in use with BCI systems using mu and beta rhythms [7], [12], [13], slow cortical potentials [14], P300 (P3) [15], [16], steady-state visual evoked potentials [17], and signals recorded from the surface of the cortex [electrocorticographic activity (ECoG)] [10] in conjunction with a variety of user applications [18].

B. Improved Sensorimotor Rhythm Control

In awake people, primary sensorimotor cortical areas often display 8–12 Hz (mu) and/or 18–26 Hz (beta) EEG rhythms when they are not engaged in processing sensory input or producing motor output (reviewed in [19]). These mu and beta rhythms are called "sensorimotor rhythms" (SMRs) and are thought to be produced by thalamocortical circuits [19], [20]. They wax and wane in association with actual movement or imagination of movement [21], [22]. With our SMR-based BCI system, people learn over a series of 40-min training sessions to control mu or beta amplitudes through motor imagery (i.e., without actual movement or sensation) and can use this control to move a cursor in one [23]–[25] or two dimensions [7] to select targets, letters, or icons on a screen [26].

In our standard protocol, the cursor movement for each dimension of control is independently determined by a linear equation of the form

$$M = b(w_1 f_1 + w_2 f_2 \cdots + w_n f_n - a) \quad (1)$$

[1]http://www.bciresearch.org

where f are the EEG features (specifically amplitudes in specific frequency bands at specific scalp locations), w are the feature weights, a is the intercept, and b is the gain. This equation translates mu- and/or beta-rhythm amplitudes from one or several scalp locations into cursor movement 20 times/s online while 64 channels of EEG (according to the modified 10–20 system [27]) are stored for offline analysis. Recent changes in automatic online adaptations of the gain (b), intercept (a), and feature weights (w), have resulted in a significant improvement in subject performance (for full description see [23] and [24]). In addition, we have extended the basic translation algorithm of our earlier studies to include larger numbers of features and interactions for improved performance [28].

To further develop EEG-based multidimensional and sequential movement control, we are improving two-dimensional (2-D) cursor control [7] and adding a select function so that users can move the cursor to an object and select it if desired. In this mouse-like application, the user first moves the cursor to hit one of multiple possible targets by controlling two independent EEG features and then selects or rejects the target by controlling a third EEG feature [26].

We continue comprehensive spectral and topographical analyses of 64-channel EEG during BCI operation to detect non-EEG artifacts such as electromyographic (EMG) or electrooculographic (EOG) activity, and to guide improvements in online operation. This analysis relies largely on the measure R^2. R^2, which is the proportion of the total variance in an EEG feature (e.g., mu- or beta-rhythm amplitude at a specific location) that is accounted for by target position, and thereby reflects the user's level of EEG control. Thus, if the user has no EEG control, R^2 will be zero; while if the user has perfect control, so that the EEG feature is completely determined by target location, R^2 will have its maximum value of 1.00 [29].

Offline, we have continued to evaluate alternate means for improving the signal to noise ratio so as to improve online performance. In [30], we determined that 2-D linear and nonlinear Bayesian classifiers offer improved performance over one-dimensional (1-D) linear classifiers. In other studies, we assessed the EEG in the time-domain while people used SMRs to control cursor movements [31]. The combination of time-domain features with SMR amplitudes could increase accuracy and help detect errors as they occur. In a method recently implemented online, an empirically derived mu-rhythm template is used as a matched filter. It relies on the fact that part of the beta-rhythm activity appears to be a phase-coupled harmonic of the mu rhythm [32].

Finally, we have developed simple "yes" and "no" and simple word processing programs that can be operated with SMR control [33], [34].

C. Improved P300-Based BCI Control

Farwell and Donchin [35] demonstrated that people can use the P300 potential evoked by stereotyped sensory stimuli to make selections on a computer screen. In this method, the user faces a 6×6 matrix containing letters and symbols and focuses attention on the desired item, while every 125 ms a row or column of the matrix is intensified for 100 ms. Intensification of the row or column containing the desired symbol elicits a P300 evoked response. More recent studies indicate that, with alternate classification techniques and minimal training [36], [37], the P300 speller matrix can serve as an effective communication device for people with ALS [14], [16], [38]. In addition, more advanced feature extraction and classification procedures such as wavelets [36], [39], support vector machines [40], [41], independent components analysis (ICA) [42], and matched filtering [39] can improve performance beyond that originally reported.

We have focused on two aspects of the P300-based matrix speller and their effects on performance: parameterization of the EEG data for each individual and matrix speller design. Results suggest that, with proper model and feature selection, stepwise linear discrimination analysis is a practical and effective tool for achieving accurate online performance of a P300-based BCI [8]. We have also shown that factors such as matrix size and inter-stimulus interval affect classification rates and accuracy, and thus affect the rate of information transfer (i.e., bit rate) [9].

III. BCI System for Home Use

A. Developing the Home System

We are developing a portable BCI system for home use that consists of a laptop computer with 16-channel EEG aquisition, a second screen that is placed in front of the user, and an electrode cap (for details see [12]). An early version of this BCI system has been used over the past several years in SMR and P300 studies in our laboratory and in our collaboration with Birbaumer and Kübler at Eberhard-Karls University, Tübingen, Germany, and Donchin at the University of South Florida, Tampa [12], [15], [16]. Our goal is to simplify the portable system by including only the hardware and software elements essential for easy home operation and eliminating those needed only in laboratory research.

B. Finding Initial Users

The initial users of our home BCI system satisfy six criteria. First, they are severely disabled with little or no usable voluntary muscle control (e.g., no more than eye movement or movement of a single digit). Thus, they are likely to include people with: late-stage ALS; brainstem stroke; severe cerebral palsy or muscular dystrophy; high-level spinal cord injuries; and a variety of other severe disorders. Second, they have found conventional assistive communication technologies, such as eye-movement-based devices or sip-and-puff switches, to be inadequate for their needs. They may simply be unable to operate them, their control may be inconsistent or easily fatigued, they may not like the devices because of the awkwardness of their use or their appearance, or their ability to use them may be deteriorating. Third, while their disorders may be progressive (e.g., ALS), they are medically stable and not acutely ill and have a reasonable prospect of continuing so for several years. Fourth, they have stable physical and social environments. Fifth, they have stable and reliable caregivers (family members and/or professionals) with basic computer skills. Sixth, they and their caregivers have a realistic understanding that there is no guarantee that participation in this research will benefit them directly. Our work with collaborators in Tübingen has facilitated these preliminary studies [12], [14], [15].

Using these criteria, we have identified our first potential users. Currently, a 47-year-old scientist with ALS uses a BCI home system independently on a daily basis with a P300-based matrix speller [e.g., Fig. 1(B)]. He has found it superior to his eye-gaze system and uses the BCI 4–6 h/day for e-mail and other important purposes. Daily cap placement and system oversight is carried out by a caregiver rather than laboratory personnel. Daily data on system operation are provided to our laboratory via the Internet. We expect to provide BCI home systems to additional users in the next several months.

C. Developing Initial Applications

The BCI system that we have developed for home use is able to use P300 responses or SMRs with sequential menu formats. EEG features (i.e., P300 or SMRs), menu formats, and sequences can be configured for the capacities, needs, and preferences of each user. Moreover, with some further changes, this BCI home system could easily accommodate use of other brain signals (e.g., slow waves [14]).

For SMR applications, each menu has a basic “2-to-n” choice format and operates in a 1-D or 2-D center-out mode [e.g., Fig. 1(A)], depending on the capability of the user. 1-D SMR control applied to a sequence of three four-choice menus [e.g., Fig. 1(A)] [34] allows a user to select individual letters for simple word-processing. For users with better 1-D control, each menu can offer six or eight choices. For those capable of 2-D control [e.g., Fig. 1(A)] [7], a center-out menu could provide ten or even more choices.

For P300 applications, each menu consists of a matrix ([35]). This can be a 3×3, 6×6, or an even larger matrix (e.g., our first home user employs a 9×8 matrix interfaced with a predictive spelling program) [43]. For users who lack sufficient visual function, the system offers a purely auditory (i.e., tone-based) mode or a combined auditory/visual mode (as described and tested in [16]). Our preliminary studies have shown that an auditory mode provides stimuli adequate for eliciting a P300 response that is effective for BCI operation. In the standard visual P300 mode, the visual stimuli are presented as intensification of rows or columns in the matrix [e.g., Fig. 1(B)]. The specific row and specific column that elicit a P300 response identify the user’s selection. In the auditory P300 mode, the auditory stimuli are words or tones representing the specific choices. They are presented in a random sequential fashion. In either visual or auditory mode, the system executes the action represented by the stimulus that evoked a P300 response from the user (i.e., the selection that the user desired).

Fig. 1(B) shows examples of icons for applications that might be accessed through P300 or SMR main menus and their respective control signals. These applications consist of menu sequences that address potential topics of importance to a severely motor-impaired person, (e.g., medical care; environmental control (such as room temperature); interactions with family members or friends; food/drink; e-mail; word-processing, answering simple questions (in print or with a speech synthesizer); entertainment; Internet access). Current work is addressing how these applications might best be delivered.

D. Technical Oversight and Evaluation of Efficacy

We train caretakers to place the cap, inspect the EEG signals, and initiate and oversee BCI operation. To ensure reliable longterm performance, full data on daily operation are transferred to our laboratory for evaluation, we maintain close contact with caregivers and users by e-mail and phone, and we make regular home visits. To assess the extent and success of BCI usage and its impact on quality of life, we measure the amount and accuracy of BCI usage and plan to conduct periodic questionnaire-based interviews of users, caregivers, and family members. These questionnaires are based on those developed and validated for persons with ALS (e.g., [44]).

IV. Future Work

We will continue to reduce the complexity of the BCI home system and increase its flexibility, capacity, and convenience. In this effort, we are developing a simpler eight-channel system using eight-channel EEG acquisition and telemetry. With appropriate adjustments of the BCI2000 software, the laptop can support applications through its second screen (e.g., word-processing, e-mail, answering questions) or through its standard output channels (e.g., for environmental control, television control, etc.). While the standard electrode cap with gel application is sufficient for the key goals of this project, we are seeking improved sensor and cap solutions that provide reliable, long-term recordings, even in electrically noisy environments and at the same time maximize comfort and cosmesis.

To improve the menu format and icon selection process both for P300 and for SMR we are continuing studies now underway in the laboratory. For example, to date these studies indicate that the actual screen size of the matrix can be substantially reduced without affecting performance [43]. We are incorporating additional windows in both SMR and P300 designs to allow the selections to be placed directly into a word processing application. For continuous or prolonged operation, we are

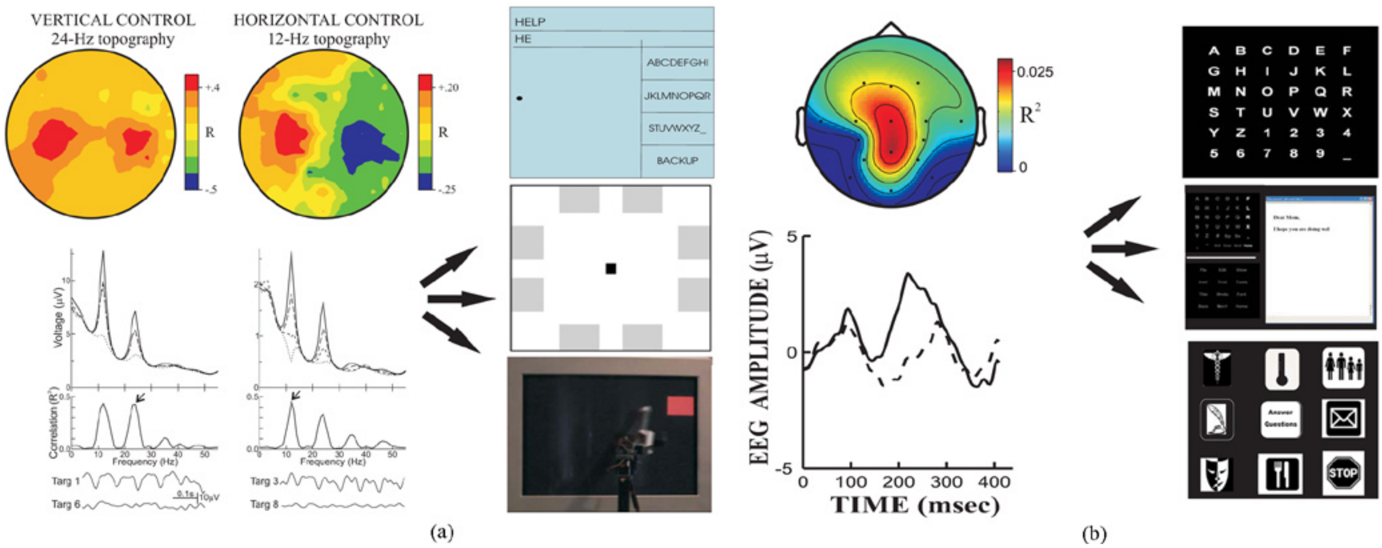

Fig. 1. (A) Sensorimotor rhythm (SMR)-based and (B) P300-based BCI operation and applications. (A) Left-side: Topographical and spectral properties of 2-D cursor control with SMRs by a user with a spinal cord injury (see [7] for full details). He controlled vertical movement with a 24-Hz beta rhythm, and horizontal movement with a 12-Hz mu rhythm. Top: Scalp topographies (nose at top) of the correlations of the 24-Hz and 12-Hz rhythms with vertical and horizontal target levels, respectively. The sites of the left- and right-side scalp electrodes (locations C3 and C4 over sensorimotor cortex [27]) that controlled the cursor are marked. Vertical correlation is greater over the left hemisphere, while horizontal correlation is greater over the right hemisphere. (The topographies are for R rather than R^2 to show the opposite (i.e., positive and negative, respectively) correlations of right and left hemisphere locations with horizontal target level). Middle: Voltage spectra (i.e., the weighted combinations of right-side and left-side spectra) from which were derived the vertical and horizontal variables, and their corresponding R^2 spectra. Voltage spectra are shown for the four vertical target levels (top to bottom: solid, long dash, short dash, and dotted) and for the four horizontal target levels (right to left: solid, long dash, short dash, and dotted), respectively. For the R^2 spectra, the arrows point to the frequency bands used for the vertical and horizontal variables, respectively. Bottom: Samples of EEG from single trials. On the left are traces from electrode C3 (i.e., the major contributor to the vertical variable) for trials in which the target was at the top (top trace) or bottom (bottom trace) screen edge. On the right are traces from electrode C4 (the major contributor to the horizontal variable) for trials in which the target was at the right (top trace) or left (bottom trace) edge. They illustrate the SMR control that enabled the user to move the cursor to the target. Right-side: User screens for several SMR-based applications tested to date. Top: A cursor moves steadily across the screen from left to right while the user controls its vertical movement alone so that it reaches the desired selection on the right edge. A series of three such selections chooses a specific letter (see [34] for details). Middle: A cursor starts in the center of the screen and moves in two dimensions controlled by the user as illustrated on the left side of this figure so that it hits a target located at one of eight possible locations on the periphery of the screen. Bottom: The tip of a simple robotic arm starts in the center of the screen and moves in two dimensions controlled by the user as illustrated on the left side of this figure so that it reaches a target located somewhere on the periphery of the screen. (B) Left-side: Top: Topographical distribution (nose at top) of a P300 potential (measured as R^2) recorded during matrix spelling. The subject is a 47-year-old man with amyotrophic lateral sclerosis who is now using the Wadsworth BCI 4–6 h/day (see [43] for details of the method). Bottom: Response at the vertex (location Pz [27]) to flashing of the row or column of the 6 × 6 matrix that contains the desired choice (solid line) and to flashing of other rows or columns (dotted line). Right-side: User screens for several P300-based applications tested to date. Top: The basic 6 × 6 spelling matrix. Middle: simple word-processing screen with basic 6 × 6 spelling matrix, 4 × 4 function matrix accessible from the 6 × 6 matrix, and a text page. Bottom: A 3 × 3 matrix of icons, each offering access to a submenu serving a particular aspect of daily living (e.g., food, medical care, entertainment, environmental control, family and friends, e-mail).

developing a function that allows the user to suspend (i.e., exit) operation (or re-commence operation) using the EEG signals (i.e., P300 or SMRs) alone [18].

Finally, to adequately evaluate the ultimate usefulness of BCI, we will continue to evaluate in a comprehensive fashion the actual impact of daily BCI use on the lives of the user, family members, and caretakers. This includes assessment of the amount of daily usage and performance level for each application and all applications together. It also includes formal measurements of satisfaction and quality of life (e.g., [12], [44]).

V. Conclusion

To achieve the central purpose of BCI research, reliable home BCI systems that provide important applications and require minimal technical support must be developed and validated by testing in appropriate user populations. Based on methods developed or adapted in our laboratory over the past 20 years, the Wadsworth Center BCI Group is developing such a system and testing it in a representative group of users. We are assessing its long-term performance, reliability, ease of use, and the contribution it makes to quality of life for its users, their families, and their caregivers.

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