BCI2000: A General-Purpose Brain-Computer Interface (BCI) System

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***Abstract*—Many laboratories have begun to develop brain-computer interface (BCI) systems that provide communication and control capabilities to people with severe motor disabilities. Further progress and realization of practical applications depends on systematic evaluations and comparisons of different brain signals, recording methods, processing algorithms, output formats, and operating protocols. However, the typical BCI system is designed specifically for one particular BCI method and is, therefore, not suited to the systematic studies that are essential for continued progress. In response to this problem, we have developed a documented general-purpose BCI research and development platform called BCI2000. BCI2000 can incorporate alone or in combination any brain signals, signal processing methods, output devices, and operating protocols. This report is intended to describe to investigators, biomedical engineers, and computer scientists the concepts that the BCI2000 system is based upon and gives examples of successful BCI implementations using this system. To date, we have used BCI2000 to create BCI systems for a variety of brain signals, processing methods, and applications. The data show that these systems function well in online operation and that BCI2000 satisfies the stringent real-time requirements of BCI systems. By substantially reducing labor and cost, BCI2000 facilitates the implementation of different BCI systems and other psychophysiological experiments. It is available with full documentation and free of charge for research or educational purposes and is currently being used in a variety of studies by many research groups.**

***Index Terms*—Assistive devices, augmentative communication, brain-computer interface (BCI), ECoG, electroencephalography (EEG), psychophysiology, rehabilitation.**

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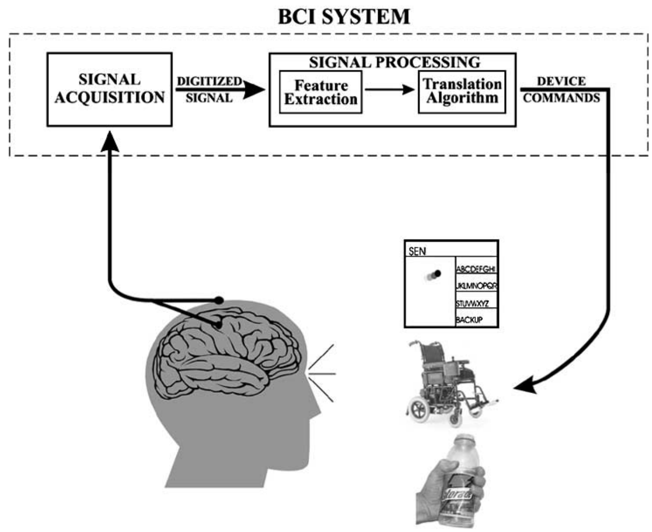

Fig. 1. Basic design and operation of any BCI system. Signals from the brain are acquired by electrodes on the scalp, the cortical surface, or from within the brain and are processed to extract specific signal features (e.g., amplitudes of evoked potentials or sensorimotor cortex rhythms, firing rates of cortical neurons) that reflect the user's intent. Features are translated into commands that operate a device (e.g., a simple word processing program, a wheelchair, or a neuroprosthesis).

I. Introduction

A. Brain-Computer Interface (BCI) Technology

MANY people with severe motor disabilities need augmentative communication technology. Those who are totally paralyzed, or "locked-in," cannot use conventional augmentative technologies, all of which require some measure of muscle control. Over the past two decades, a variety of studies has evaluated the possibility that brain signals recorded from the scalp or from within the brain could provide new augmentative technology that does not require muscle control (e.g., [1]–[8]); see [9] for a comprehensive review. These BCI systems measure specific features of brain activity and translate them into device control signals (see Fig. 1, modified from [9]). The features used in studies to date include slow cortical potentials, P300 evoked potentials, sensorimotor rhythms recorded from the scalp, event-related potentials recorded on the cortex, and neuronal action potentials recorded within the cortex.

These studies show that nonmuscular communication and control is possible and might serve useful purposes for those who cannot use conventional technologies. To people who are locked-in (e.g., by end-stage amyotrophic lateral sclerosis, brainstem stroke, or severe polyneuropathy) or lack any useful muscle control (e.g., due to severe cerebral palsy), a BCI system could give the ability to answer simple questions quickly, control the environment, perform slow word processing, or even operate a neuroprosthesis or orthosis (see [10]–[12]). At the same time, the performance of this new technology, measured in rate and accuracy, or in the inclusive measure, information transfer rate (i.e., bit rate), is modest. Current systems can reach no more than 25 bits/min,[1] even under optimal conditions [13]. The ultimate value of this new technology will depend largely on the degree to which its information transfer rate can be increased.

B. Further Development of BCI Technology

Many factors determine the performance of a BCI system. These factors include the brain signals measured, the signal processing methods that extract signal features, the algorithms that translate these features into device commands, the output devices that execute these commands, the feedback provided to the user, and the characteristics of the user. Thus, future progress requires systematic well-controlled studies that evaluate and compare alternative signals and combinations of signals, alternative feature extraction methods and translation algorithms, and alternative communication and control applications in different user populations.

Unfortunately, most current BCI systems do not readily support such systematic research and development. While a few systems have attempted to solve this problem (e.g., [14]–[16]), BCI research up to the present has consisted mainly of demonstrations that a certain brain signal recorded and measured in a certain way, and translated into control commands by a certain algorithm, can control a certain device for one or a few users [9]. The systems used in these demonstrations lack the flexibility needed to pursue the improvements that might be achieved by incorporating and comparing diverse brain signals, processing methods, and output modalities.

In recognition of this situation, we set out to develop and test a general-purpose BCI research and development system, called BCI2000, that can facilitate the systematic studies described above.

II. BCI2000 System Design

A. Essential Features

1) Common Model: BCI2000 is based on a model that can describe any BCI system and that is similar to the one described in [17]. This model, shown in Fig. 2, consists of four modules that communicate with each other: source (data acquisition and storage), signal processing, user application, and operator interface. The modules communicate through a documented network-capable protocol based on TCP/IP. Thus, each can be written in any programming language and can be run on any machine on a network.

2) Interchangeability and Independence: To maximize interchangeability[2] and independence[3] in BCI2000, we based it on principles applicable to all BCIs and implemented these principles using current techniques of object-oriented software design.

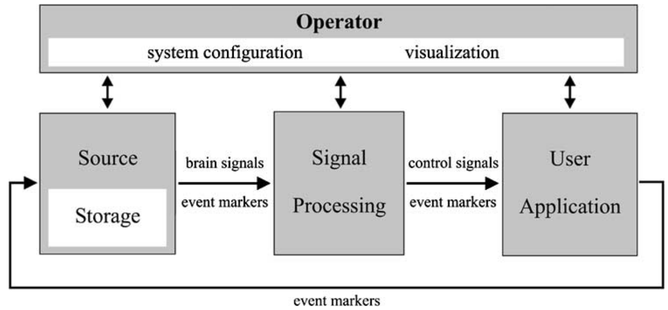

Fig. 2. BCI2000 design. BCI2000 consists of four modules: operator, source, signal processing, and application. Operator module acts as a central relay for system configuration and online presentation of results to the investigator. It also defines onset and offset of operation. During operation, information (i.e., signals, parameters, or event markers) is communicated from source to signal processing, to user application, and back to source.

Communication between modules uses a generic protocol that can transmit all information (e.g., signals or variables) needed for operation. Thus, the protocol does not need to be changed when changes are made in a module. The information that passes from one module to another is highly standardized to minimize the dependencies between modules.[4] Each necessary BCI function is placed in the module to which it logically belongs. For example, because each processing cycle is initiated by the acquisition of a block of data samples, source acts as BCI2000's system clock. Similarly, because feedback control varies with the application (e.g., fixed-length versus user-paced applications), it is placed in user application. This principle further reduces interdependence between modules.

3) Scalability: The four modules and their communication protocol do not place constraints on the number of signal channels or their sampling rate, the number of system parameters or event markers, the complexity of signal processing, the timing of operation, or the number of signals that control the output device. Thus, these factors are limited only by the capacities of the hardware used.

4) Real-Time Capability: Any BCI system must acquire and process brain signals (potentially from many channels at high sampling rates) and respond with appropriate output within a short (i.e., on the order of milliseconds) time period with minimal variation (i.e., latency jitter). To satisfy these requirements, we designed BCI2000 such that the effect on response time of the operating system, the hard drive, and other sources of interruptions is minimized.

5) Support and Facilitation of Offline Analyses: BCI2000 supports comprehensive offline analyses of data gathered during online operation: The data storage format accommodates all possible variations in the digitized brain signals (e.g., number of channels, sampling rate), defines the operating protocol, and

[1]Exceptions are systems based on steady-state visually evoked potentials. While these systems do not directly depend on muscle control, they do require the user to control gaze direction. Thus, they cannot be used by people who are totally paralyzed.

[2]Components are interchangeable if different implementations of each can be used without changes elsewhere in the system.

[3]Components are independent if they can be combined in any fashion.

[4]User applications might employ distinctive stimuli to evoke brain responses (such as the P300 speller described in this paper). Because these BCI paradigms depend on the brain's responses to the stimuli, their user applications cannot be interchanged with ones that do not provide the stimuli. In other situations, online adaptations occurring in the signal processing module depend on the feedback provided to the user. Thus, a certain degree of module interdependence is sometimes unavoidable.

includes a record of all events (e.g., feedback to user, device control, artifact detection) that occur during operation.

6) Practicality: Finally, BCI2000 offers a number of different BCI methods that are readily usable by interested researchers without highly specialized software expertise, and it uses readily available and relatively inexpensive hardware components. We maintain and properly update the code base and a roster of existing implementations and provide documentation that is suitable for engineers as well as for end users.

B. Modules

1) Source Module: The source module digitizes and stores brain signals and passes them on without any further preprocessing to signal processing. It consists of a data acquisition and a data storage component. Data storage stores the acquired brain signal samples along with all relevant system variables (such as system parameters or all current event markers) in a data file. The documented file format consists of an ASCII header, followed by binary signal sample, and event marker values. The file format can accommodate any number of signal channels, system parameters, or event markers.

2) Signal Processing Module: The signal processing module converts signals from the brain into signals that control an output device. This conversion has two stages: feature extraction and feature translation. In the first stage, the digitized signal received from the source module is subjected to procedures that extract signal features (e.g., firing rate of a cortical neuron, amplitude of an evoked potential, etc.). In the second stage, a translation algorithm translates these signal features into control signals that are sent to the user application module.

Each of the two stages of signal processing consists of a cascade of signal operators, each of which transforms an input signal into an output signal. The individual signal operators (e.g., spatial filter, temporal filter, linear classifier) are themselves independent of each other and can, thus, be combined or interchanged without affecting others.

3) User Application Module: The user application module receives control signals from signal processing and uses them to drive an application. In most present-day BCIs, the user application is presented visually on a computer screen and consists of the selection of targets, letters, or icons (e.g., [1], [2], [8], and [18]–[22]). User feedback could also be auditory or haptic. Selection is indicated in various ways. Some BCIs also give interim output, such as cursor movement toward the item prior to its selection (e.g., [2] and [22]). Other studies are exploring BCI control of a neuroprosthesis or an orthosis that provides hand closure (see [11] and [23]). Each of these applications could be realized with BCI2000.

4) Operator Module: The operator module defines the system parameters (e.g., the trial length in a specific application or a specific signal processing variable) and the onset and offset of operation. The system model does not specify how these definitions are made—they could come from an automated algorithm and/or from the investigator. In addition, operator can display information (e.g., a text message or a signal graph) sent to it from any other module without needing any prior information about the nature of this information. This allows an investigator to control an experiment and to receive real-time information about online events (e.g., display of unprocessed brain signals) using the same operator module, irrespective of the details of the experiment.

C. System Variables

BCI2000 incorporates three types of system variables: parameters, event markers, and signals. System parameters are those variables that do not change throughout a data file (i.e., during a specified period of online operation). In contrast, event markers record events that occur during operation and that can change from one data sample to the next. The inclusion of all event markers in the data file allows full reconstruction of the session and comprehensive data analyses.

Each module has access to these event markers and can modify and/or simply monitor them. Finally, system signals are functions of the user's brain signals that are received and modified by the modules. Each module can request that the operator module create any number of system parameters (of different data types such as numbers, vectors, matrices, or strings) or event markers (each 1–16 bits long). For example, the source module might request a parameter that defines the signal's sampling rate. This parameter is constant during some defined period of online operation and is available to all other modules. Similarly, the signal processing module might request an event marker with which to mark artifacts (such as ones created by muscle movements) in the signal.

III. Initial Implementations of BCI2000

A. Platform

The BCI2000 system model accommodates any programming language, any development environment, and any operating system. For our initial implementation, we chose C++ as the programming language because it is the highest level language that can satisfy all system requirements, and Borland C++ Builder as the development environment because it offers an excellent rapid-application development platform for C++.

We chose Microsoft Windows™ 2000/XP as the operating system because it offers the most auxiliary components (e.g., hardware device drivers). Like most operating systems, it is not a real-time system (i.e., the time course of events is not deterministic). Thus, to ensure that it satisfied real-time requirements, we carefully designed the software to depend as little as possible on potentially lengthy operating system functions, and we assessed the time course of online operation for representative implementations of BCI2000. As documented in Section IV-A, Windows™ 2000/XP (but not Windows™ 95/98/ME) provides very satisfactory performance with current hardware.

B. Modules

1) Source Module: Five source module implementations have been created to date. Three of them control A/D converter boards from different manufacturers (Measurement Computing, Inc.; Data Translation, Inc.; National Instruments, Inc.), one provides support for Brainproducts, Inc. EEG recording systems, and the fifth is a signal generator for use in system development and testing. In the case of A/D converter boards, brain signals must first be conditioned (i.e., band-pass filtered and amplified) so that they can be detected by the

TABLE I
PERFORMANCE MEASUREMENTS

PC Cfg	Processing Configuration	Output Latency (ms)	Latency Jitter (ms)	System Clock Jitter (ms)	Processor Load (%)					Performance Metrics		
					Total	Operator	Src	Sig.Proc.	Appl.	A	B	C
1	A	4.26	0.57	4.31	15	9	2	3	1	0.03	0.28	1350
1	B	15.11	0.57	2.65	36	15	3	17	1	0.09	0.85	1350
2	A	3.22	0.67	0.57	23	7	10	4	2	0.03	0.40	1846
2	C	11.02	0.75	0.69	59	7	28	22	2	1.60	3.05	4337

Performance measures for two different hardware configurations and three different data acquisition/signal processing implementations. PC configuration 1 was a machine with a 1.4-GHz Athlon processor, 256 Mb RAM, IDE I/O subsystem, and Data Translation DT3003 data acquisition board, running Windows 2000. PC configuration 2 was a machine with a 2.53-GHz Pentium 4 processor, 1 Gb RAM, SCSI I/O subsystem, and National Instruments NI 6024E data acquisition board, running Windows XP. Both configurations provided the operator with real-time display of the raw signals; and for both the User Application was one of the two cursor movement applications (Section III-B3). In configuration A, the source module sampled and stored 16 channels at 160 Hz each and 16 times/s sent the results (i.e., all 16 channels at 10 values per channel) to the signal processing module. The signal processing module extracted signal features from all channels by using an autoregressive method to calculate voltage spectra. (All voltage spectra were displayed in real time.) Configuration B was the same as configuration A, except that 64 channels were acquired and processed. In configuration C, the source module sampled 16 channels at 25 kHz each and 25 times/s sent the results (i.e., all 16 channels at 1000 values per channel) to the signal processing module. The signal processing module used a simple spike detection method to extract spike firings from all 16 channels. For each configuration, Output Latency was the average time between acquisition of a block of data and output reflecting that block, and Latency Jitter was its standard deviation. System Clock Jitter was the standard deviation of the intervals between successive completions of acquisitions of blocks of data. Processor Load was the average load on the processor created by each of the four modules. Performance Metrics A, B, and C were Memory Pages/s, % Disk Time, and TCP/IP Segments/s, respectively.

A/D hardware. The data storage component incorporated in these source implementations is highly optimized so that many data channels and/or high digitization rates can be used with minimal effect on the latency of real-time operation (see Table I). In consequence and as described in Section II-A3, the maximum possible number of data channels and their associated digitization rates are mainly determined by the data acquisition hardware.

2) Signal Processing Module: The first stage of signal processing, feature extraction, extracts features from the digitized brain signals. In all implementations to date, feature extraction consists of a series of three signal operators. The first signal operator is a calibration routine that performs a linear transformation of the input matrix (i.e., sample block) so that the input signal (i.e., a matrix of values in A/D units) is converted to an output signal in units of microvolts. The second signal operator is a spatial filter that performs a linear transformation (i.e., a matrix multiplication of weights with the output of the calibration module) so that each output channel is a linear combination of all input channels. This signal operator can accommodate any linear spatial filter operation (e.g., Laplacian derivation or common average [24], independent components [25], or common spatial patterns [26]). The third signal operator is a temporal filter. To date, we have implemented five variations: a slow wave filter (see [7], [27], and [28]),[5] autoregressive spectral estimation [29], a finite-impulse response filter (e.g., [30]), a peak detection routine that extracts firing rates from neuronal action potentials, and a filter that averages evoked responses (e.g., P300).

The second stage of signal processing, the translation algorithm, translates the signal features into control signals to be used by the user application. In all implementations to date, it is comprised of two signal operators. The first signal operator is a classifier that performs a linear transformation (i.e., a matrix multiplication of a classification matrix with the output of the temporal filtering module) so that each output channel is a linear combination of all input channels. For example, when the output of the temporal filter is a power spectrum, the classifier can add the spectral amplitudes for defined channels and frequencies together after multiplying them by specified weights. The second signal operator in the translation algorithm is a normalizer that performs a linear transformation on each output channel in order to create signals that have zero mean and a specific value range. The output of the normalizer is the output of the signal processing module.

An additional statistics component can be enabled to update in real-time certain parameters of the signal processing components such as the slope and intercept (i.e., baseline) of the linear equation the normalizer applies to each output channel so as to compensate for spontaneous or adaptive changes in the distribution of the control signal values (e.g., see [31] and [32]). For some implementations of BCI2000, this procedure requires information about the current status of the user application module (which is recorded in event markers). To minimize the module interdependence necessitated by this requirement, BCI2000 allows the investigator to define the period in which to calculate the baseline, rather than hard coding this information into the software. In other words, rather than explicitly tying signal processing and user application module together by writing dependent software code, we assign this responsibility to a knowledgeable operator (who has to input this information through a menu). As a result, a change in the user application module requires that the signal processing module be merely reconfigured rather than rewritten.

The decomposition of signal processing into a sequence of signal operators provides a high level of interchangeability and independence. For example, changing from a temporal filter that produces power spectra to one that generates average evoked responses does not require any change in the next stage, the linear classifier. Thus, the current implementations can readily accommodate a variety of different signal processing methodologies, and other methodologies (such as those using nonlinear classifiers) could be realized with minimal effort.

3) User Application Module: To date, we have implemented seven different user applications: four cursor movement applications (see [33]–[36]), an application for evaluating prospective users [37], an application that can present user-selectable auditory and visual stimuli, and a spelling application based on

[5]The low-pass slow wave filter calculates a moving average of the past 500 ms. Subsequently, a baseline correction procedure subtracts the average signal amplitude prior to output. Finally, an artifact correction procedure removes ocular artifacts [27].

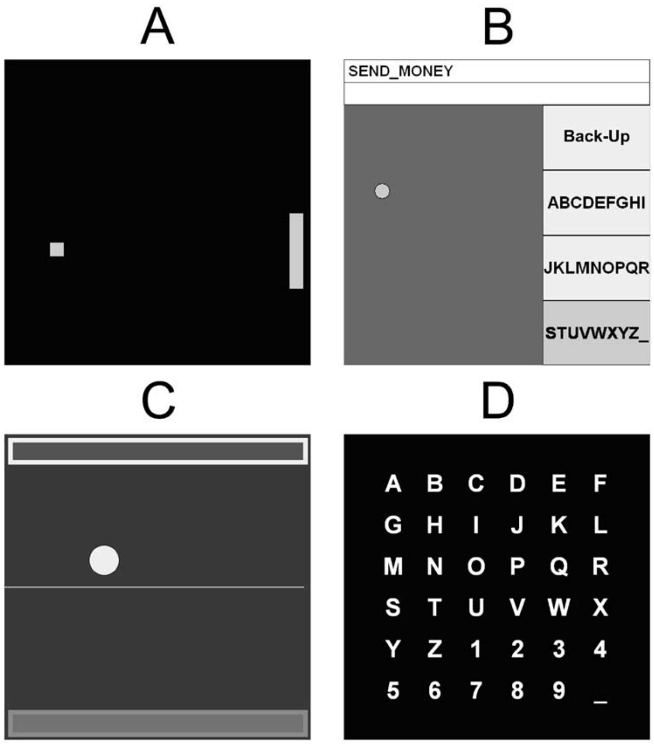

Fig. 3. Output screens for several BCI2000 implementations tested to date. (A) Sensorimotor rhythm control of cursor movement to a variable number of selections (as in [35]). (B) Simple spelling application using sensorimotor rhythm control (as in [34]). (C) Slow cortical potential (SCP) control of cursor movement to two possible selections (as in [33]). (D) P300-based spelling application (as in [1] and [38]). In (A)–(C), the cursor moves from left to right at a constant rate with its vertical movement controlled by the user's brain signals. In (D), rows and columns of the matrix flash in a block-randomized fashion.

evoked potentials as described by [1] and [38]. Fig. 3 shows the user screens for four of these applications.

In the three cursor movement applications shown in Fig. 3(A)–(C), the cursor moves horizontally from left to right at a fixed rate and vertical cursor movement is controlled by the output of the signal processing module. The possible selections are stacked vertically along the right edge of the screen or presented as colored horizontal bars on the top and bottom of the screen. A trial is divided into several distinct intervals: a period (usually 1 s) during which the screen is blank, a pretrial pause (usually 1 s) during which the selections alone are visible, a movement interval (usually 2.5 s) during which the cursor moves across the screen with its vertical movement controlled by the signal processing output, and a post-trial interval (usually 1 s) during which the selection results are shown on the screen. Each of these events is coded using event markers. This allows complete offline reconstruction of the online operation.

In the user evaluation application, the user is instructed to perform specific movements or movement imagery when a specific target appears on the screen and the signal features associated with this movement or imagery are evaluated. No feedback based on these features is provided to the user.

The BCI2000 auditory-visual stimulation application can present any number of user-selectable auditory or visual stimuli. These stimuli are stored as files in wave and bitmap format, respectively. Presentation rate, sequence, or frequency of occurrence if presentation is random, and many more presentation-specific details can be specified. In stimulation paradigms in which the user is asked to focus attention on one of these stimuli, presentation of this stimulus might evoke a brain signal response (e.g., [39]). These evoked responses can be classified (by the associated signal processing module), and the selected stimulus is indicated after stimulus presentation is complete.

The second BCI2000 spelling application shown in Fig. 3(D) is similar to the paradigm described in [1] and [38]. The screen shows a 6 by 6 matrix of characters, and the user focuses attention on the desired character (which is either specified by the investigator ("copy" mode) or chosen by the user ("free-spelling" mode). The rows and columns of this matrix are successively and randomly intensified. The evoked responses are classified (by the associated signal processing module), and the character that the system identifies as the desired character is shown on the screen.

4) Operator Module: The current operator module provides the investigator with a graphical interface that displays current system parameters and real-time analysis results (e.g., frequency spectra) communicated by other modules. It allows the investigator to start, stop, suspend, resume, or reconfigure system operation. In a typical BCI2000 configuration, user feedback is displayed on one monitor and the operator module's graphical interface is displayed on a second monitor.

5) Offline Analysis Tools: As noted, BCI2000 stores all brain signal input and concurrent online events in a standard format. Currently available tools for offline analyses include software options that provide: frequency spectra for amplitude and for the statistical measure r^2 for specified periods of online operation and for specified data channels; scalp topographies for amplitude and r^2; visualization of signals in the time domain; and conversion of data to ASCII and Matlab™.

IV. Online Evaluation and Validation of BCI2000

A. Real-Time Capabilities

To determine the timing performance of BCI2000 in actual online operation, we evaluated for different representative implementations: output latency and output jitter (i.e., variation in latency), system clock jitter (i.e., the variation in latency between completions of successive acquisitions of data blocks), and average processor load in different hardware configurations. The results are summarized in Table I. For all implementations, average output latency and latency jitter were low, i.e., $<$15.11 ms and $<$0.75 ms, respectively. System clock jitter was also low ($<$4.31 ms). Finally, average processor load did not exceed 59%.

These results led to three conclusions. First, BCI2000 implementations easily fulfill the real-time requirements described in Section II-A4. Second, effective BCI operation does not require dedicated real-time systems (such as Matlab with Real-Time Windows Target, LabView™ RT, or real-time operating systems). Third, BCI2000 could support implementations considerably more demanding than those created to date (e.g., more data channels, higher sampling rates, more complex signal processing methods).

B. Online Performance

We tested the adaptability and online performance of BCI2000 by using it to implement three very different BCI designs, each of which had previously been implemented only by its own highly specialized software/hardware system. In each case, the BCI2000 implementation required minimal effort to set up and yielded results comparable to those reported for the dedicated system. Furthermore, in each case the standard BCI data storage format readily supported the appropriate offline data analyses.

1) Sensorimotor Rhythms and Cursor Control: Most adults display 8–12 Hz (i.e., μ) and/or 18–26 Hz (i.e., β) rhythms in the EEG recorded over primary sensorimotor cortices. Normally, these sensorimotor rhythms show amplitude increases and decreases that are related to sensory input and/or movement or movement imagery (see [40] and [41]). Many studies have demonstrated that humans can learn to control μ or β rhythm amplitudes independent of actual movement and use that control to move a cursor to targets on a computer screen (e.g., [2], [4], [5], and [42]–[44]).

To implement μ/β rhythm cursor control, we configured BCI2000 with autoregressive spectral estimation (i.e., Section III-B2) and one of the cursor movement applications (i.e., Section III-B3). A target appears in one of four possible locations along the right edge of the screen. Then, a cursor appears at the left edge and moves from left to right at a constant rate with its vertical movement controlled by the power in a μ or β rhythm frequency band at a location over sensorimotor cortex (see [4] for further details). To date, 78 people have used this system extensively (i.e., 4–300 sessions each). The results have been indistinguishable from those previously achieved with the original dedicated hardware/software system (e.g., [2]). Fig. 4(A) illustrates the spectral and topographical features of the μ/β rhythm control that users achieve and that allows them to move the cursor to the designated target.

2) Slow Cortical Potentials and Cursor Control: Slow cortical potentials (SCPs) are potential shifts in the scalp-recorded EEG that occur over 0.5–10 s. Negative and positive SCPs are typically associated with functions that involve cortical activation and deactivation, respectively (see [46] and [47]). People can learn to control SCPs and thereby control movement of a cursor on a computer screen (see [6], [19], and [33]). In the standard format, the BCI system records EEG at the vertex referenced to both mastoids and measures SCPs after eliminating artifacts caused by eye movements or blinks. The resulting signal controls vertical cursor movement to a target located at the bottom or top of the screen. Each trial begins with a 2-s preparation period that defines a reference voltage. Then, in the next 2-s period, the user controls the SCP so as to move the cursor to the target [6].

To implement a similar SCP cursor control protocol, we configured BCI2000 with the slow-wave filter (i.e., Section III-B2) and one of the cursor movement applications (i.e., Section III-B3). As Fig. 4(B) illustrates, the BCI2000-based SCP system yielded results comparable to those reported for the standard dedicated SCP system [33].

3) P300 Potential and Spelling: Infrequent stimuli typically evoke a positive response in the EEG over parietal cortex about 300 ms after stimulus presentation (see [48]–[50]). This response (called the "P300" or "oddball" potential) has been used as the basis for a BCI system (see [1], [15], and [51] for review). Donchin and colleagues presented the user with a 6×6 matrix of characters. The rows and columns in this matrix flashed successively and randomly at a rate of eight flashes per second. The user selected a character by focusing attention on it and counting how many times it flashed. The row or column that contained this character evoked a P300 response, whereas the others did not. After averaging a number of responses, the computer could determine the character's row and column (as the row/column with the highest P300 amplitude) and, thus, the desired character.

To implement this BCI paradigm, we configured BCI2000 with the temporal filter that averages evoked potentials (i.e., Section III-B2) and the second spelling application described in Section III-B3. To date, this implementation has been tested in five users. As illustrated in Fig. 4(C), the results are similar to those reported for the original hardware/software P300 BCI system [1].

V. Discussion

A. Summary

BCI2000 is intended to help BCI research and development move beyond the current stage of isolated laboratory demonstrations of highly specialized and mutually incompatible BCI systems. It provides a flexible general-purpose platform that facilitates the evaluation, comparison, and combination of alternative brain signals, processing methods, applications, and operating protocols that are essential for continued progress. By reducing the time, effort, and expense of testing new designs, by providing a standardized data format for offline analyses, and by allowing groups lacking high-level software expertise to engage in BCI research, BCI2000 can increase the rate of progress in both laboratory research and clinical applications.

To achieve this purpose, BCI2000 embodies two basic principles. The first is a system model of four modules that encompass the four essential functions of any BCI system: signal acquisition, signal processing, output control, and operating protocol. As a result, BCI2000 should allow for implementation of any conceivable BCI design. The second principle is maximization of the independence, interchangeability, and scalability of each module and its components. As a result, a change in a module or a component should require little or no change in other modules or components.

The BCI2000 implementations and results described in Sections III and IV demonstrate its capacities. With readily available and relatively inexpensive hardware, it easily satisfies the real-time requirements of BCI operation and should be able to accommodate the potentially greater demands of newer signal acquisition and processing methods. BCI2000 has proved able to satisfy the different signal processing needs of BCI designs based on sensorimotor rhythms, cortical surface rhythms, slow cortical potentials, and the P300 potential, and to provide the different outputs needed for several kinds of cursor control and for selection from a matrix. From the online operation of each design, BCI2000 produced complete data in a standardized format for analysis by standardized routines. Furthermore, these analyses showed that the BCI2000

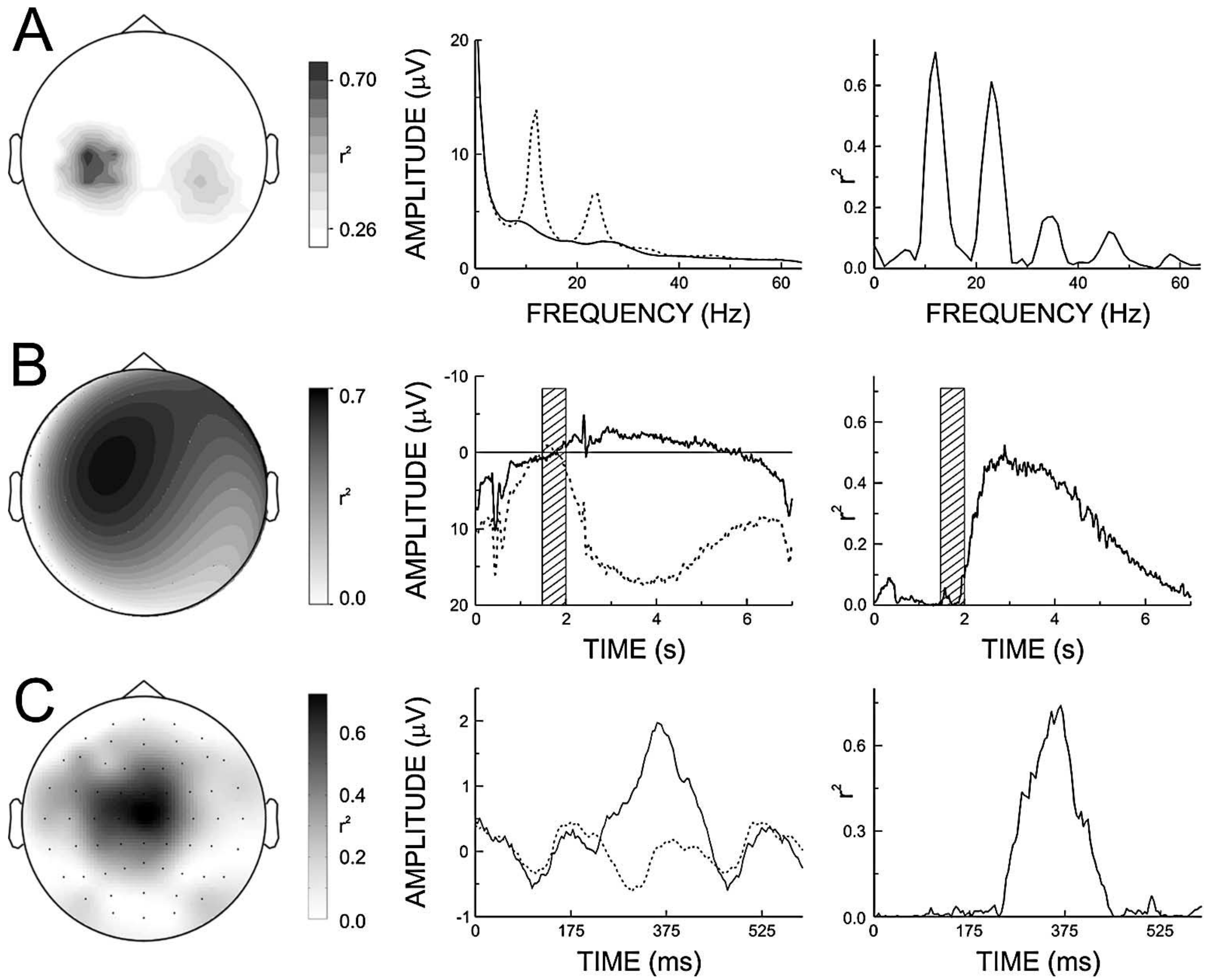

Fig. 4. BCI2000 implementations of common BCI designs. (**A**) μ/β rhythm control of cursor movement. Left: Topographical distribution on the scalp (nose on top) of control (measured as r^2 (the proportion of the single-trial variance that is due to target position), calculated between top and bottom target positions for a 3-Hz band centered at 12 Hz). Center: Voltage spectra for a location over left sensorimotor cortex [i.e., C3 (see [45])] for top (dashed line) and bottom (solid line) targets. Right: Corresponding r^2 spectrum for top versus bottom targets. User's control is sharply focused over sensorimotor cortex and in μ and β rhythm frequency bands. Data are comparable to those of earlier studies that used a specialized hardware/software system (e.g., [2]). (**B**) SCP control of cursor movement. Left: Topographical distribution of SCP control, calculated between the two tasks of producing cortical negativity (top target) or positivity (bottom target). Center: Time courses of the EEG at the vertex for the negativity task (solid line) and for the positivity task (dashed line). For each task, 280 trials were averaged. Average potential during the hatched period served as baseline. Right: Corresponding r^2 time course (calculated from single trials). Data are comparable to those of earlier studies using the Thought Translation Device (e.g., [33]). (**C**): P300 control of a spelling program. Left: Topographical distribution of the P300 potential at 340 ms after stimuli, measured as r^2 (calculated from averages of 15 stimuli) for stimuli including versus not including the desired character. Center: Time courses at the vertex of the voltages for stimuli including (solid line) or not including (dashed line) the desired character. Right: Corresponding r^2 time course. Data are comparable to those of earlier studies using a dedicated hardware/software system (see [1] and [38]). Stimulus rate was 5.7 Hz (i.e., one every 175 ms).

implementation of each BCI design provided online function comparable to that previously obtained with a dedicated hardware/software system.

B. Benefits of BCI2000

BCI2000 provides a number of benefits to the investigator, to the software engineer, and to the user. The many BCI methods that have been created to date using BCI2000, and the rapid implementation of the system by a growing number of laboratories (i.e., more than 20 as of early 2004), illustrate its ease of use and practical advantages.

1) Benefits to the Investigator: The primary benefit of BCI2000 to the investigator is the availability of a complete system that can already realize established BCI methods and that can be used with little or no change to the software to implement BCI paradigms that have not been previously reported (e.g., item selection using auditory evoked potentials). The growing number of contributions from laboratories using BCI2000 ensures that new methods are being developed continually.

BCI2000 is an open system that is available free of charge for research and educational purposes and that places no restrictions on how it might be used. To date, most groups using the system are following one of the following three patterns:

a) using the existing BCI2000 system without changing the software;

b) implementing new methods or system capabilities into BCI2000;
c) using BCI2000 as a platform to develop systems for research not related to brain-computer interfaces.

2) Benefits to the Software Engineer: BCI2000 also benefits software engineers, who can build on the existing modules and on the application programming interface (API) that BCI2000 provides (e.g., functions that provide access to signals, parameters, event markers), and can thereby concentrate on the aspects that are unique to a particular method.

3) Benefits to the User: BCI2000 is also directly beneficial to users with severe disabilities. Since it supports all major BCI methods that have been developed to date for use in humans, it can be configured to use the specific brain signal, analysis method, application, and protocol that are best suited for each user.

C. Future Development of BCI2000

1) Platform: Future implementations of BCI2000 could support other programming environments (e.g., Matlab or LabView), or operating systems (e.g., Linux, Windows CE™).

2) Modules:

a) Source module: BCI2000 currently supports data acquisition hardware from four different vendors (Section III-B1). This list can be readily expanded.

b) Signal processing module: Currently, BCI2000 can extract features from scalp-recorded sensorimotor cortex rhythms, cortical surface rhythms, slow cortical potentials, cortical single neurons, and P300 evoked potentials. Other brain signals, such as the error potential [52], cortical field potentials [53], or intracortical neuronal activity, may require alternative feature extraction methods (e.g., templates [53] or wavelets [54]). BCI2000 can readily implement such methods.

c) User application module: At present, most User Application modules in BCI2000 provide visual output on a computer screen. However, this output may not be suitable for users with decreased visual acuity (e.g., due to late-stage ALS) or gaze instability (e.g., due to cerebral palsy). Solutions include a virtual reality display or auditory rather than visual feedback, both of which can be readily implemented using BCI2000. Additional applications under development include multidimensional cursor control (see [36] and [42]) and a web browser based on [55].

3) Evolution of Specific Clinical Applications: BCI2000 is able to satisfy the requirements of BCI research and development programs. On the other hand, once a specific BCI design is validated for clinical use, the flexibility of BCI2000 may become superfluous or even cumbersome. In such situations, reduced versions of BCI2000, in which some module components or even entire modules are fixed, could prove most convenient and efficient. Nevertheless, even in these cases, the continued adherence to the same common model and the standard BCI2000 data format should facilitate continuing oversight of system function and implementation of future modifications and expansions.

VI. Availability of BCI2000 to Other Research Groups

BCI2000, with executables, source code, and documentation, is available free of charge for research and educational purposes at http://www.bci2000.org. This web site provides additional information for and from the growing number of BCI2000 users.

VII. Conclusion

BCI research and development is a complex interdisciplinary endeavor that depends on careful evaluation and comparison of many different brain signals, signal processing methods, and output devices. The inflexibility and limited capabilities of most current BCI systems significantly impedes this work. BCI2000 is a general-purpose research and development platform that greatly facilitates implementation, evaluation, and comparison of different BCI options.

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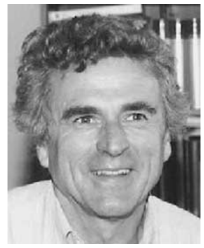

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