Guest Editorial
Brain–Computer Interface Technology: A Review of the Second International Meeting

Abstract—**This paper summarizes the *Brain–Computer Interfaces for Communication and Control, The Second International Meeting*, held in Rensselaerville, NY, in June 2002. Sponsored by the National Institutes of Health and organized by the Wadsworth Center of the New York State Department of Health, the meeting addressed current work and future plans in brain–computer interface (BCI) research. Ninety-two researchers representing 38 different research groups from the United States, Canada, Europe, and China participated. The BCIs discussed at the meeting use electroencephalographic activity recorded from the scalp or single-neuron activity recorded within cortex to control cursor movement, select letters or icons, or operate neuroprostheses. The central element in each BCI is a translation algorithm that converts electrophysiological input from the user into output that controls external devices. BCI operation depends on effective interaction between two adaptive controllers, the user who encodes his or her commands in the electrophysiological input provided to the BCI, and the BCI that recognizes the commands contained in the input and expresses them in device control. Current BCIs have maximum information transfer rates of up to 25 b/min. Achievement of greater speed and accuracy requires improvements in signal acquisition and processing, in translation algorithms, and in user training. These improvements depend on interdisciplinary cooperation among neuroscientists, engineers, computer programmers, psychologists, and rehabilitation specialists, and on adoption and widespread application of objective criteria for evaluating alternative methods. The practical use of BCI technology will be determined by the development of appropriate applications and identification of appropriate user groups, and will require careful attention to the needs and desires of individual users.**

Index Terms—**Augmentative communication, brain–computer interface (BCI), electroencephalography (EEG), rehabilitation.**

I. Introduction

A BRAIN–COMPUTER interface (BCI) allows a person to communicate or to control a prosthesis without using nerves and muscles. In the last 15 years, the pace of BCI research has grown rapidly. Encouraged by growing recognition of the needs and potentials of people with disabilities, new understanding of brain function, and the advent of powerful, low-cost computers, researchers have concentrated on developing new communication and control technology for people with severe motor disorders (for example, amyotrophic lateral sclerosis (ALS), brainstem stroke, cerebral palsy, and spinal cord injury). Current BCIs use electroencephalographic (EEG) activity or cortical single-neuron activity to control cursor movement, select letters or icons, or operate neuroprostheses.

BCI research is an inherently interdisciplinary field, involving neuroscience, psychology, engineering, mathematics, computer science, and clinical rehabilitation. Forums to discuss results and issues common to BCI researchers from these disparate disciplines have been scarce to date. In 1999, the National Institutes of Health (NIH) sponsored, and the BCI group at the Wadsworth Center of the New York State Department of Health organized, an international conference held in Rensselaerville, NY entitled *Brain-Computer Interface Technology: Theory and Practice*. It drew 50 researchers from 22 laboratories around the world to present their findings and discuss issues important to BCI research, and was summarized in 16 papers in a Special Section in the June 2000 issue of the IEEE Transactions on Rehabilitation Engineering. Last year, the Wadsworth Center organized the second such conference, entitled *Brain-Computer Interfaces for Communication and Control, Second International Meeting*: *Moving Beyond Demonstrations*. Held in Rensselaerville in June, 2002, it drew 92 people from 38 laboratories in the U.S., Canada, Europe, and China, to participate in a three-and-a-half day meeting. The NIH again provided major funding. Additional support came from the Eastern Paralyzed Veterans Association, the Department of Defense Advanced Research Project Agency (DARPA), the Whitaker Foundation, and the Deutsche Forschungsgemeinschaft (DFG). The central purpose was to sum up advances in this rapidly growing field and to provide a forum for discussion of the major issues it faces. The organizing theme was the need to "move beyond demonstrations," that is, to begin to undertake methodical and comprehensive studies aimed at improving BCI technology and establishing its practical value.

On the first day of the conference, each of the 38 groups presented a concise description of its current research. The substance of these presentations is contained in the peer-reviewed papers that comprise the bulk of this Special Issue of the IEEE Transactions on Neural Systems Rehabiliation Engineering. The papers include descriptions of: functioning EEG-based or single-neuron based BCIs; promising signal-processing methods; software developments; issues important for applications; and training protocols for clinical application. Together, these papers constitute a comprehensive review of the present state of BCI research. The next two and a half days of the conference featured six panel-led discussions, four focused debates, four special-issue satellite sessions, many demonstrations of BCI technology, and numerous poster

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presentations, including a student poster contest with both technical and scientific design categories.

The six panel discussions focused on four key themes of BCI research:

1) two panels discussed the available brain signals and their BCI applications;
2) one panel discussed alternative methods for translating these signals into device commands;
3) two panels discussed potential applications, their value to various users, and issues involved in user training;
4) one panel discussed standards for designing studies and for assessing and comparing their results.

The high level of interest in signals and in applications allowed us to have two panels on each of these subjects, thus giving us the advantage of two relatively different approaches to each topic.

In each of the four debates, two debaters and one moderator addressed an important and highly controversial issue. These four controversies were: 1) spikes (i.e., single-neuron activity) versus field potentials (i.e., EEG and related signals) as BCI control signals; 2) linear versus nonlinear methods for BCI signal processing; 3) behavioral versus cognitive approaches to understanding BCI operation; and 4) importance versus unimportance of developing a standard BCI taxonomy and standard benchmarks for research and development.

The four satellite sessions were led by research groups representing four different disciplines (psychology, neuroscience, computer science, and signal-processing) and each focused on an important topic of general interest. These were, respectively: 1) the training of BCI users; 2) implantable microelectrodes for BCI systems; 3) human–computer interactions and BCI operation; 4) a BCI signal-processing competition. Each session discussed the interests and perspectives of the presenting group as well as what the group had learned over the course of the meeting. It provided an opportunity for researchers to discuss BCI development in the context of common practice in their respective fields. These discussions also provided new perspectives to researchers from other disciplines. The results of these sessions are incorporated in the papers contained in this Special Issue.

The next sections of this paper summarize the six panel discussions and the four debates. These summaries, together with the 28 papers that constitute the rest of this issue, encompass the current state of BCI research, explicate the most important and controversial issues, and address the factors critical for further progress and for development of valuable applications. The reader should be aware that this paper attempts to present in a cogent fashion what was a very dynamic process. These summaries represent exchange between panel members, debaters, and conference attendees. We have attempted to maintain the flavor of the exchange whenever possible and in many cases not attempted to reference the bases of what, in some instances, may appear to be rather strong statements of fact. We expect that this paper will be read as a companion to the accompanying papers in which many of these topics are covered in much more detail. Our hope is that these proceedings will facilitate and guide continued BCI research and development.

II. Panel and Debates

A. Panel 1: SIGNALS I—The Relative Advantages and Disadvantages for BCI Use of Different Brain Signals and Different Signal Recording Technologies. (Chair—W. Heetderks. Panelists—G. Gaal, C. Guger, T. Hinterberger, D. Kipke, B. Mensh, M. Mojarradi, P. Nunez, and R. Rosipal.)

Panel 1 was charged with discussing the relative advantages and disadvantages of different brain signals, different signal-recording technologies, and different signal-analysis methods for use in a BCI. To develop effective and useful BCIs, it is important to determine the electrophysiological features (EEG rhythms, evoked potentials (EPs), or single or multiple neuron activity) that people are best able to control, to characterize these features fully, and to develop improved methods for detecting and measuring them. In preparation for the session, the Signals I panel met to discuss the spectrum of potential signals that might be used to provide the input signal to a BCI. After a spirited discussion among the panel members, it was decided that advantages and disadvantages of signals could best be discussed in the context of specific target applications. To facilitate this discussion, the panel proposed developing two or three target applications that could provide the framework for a discussion of the signal advantages and disadvantages. Further discussion then focused on three specific BCI applications: an environmental controller, a speller, and a robot arm controller with three-dimensional (3-D) spatial positioning and grasp.

When this approach to the problem was outlined during the symposium discussion, it became clear that there was no consensus among all participants regarding either the relevance of the proposed target applications or what the details of performance should be for a specific application. In addition, some participants supported discussion of signal advantages and disadvantages outside the context of specific applications. The report that follows represents an attempt to capture both the initial thoughts of the panel and the range of ideas put forward in the discussion of this important issue.

1) Universe of Potential Signals: Normal human brain activity produces a wide variety of signals that can be measured and that have potential for use in a BCI. These signals include electrical, magnetic, metabolic, chemical, thermal, and mechanical responses to brain activity. These signals can be detected with appropriately designed sensors for potential use in a BCI. Electrical currents produced by synchronized synaptic currents can be measured by (in order of increasing invasiveness) scalp EEG, epidural electrodes, and electrocorticography (ECoG). Action potentials from individual neurons can be recorded using microelectrodes that penetrate the brain. Neural activity also produces associated magnetic fields that can be recorded using magnetoencephalographic (MEG) activity. Metabolic consequences of neural activity include changes in blood flow and metabolism, which can be imaged using functional magnetic resonance imaging (fMRI), positron emission tomography (PET), and recently developed optical techniques, including infrared imaging. The chemicals released by neurons and glia can be measured using magnetic resonance spectroscopy and invasive probes. Small physical movements and temperature fluctuations of brain tissue may also provide a measurable signal related to underlying activity.

In addition to these actual brain signals, the outflow of neural information through nerves to their effectors is a potential source of signals that reflect brain activity, using techniques such as peripheral nerve recording, electromyographic (EMG) recording, galvanic skin response, and simple video recording of the physical movements of the body.

2) Signal Attributes and Problems With Specific Signal Sources: All physical and biological signals have several fundamental attributes, including spatial and temporal scale and signal-to-noise ratio (SNR). For example, the temporal scale of raw EEG digitized at 500 Hz is 0.002 s, whereas the scale of a typical P300 waveform is 10 s as a result of the necessary averaging process. In the latter example, temporal resolution is sacrificed to improve SNR. The spatial scale of an intracortical electrode ($\gg$ 10 μm–1 mm) depends on the size of the electrode tip, whereas the scale of unprocessed scalp EEG ($\gg$ 6–10 cm) is largely independent of electrode size. Scalp EEG scale may be reduced (to $\gg$ 2–3 cm) by using a combination of multiple electrode arrays ($\gg$ 64–128 electrodes) and high-resolution EEG algorithms (Laplacian or dura imaging). The skull causes most of the spatial smearing of intracortical potentials, thereby increasing measurement scale. Thus, skull electrodes with tips just inside the inner skull surface may achieve millimeter-scale resolution.

Intracortical electrodes achieve higher spatial resolution at the expense of spatial coverage and significant increase in cost and risk. Thus, arguments about invasive versus noninvasive electrodes depend strongly on the volume of tissue producing useful information. The argument also depends on the ability of the intracortical electrode to be located in the appropriate tissue masses (cells or columns) and on the ability of scalp EEG analysis to produce stable, robust, intentional signals that have appropriate bandwidths and response times and are also independently controllable.

3) Performance Criteria: System performance can be measured as: 1) speed and accuracy in specific applications and 2) theoretical performance measured as information transfer rate. Information transfer rate, as defined by Shannon [1], [2], is the amount of information communicated per unit of time. This parameter encompasses speed and accuracy in a single value. The bit rate can be used for comparing different BCI approaches and for the measurement of system improvements. If the speed and the accuracy of a BCI can be substantially increased, the number of users and the applications would increase.

In addition to considering information transfer rates, developers must consider how well the BCI can be integrated with the individual user's other remaining communication and motor channels. For example, some systems may require concentrated focus and, therefore, not allow an individual to attend to a conversation while using the BCI.

Important points in evaluating different BCI approaches are the system costs including the learning effort for the individual. The ideal BCI approach should ensure that the user can learn some level of control within a few weeks and that the control is stable or improves over months after initial learning. (For example, if a BCI is the only communication channel for a totally paralyzed individual, reliable long-term performance is essential.) BCI systems must also be able to operate without expert oversight. Family members must be able to help in operation of the BCI system on a daily basis. Therefore, the systems must be easy to use. System appearance and how the users look while employing it are also important constraints on the signal acquisition system.

BCIs require some degree of normal brain function and sensory input. Thus, specific disabilities could affect a user's ability to achieve control of cortical potentials, mu or beta rhythms, or cortical neurons. Therefore, specific BCIs may be needed for specific user groups. At the same time, to be practical, a BCI approach must be suitable for a significant fraction of the patients in a specific user group.

4) Test Beds: The panel discussed the need to identify and develop a small set of test-bed applications that would enable comparison and cross-validation of diverse BCI systems. Three test beds that span a range of system performance requirements were proposed and outlined: a) environmental control; b) speller; and c) continuous robotic control.

The environmental control test bed (e.g., TV remote) involves a set of switches that could be independently controlled and mapped to various actuators. A universal television remote control unit is a particular example for this test bed. The discussion by the panel suggested that this test bed—and the other test beds as well—could be quantitatively described in terms of the general system performance metrics: channel dimensionality, channel bit rate (channel capacity), degree of bidirectional control (feedback), degree of reliability, and cost effectiveness. The environmental control test bed, as formulated, was thought to present the lowest overall system performance criteria.

A spelling task represents a repetitive 1-of-N selection process. In contrast to the environmental control where a few selections might result in a significant outcome such as turning a light on or off, spelling typically requires many successive selections to spell out a sentence and even more to create a paragraph. Factors such as the level of concentration required will be important for this application where prolonged use may occur only if the level of concentration required is not excessive. In comparing speller performance, it would be valuable to agree on a standard size for N.

A third potential test bed—robotic control—involves control of an artificial arm producing 3-D arm movement with hand grasp. The panel suggested an arm that could reach to a point in 3-D space and then grasp an object. Factors that will be important in this application include the bit rate of data transfer, dimensionality, closed-loop feedback, short- and long-term reliability, and redundancy. Feedback, in addition to visual feedback, may be very useful for touch and grasp. Wheelchair control was considered as a potential alternative to arm control as a test bed. In some ways it is simpler, but still involves real-time control with implicit requirements for reliability and redundancy and a need to be able to respond to some events quickly.

5) Critical Problems: Several criteria for a BCI signal must be fulfilled to achieve a robust, portable, and easy-to-use system for communication or environmental control in daily life. These criteria can be subdivided into three groups.

a) The signal acquisition system should be easy to set up so that anyone can use the system without extensive training. It should be small enough to be portable and inexpensive enough to be affordable for those who need a BCI.

b) Each signal source has associated noise sources and artifacts that should be eliminated or, at least, minimized.

The SNR, which determines the reliability of a desired response, should be high. The predefined intention of a BCI user should be correlated to the signal controlled by the user or to a component derived from the signal.

c) Signal properties such as the latency of the response and properties of the experimental paradigm should be adapted to the individual application.

At present, physical dimensions and costs are prohibitive for fMRI and MEG. Both systems are large, very expensive, and require a magnetically shielded environment. Although real-time fMRI appears to provide a method to successfully self-regulate the blood oxygenation level-dependent (BOLD) signal of specific brain areas [3], the preprocessing, especially the correction of movement artifacts that must be carried out online, is very time-consuming (up to several seconds) even on modern computers. When focusing on a small area, preprocessing can be accomplished in less than one second. A basic limit to the speed of a response is given by the high latency of the BOLD response (2–6 s). Similar to fMRI, MEG could presumably be used as a BCI by teaching a person to self-regulate MEG activity. Both methods are beginning to be investigated (e.g., Birbaumer *et al.* [37]). Optical spectroscopy is a new method that has some potential, but at present is expensive and has an SNR that may not be sufficient for use in a BCI. Long latencies between intention and signal response also occur in skin conductance and heart-rate modulation, rendering those variables of minimal use as communication systems in many applications.

EEG offers the easiest method to detect brain signals from cortical areas. Whether a BCI is using spectral EEG (e.g., the mu-rhythm or alpha activity), slow cortical potentials, EPs or steady-state EPs, the most critical problems are the moderate SNR and artifacts caused by movements or muscle activity. Face movements (e.g., eye or tongue) and breathing may cause considerable artifacts in slow cortical potentials, and, thus, have to be either prevented, or recognized and removed [4]. Muscular tension (e.g., in neck, forehead, or jaw muscles) can cause artifacts in higher frequencies. The system user can readily control most of these artifacts. Thus, unless they are avoided or detected, they may masquerade as activity and lead to misleading conclusions about the users' ability to use EEG for communication and control. Another issue is that while EEG sensorimotor rhythms have response latencies of about 0.5 s, some EEG components have response latencies of two and more seconds. In addition, when using event-related potentials (ERPs) such as the P300, several ERPs have to be accumulated to obtain a reliable response or the poor SNR can result in response classification problems (reviewed in [5]).

The SNR can be increased substantially by invasive technologies such as ECoG [6] and single-neuron recordings which show much higher amplitudes than noninvasive recordings. However, people may be reluctant to agree to brain implants for research purposes especially because, at present, successful control or communication with an invasive BCI cannot be guaranteed.

Other problems may occur when combining different types of signals. As long as different signals can be controlled independently, each signal provides additional possibilities for communication or control. However, it might not be possible to use different signals as independent control channels. For example, mu-rhythm control may cause simultaneous shifts in slow cortical potentials. A combination of two correlated signals might be used to increase extracted information. To date, few studies have examined the combination of signals, so a detailed consideration is not yet possible.

6) Conclusions: The diversity of the signal sets available for establishing interfaces between the brain and computer, coupled with the fact that BCI is a very young research field, reduces the need for a set of standard test beds at this time. However, test beds in general can assist the BCI community to understand and catalog the limitations/usefulness of each signal set and its proper use. The panel's attempts to probe the audience regarding the standard test beds produced an interesting observation. While everyone agreed with the need for standard test beds, there was no concurrence on their definitions. The panel's suggestion for using a TV remote, a speller, and a robotics controlled arm as test beds met with mixed reactions. The strong diversity of opinions on this subject is a clear reflection of the early state of this rapidly advancing field. The panel felt that a set of universal test beds for looking at BCI signals would naturally evolve as a result of further progress in the field.

B. Panel 2: SIGNALS II—The Relative Advantages and Disadvantages for BCI Use of Different Brain Signals and Different Signal Recording Technologies. (Chair—L. Trejo. Panelists—X. Gao, J. Pineda, J. Principe, F. Cincotti, P. Sajda, D. Peterson, B. Wilhelm.)

Panel 2 also considered the relative advantages and disadvantages of using different brain signals and different signal recording techniques in BCI. This panel broke down the problem of BCI signals and recording techniques into four interrelated domains: 1) applications; 2) signal classes; 3) methods and features; and 4) classifiers and algorithms. It then described each of these domains as a framework of ordered concepts. From the perspective of this framework, the panel generated a list of eight discussion points which address current trends in BCI research. These points were discussed by the panel and then reported to the entire group. During this general session, workshop participants contributed comments that extended or revised the panel's initial findings. The report presented here summarizes the discussions.

The choice of BCI signals and recording techniques depends strongly on the interaction of the four conceptual domains listed previously. For example, the choice of signals depends on the recording technology; different sensors are required for surface EEG signals than for intracranial recordings or neuronal spike trains (e.g., [38]–[40]). The choice of signals can also be affected by the application. For precise control functions, such as rapid motion of physical devices, the relatively slow changes of some EEG signals may be inadequate, whereas the more rapid dynamics of neuronal spike trains may suffice. However, such a choice forces another tradeoff: surface electrodes are convenient and involve little risk whereas implantation of electrodes in the brain is invasive and, therefore, involves more risk.

Once a balance is struck between application and signal class, one can address the question of which methods or signal features offer the most reliable information, and which classifiers or algorithms offer practical and robust performance. Here again, there is interdependence. Some features, such as oscillatory waves, including mu rhythms, are more amenable to frequency-domain methods such as linear filters and autoregressive (AR) models [41]. Other properties of signals, such as nonlinear measures of complexity that do not depend on specific oscillation frequencies, are better handled by nonlinear dynamic estimators, such as the coarse entropy rate. At the NASA Ames Research Center, initial studies have shown that some users can learn control of a one-dimensional cursor motion task with a linear filter of EEG signals, whereas others benefit more from nonlinear EEG measures [42]. Such choices introduce additional tradeoffs. Nonlinear methods may require longer times than linear methods to provide stable estimates, i.e., slowing the response of the BCI system [43].

Thus, it is impossible to prescribe signals and methods for BCI without considering the four domains and weighing the tradeoffs associated with different choices. The presentations and discussions at this meeting showed that signals, methods, and algorithms of several types are available for a range of applications. We discuss some of these in the next section.

1) Applications, Signals, Methods, and Algorithms: The panel considered the applications domain as a continuum that runs from a binary switch (one bit, on or off) at one end to complex robotics at the other. Along this continuum, more and more degrees of control appear, and these may show finer gradations of control—going from binary on–off to analog positioning. For example, several groups at this meeting presented data on BCI spelling paradigms, which use either mu rhythms or slow cortical potentials. (These data are reported in other papers in this issue.) Each of these paradigms provides a signal that positions a pointer to select letters for spelling. A simple binary-control system could move the pointer up or down at a constant rate, always being either on or off. A more complex system could translate the BCI signal into a precise level that holds the pointer at one of more than two positions. Further along this continuum lie applications that involve motion in two or three dimensions. Several groups have now shown that groups of motor neurons in rat and monkey motor cortex can learn 2- or 3-D control ([7], [8], and [44]). Two-dimensional (2-D) control is also possible with scalp-recorded mu rhythms [45]. It is possible that the degrees of freedom required for adaptive automation of cognitive tasks, prosthetics, and complex robotics may lie beyond the range of current BCI signals and methods.

The panel also considered that the signals domain forms a partial continuum of neuronal signals, and an ordered set of other signals. Neuronal signals range from action potentials or spikes to the macroscopic summation of these signals in volume currents measured by EEG or by MEG. Along this continuum, the level of summation increases with the scale and position of the sensor, as with multineuron activity and the ECoG. This continuum maps almost inversely with that of applications: complex control may require neuronal signals at smaller scales. In addition to neuronal signals, we considered that other measures, such as optical or magnetic resonance (MR) sensing of cerebral blood flow, may offer yet another class of signals for BCI, but that such signals will be at the coarse end of this continuum and their utility is as yet uncertain.

The methods domain corresponds to a set of features that can be analyzed at a given signal scale. For electrophysiological signals, the features may include oscillatory sources, such as periodic spiking or EEG rhythms. ERPs are another class of electrophysiological feature that requires time locking to an external event. In some applications, the presence of such an event may be convenient and useful, such as in the case of a blinking cursor on a computer screen, or the flashing rows and columns of the Farwell–Donchin P300-based BCI system for spelling [30]. A combination of oscillatory sources and ERPs is provided by the steady-state ERP or SSERP, in which the modulation of an external event is rhythmic, and demodulation of the neuronal signal provides control. The work of Gao *et al.* in Beijing (see [46]) is a very nice demonstration of this method. For completeness, we mentioned that blood flow methods may offer some potential for BCI and that features include optical and magnetic consequences of blood flow change. Of these two, the optical method offers the most promise for BCI applications, because of the relatively small size and cost of the sensors.

The fourth domain—classifiers and algorithms—is an ordered set which ranges from systems analysis approaches (linear and nonlinear) to machine-learning approaches of many types. The traditional systems methods have performed quite well for current BCI systems. However, to extend BCI functions to higher degrees of control and to make them more reliable, other methods may be needed. Here, there is a scientific and engineering debate. Systems methods often seek to model the underlying biophysical system, whereas machine-learning methods need not create a mechanistic model. Machine-learning methods may actually work well for an application without offering much insight into the underlying system. Both approaches will probably be needed. In the near term, machine-learning algorithms may provide useful solutions for BCI signal processing; in the long term, the models developed by systems approaches may offer better insight and generate hypotheses for future experiments. To better harness the information provided by neuronal signals for BCI applications, we might need entirely new ways of describing brain activity. The search for methods specific to this biological problem should be encouraged.

2) Discussion Points: The discussion of signals and methods was opened to all meeting participants and was organized into treatment of eight major questions. The following is a synopsis of these discussions.

a) *Should the scope of BCI be expanded to include other signals such as the EMG?* The majority of meeting participants felt that the BCI enterprise should not expand its scope beyond brain signals. There was a fear that using other methods would converge back to just another kind of keyboard control. However, a minority argued that since residual EMG and other nonbrain signals are available even in some locked-in patients, BCI designers should use whatever signal is available. In this regard, some also argued that we should distinguish between BCI and what we want to do for people with disabilities—the two may have different objectives [47]. To make the case against expanding BCI to include other signals, participants observed that we need to record other signals, like EOG and EMG, to remove artifacts, and ensure that we are working with brain activity. That is, we have to protect against claims that brain activity is being used for control and communication when instead there is another physiological signal that is, in fact, transmitting the information.

To make the case for expanding BCI to include other signals, some argued that hybrid systems might use mixtures of neuronal and nonneuronal signals to achieve higher degrees of control than is possible with either signal class alone. This may be important for new, multimodal interfaces for computers or other systems that respond to user intentions as well as to their actions.

b) *Is it too early to rule out entire classes of signals or methods?* There was unanimous agreement that it is too early to rule out any class of signals.

c) *Does the application determine the choice of signal and method?* There were mixed opinions concerning to what extent an application determines the choice of signal and method.

d) *Is it better to focus on system-modeling and identification instead of massive search and machine-learning?* Several interesting observations were made concerning this question. First, it was suggested that we need to do careful training of signal-processing methodologies since high-dimensional data can result in a high probability of over-fitting the data. Second, theoretical and system models need to be used to verify machine-learning approaches. Thus, the two approaches should interact. Another observation was that it would be better to consider using modeling in addition to machine-learning, rather than choosing one approach over the other. Finally, there was some discussion about a need for new methods to describe point processes, clustering of spikes, and correlations as carriers of BCI-relevant information, as compared to rate and amplitude information.

e) *Is it necessary to invent new methods for bio-signal analysis?* There was some discussion of the fact that existing signal-processing methods are not appropriate for BCI. Biological systems work differently from man-made systems, yet most signal-processing methods were invented to deal with man-made signals. Therefore, we must consider biological signals in new and different ways. One of these ways is to make use of recursion and recurrence in the algorithms that detect and measure features for BCI applications.

f) *Should "maximalist" approaches be used to set things up and "minimalist" approaches be used for applications?* This question addressed the idea that existing BCI data are quite splintered, varied, and highly dependent on the desires of the labs from which they come. An alternative approach is to coordinate BCI research at a high level, and have the labs work in concert on a few "big problems." No one argued for "mega-projects" at this time. However, choosing standard data sets and using them to test processing methods may be valuable (e.g., [48]). Though it may still be too early to choose standard methods, it is not too early for standard data that can be used to compare algorithms. Other technologies (e.g., mammography) have been hurt by not having standards early enough in their development. BCI data sets tend to be more varied than those typical of other technologies, but we can nevertheless find a few that allow for testing of algorithms. Standard data sets will be limited to specific tasks, but we can choose the ones that we think will be important for applications in the near future, e.g., mu-rhythm data, P300 data, and slow cortical potential data.

g) and h) *Is it necessary to create standards for signal processing (and should such standards be used to conduct competitions between methods)? Should cost functions be allowed to supplement evaluation criteria such as the bit rate?* Several discussants argued that methods need metrics, including standard evaluation criteria and cost functions. For example, the cost of hits and false alarms is task-dependent, so measures of BCI performance such as bit rate should take this into account.

Other responses included discussion of the following issues:

a) modularizing systems and selecting performance criteria accordingly;
b) distinguishing between tools and applications;
c) learning from the practice of software engineering, which has rigorous methods for validation and verification of modules;
d) the need for theoretical or model-based methods for comparing applications;
e) consideration of the idea that bit rate is not necessarily the only criterion for evaluation.

C. Panel 3: METHODS—Alternative Methods for Measuring Brain Signals and for Translating These Measurements into Communication and Control Commands. (Chair—W. Z. Rymer. Panelists—G. Müller, J. Millán, S. Gao, D. Taylor, J. Bayliss, M. Sun, P. Sykacek, B. Blankertz.)

Panel 3 started by outlining four key topics relevant to its discussion of BCI methods: 1) approaches to measuring different brain signals; 2) different signal processing methods for decoding these signals; 3) different outputs possible from these decoded signals; and 4) different types of performance evaluation. These issues were considered under the rubric of translating brain signals into communication and control by developing methods to provide functional BCI systems useful to consumer groups.

Developing real-time BCI control beyond its current state of demonstration requires addressing two separate but related needs: the need for controlled studies and the need to deliver service. Clearly, to formulate good model systems, more research is needed: more subjects, more studies, and more data. To generalize these systems so that they can deliver service to the rehabilitation community, it will be crucial to carry out controlled clinical studies, studies that go beyond the performance of a few individual subjects. In this context, it will be necessary to develop methods to compare and evaluate the performance of various BCIs. The panel put forward several assumptions. Natural is better: signals are better if they correspond to natural intent. Simpler is better: for example, if control can be achieved with a linear classifier, then a nonlinear classifier should not be used [43]. Cheaper is better as long as a low price delivers an effective product. Smaller is better because it is more portable [49]. Physiological knowledge can wait if necessary: while it is important to understand the underlying processes that produce signals from the brain, it is more important first that the systems work.

In light of these needs and these assumptions, the BCI Methods panel addressed three immediate areas that present important challenges: 1) adaptive control algorithms; 2) greater bandwidth; and 3) intelligent controllers. The comments made by participants and/or issues raised with regard to these challenges are presented in the following.

1) Adaptive Control Algorithms: Adaptive control algorithms are necessary in a BCI because the signals recorded change over time due both to technical and to biological factors. The biological signals that are being used are typically nonstationary. In addition, they change due to subject fatigue and attention, due to disease progression, and/or with user training. They also change due to technical aspects of recording including electrode impedances, amplifier noise, or environmental noise. Thus, static classifiers will not suffice, and the question becomes, what approach is best?

There are two basic approaches for nonstationary signals: a) one can try *a priori* conditions and choose the best model for the time; or b) one can use a tracking approach. The tracking approach is usually slower because there is an adaptation versus tracking problem that depends on how fast the signals change. Adaptive filters can give flawed results as they track very short-lived changes in the signal. With sufficient information, a multiple model approach may be best. Otherwise, tracking is probably most appropriate.

One can define behavioral models (e.g., degrees of attention, fatigue, etc.) and track very slowly within each category. Methods for assessing these factors would be valuable. Day-to-day changes and abrupt changes in user strategies must also be considered. If models are to be constructed, large data sets are needed. In this regard, it might be useful to consider what has been learned from work with brainstem EPs. In the case of EPs, investigators know what constitutes tolerable noise. It is known that brainstem EPs are correlated with body temperature, that there are differences when subjects are newly awakened from sleep, and that alcohol use affects brainstem EPs. Still other variables may be involved.

Particular attention should be paid to the long-term variations in the signals, both those that are spontaneous and those that are related to disease. We need methods to reduce the effects of these changes. All brain signals are likely to undergo such changes. Although we may not understand all of these changes, they must all be dealt with in some fashion. Within-subject studies can be valuable in that each patient becomes his/her own study and the BCI system is configured for that individual.

Additional issues arise for people using a BCI system continuously for real-life applications. A control system must know what the intended result is in order to correct itself as variables change. On the one hand, for example, in a reasonably accurate spelling system the controller eventually knows what the intent is because the user corrects the mistakes. In contrast, in continuous BCI-controlled arm movements, the system cannot correct itself since it does not know the user's intent. The latter systems may need a built-in calibration mode in which the user periodically makes a sequence of known movements to tune the control algorithm. It is also worth noting that with intracortical BCIs, changes in the recorded cell population could be made transparent to the user by incorporating new cells into the control algorithm based on how their firing patterns are correlated to the cells already in use.

It is also important to examine issues of reinforcement and reward. BCI training may not adhere to normal reward structure. One investigator noted, for example, that his group was not successful in inducing people to improve performance by offering them a higher monetary reward. Children performed better when candies rather than money were used as a reward. It was also pointed out that there is a Pavlovian component in training and that users associate a target with failure and may not be learning what we think they are learning in training. In general, we need to be better able to identify the actual reinforcements. Moreover, although feedback can enable better performance, it may also interfere with performance (e.g., if it is improperly timed). Feedback other than visual (e.g., proprioceptive) may be effective, particularly in users with visual deficits. In addition, we need to consider the level of difficulty of the task itself. It is probably best to start with a task at which the user can succeed, and increase the difficulty level as the user's skills improve. For all these issues, large-scale studies are important [50]. (It was noted that Skinner used about 1000 animals before he was able to define reinforcement schedules.)

2) Greater Bandwidth: Greater bandwidth than that currently obtainable is clearly needed. More bandwidth permits more control possibilities. Bandwidth could be improved by improving signal processing or by identifying better signals. To some extent, the most promising means of improvement will be determined by the particular application. For example, in a simple spelling application, the limitation may be in the signal itself (i.e., the user's control over the signal) rather than the signal processing that measures the signal. In this case, the most effective strategy might be to improve user training.

One important issue is whether control is to be discrete, continuous, or hybrid [51]. Again, this is often application-dependent. It may be most worthwhile to determine the subject's intent rather than to control in detail the process that achieves that intent. For example, in the case of controlling a robot, the user would need only to communicate the desired direction. Intelligence can be in the controller, so that the user does not need to exert continuous low-level control. Even EEG-based devices can obtain good control in this manner. There are two interesting and relevant examples of this kind of control. First, patients with spinal cord injuries learned nicely when their task was just to convey the intent to walk. Second, implanted rats in Dr. Chapin's experiments needed to be told only where to go, not how to get there [9]. Some discussants thought that this may be the best way to think about BCI development. It concerns how intelligence should be distributed, that is, what the BCI should do and what the device should do. Depending on the answer, the demands on bandwidth may be more or less stringent. Methods to correct errors must also be considered. It was also pointed out that it might be useful to consider combining BCI control with other, nonbrain, sources of control such as eye movements.

In addition, it is important to consider how controllers are to be evaluated and this will differ according to the specific applications (e.g., environmental control, spelling/keyboard control, various types of robotic control). Certainly, control failure is more dangerous in some applications (e.g., driving a wheelchair or controlling a neuroprosthesis that provides walking) than in others (e.g., word-processing). Evaluation also involves formal measures of information transfer, such as bit rate. In sum, we need to maximize bandwidth and we also need to optimize how that bandwidth is used.

3) Intelligent Controllers: Intelligent controllers are needed so that control can be achieved with the limited bandwidth signals now available. While greater bandwidth is clearly desirable, intelligent controllers can allow much of the high-bandwidth details of control to be delegated to the controller. In this way, the user can focus on communicating goals rather than on the details of control. An adaptive neural net controller could allow a person to use EMG signals to fly a plane. The controller can even adapt to problems with the interface, such as the loss of an electrode. For functions such as multidimensional control of a neuroprosthesis, an intelligent controller is probably essential: cortical single-neuron activity, for example, is not directly transferable to muscle control but must be properly interpreted and then implemented. Just as the central nervous system itself is organized in a distributed and hierarchical manner, much of the work in development of BCIs, particularly for prosthesis operation, will need to focus on the distribution of functions across levels with the provision of appropriate and timely feedback at each level. The concept of motor primitives, now being applied to understanding of spinal cord function, is relevant here. It remains unclear to what extent such organization can effectively increase degrees of freedom without putting undue burden on the user or on the bandwidth of the interface.

It was pointed out in the discussion, however, that people do not necessarily want or like to relinquish too much direct control. For example, while a word-prediction algorithm can greatly increase communication rate, it has been found that people with ALS often prefer to communicate one letter at a time because it gives them a greater sense of control. Similarly, cars can be made to operate without a driver, but people do not necessarily like this. Furthermore, we certainly do not want a system that makes incorrect assumptions about the user's wishes and requires constant correction. People like to have control and it is important not to automate a system so much that potential users do not want to use it.

D. Panel 4: APPLICATIONS I—Identification of Those Applications of Most Practical Value to Users, Facilitation of User Training, and Long-Term Support of Applications. (Chair—M. Weinrich. Panelists—P. Kennedy, N. Neumann, C. Neuper, J. Onton, L. Pickup, T. Vaughan, D. Weston.)

A central question in BCI research focuses on the practical benefit of applications to individuals with severe disabilities. A discussion of these benefits must address the following attributes of specific applications: efficacy; reliability; efficiency; training protocols; and measures of consumer satisfaction (especially cosmesis and total system costs). The Applications I panel decided to focus on the need for systematic evaluation of these attributes as a means of providing useful applications and improved quality of life for individual users.

In present-day BCIs, the output device is a computer screen and the output consists of the selection of targets, letters, or icons presented on this screen. Selection is indicated in various ways (e.g., the letter flashes). To be a useful application, a product must: improve some life function for the user, be reliable, be easy to use, require little assistance from others, and be easily serviced.

There are many obstacles to training subjects in the use of BCIs. For some of the target populations, the users' lack of conventional communication ability makes it difficult to assess their cognition or even their consciousness. The lack of conventional communication ability may impede the operator/user interactions needed in initial BCI training. Moreover, the same deficits that abolish all voluntary muscle control may also impair the users' ability to control the signal features used by a particular BCI.

Even in its current early stage, BCI technology may provide crucial functions to extremely disabled people if these and other obstacles can be overcome. For people who are totally paralyzed ("locked-in") (e.g., by ALS or brainstem stroke), a BCI system can provide the ability to: answer simple questions (i.e., 20 b/min is one "yes/no" answer every 3 s); control the environment (e.g., lights, temperature, television, etc.); perform slow word-processing (i.e., with a predictive program, 25 b/min can produce 2 words/min); or even operate a neuroprosthesis (reviewed in [5] and [10]).

1) Moving BCIs Out of the Laboratory: Until now, most BCIs have been tested in the laboratory only. Only a few groups have explored BCI integration into life outside the laboratory. These include: the Tübingen group's Thought Translation Device (TTD); Dr. Kennedy's group's implanted electrodes; and the Graz group's BCI with telemedicine linkage.

The Tübingen group's TTD has been tested extensively in people with late-stage ALS and has proved able to supply basic communication capability [10]. Subjects are trained to use a two-choice spelling program; for subjects who cannot read, a protocol allowing selection of visual signs and symbols is available. Moreover, a stand-by mode allows users wearing collodion-fixed electrodes to access the BCI 24 h/day by producing a specific sequence of positive and negative slow cortical potentials (SCPs). This sequence, thus, serves as a switch for turning the BCI on and off and represents an encouraging and important initial solution to the on/off problem that must be solved to move BCIs out of the laboratory so that they can serve practical purposes [11], [37], [52].

In initial studies by Kennedy's group, two cone electrodes were implanted in each of three patients who were nearly locked-in by ALS, mitochondrial disease, or brainstem stroke. Two of these patients learned to control single-neuron firing rates to move a cursor to icons or to letters presented on a computer screen. They used single-neuron activity to control one dimension of cursor movement and used residual EMG to control the other dimension and, thus, the final selection. In these two patients, this system achieved communication rates up to about 3 letters/min (i.e., about 15 b/min) [12], [13].

The Graz BCI group has developed telemedicine capabilities that allow the BCI to function in users' homes while the classification algorithm is updated remotely in the central laboratory [14], [53]. With this remote control system, a 22-year-old man who is quadriplegic due to a high cervical (C4-5) spinal cord lesion uses right hand and foot motor imagery to control an orthosis that provides hand grasp [14].

2) Lack of Systematic Study of BCI Effectiveness in Improving Quality of Life: Despite the impressive demonstrations described previously, despite the large number of different BCI methods in existence or in development, and despite the pressing demands of the individuals who are the initial target populations of BCI technology, there has been to date little systematic study of the effectiveness of these systems in improving quality of life. Ideally, a BCI and its applications should be optimized for each individual user or user group: each BCI and its application(s) should match the needs of the individual and his or her BCI communication and control capabilities. To date, there is little empirical evidence to support the contention that one or another method may be more or less effective with any particular population group.

Despite the theoretical advantages of conducting controlled studies, this undertaking is fraught with challenges when applied to BCI applications development.

a) The needs and capabilities of a particular subject in a study may change over the course of a study (e.g., a patient with ALS or other progressive disease). With such changing conditions, it is difficult to conduct a strictly controlled study.
b) Changes in physical environment or social interactions can greatly affect an individual's motivation to use the BCI. These may occur over the course of the study.
c) Every patient is different. Applications have to be individualized to take into account an individual's needs and capabilities. This may make it extremely difficult to conduct well-controlled studies of a particular BCI in a particular population group.
d) A BCI's effectiveness in improving quality of life must be assessed and continually reassessed as changes such as those described in a) and b) occur.

3) Comparisons to Other Fields: The panel suggested that lessons learned by professionals working with augmentative and alternative communication (AAC) in patients with aphasia may prove useful in BCI development. The comparison is a worthy one. In both instances, there are pressing and large clinical needs, seemingly unique patient deficits, a profusion of commercial products, and very limited data. A review of the AAC literature to date suggests a lack of balance between relevance and scientific rigor. This, in turn, resulted in a failure to resolve treatment issues for the most severely aphasic patients [15], [16]. Efforts are underway to encourage investigators to address these issues [17]. BCI development should, likewise, address the issue of defining and studying measurable functional outcomes.

4) Conclusions: To provide reliable and useful systems for consumers, BCI methods and applications should be systematically evaluated in target populations. In spite of the obstacles described above, attempts should be made to develop and use objective measurements to determine how much and how successfully individuals with various disabilities actually employ a particular technology and to what extent that technology makes long-term contributions to their communication and control capacities and to their well-being [18], [52]. Individuals with ALS, brainstem stroke, cerebral palsy, or other severe neuromuscular disorders should be included in clinical trials that evaluate which BCI methods might be best for each group. These studies should compare the performances of different BCI systems and different electrophysiological inputs in comparable user groups. These clinical trials should address issues of: patient selection; device specification; training protocols; maintenance protocols; functional measurements; patient/caregiver satisfaction; and participation measurements. Although a double-blind design paradigm is generally not practical in such work, training procedures and study designs that maximize comparability should be used and controls for placebo effects should be incorporated.

E. Panel 5: APPLICATIONS II—Identification of Those Applications of Most Practical Value to Users, Facilitation of User Training, and Long-Term Applications. (Chair—M. Moore. Panelists—B. Allison, M. Gibbs, I. Goncharova, J. Green, J. Judy, A. Karim, L. Quatrano, R. Schmidt.)

Panel 5's task was to consider possible future uses for BCI technologies, both for augmentative use and for mainstream use. Any complete delineation of ideas for applications for brain-signal control can, however, lead to misconceptions by the general public about what BCI technology is currently capable of delivering. It is, therefore, important that public statements by investigators be realistic and clear, so that the general public and the scientific community do not have unrealistic expectations. With that caveat in mind, this panel discussed a variety of possible BCI applications for the near and far future.

Underlying the panel's discussion were two major themes: 1) what BCIs can do that other techniques or methods cannot do; and 2) the areas in which BCIs might go beyond augmentative (or medical) applications and into the mainstream.

1) Medical Applications: The areas in which BCIs can clearly help people with disabilities to improve their quality of life include simple communication (including Internet use), environmental control, and movement restoration (e.g., creating an artificial link from the brain to paralyzed limbs). In addition, development of a variety of other therapeutic technologies holds promise for new applications in which BCIs might play a significant role. BCI technology might contribute to further development of therapeutic methods such as deep brain stimulation for people with Parkinson's disease. Current work in functional electrical stimulation shows that movement can be restored in people paralyzed from spinal cord injuries. In these contexts, a BCI might be used to create a feedback loop to enhance the benefits of these therapeutic methods. Similarly, BCI technology might contribute to restoration of bladder control or control of other bodily functions. (This is a particularly important quality of life issue for people with spinal cord injuries, many of whom consider bladder and bowel control of much greater concern than their inability to walk.) Even more hypothetically, BCI technology could conceivably contribute to tissue replacement strategies (such as those using stem cells) by providing means for inducing and guiding the development of useful function in newly regenerated structures. BCI technology might also contribute to the development of passive devices for monitoring function: it might help monitor long-term drug effects, predict seizures, or evaluate psychological state. Brain signals may also be capable of providing enhanced control of devices such as wheelchairs, vehicles, or assistance robots for people with disabilities (e.g., robots might perform routine household chores or help with personal care).

2) Beyond Medical Applications: Although much of the current research in BCI technology centers around medical applications and augmentative technology for people with severe disabilities, as BCI technology improves it will probably expand to serve people with less severe disabilities, partial disabilities, or no medical disabilities. As discussed previously, there are potential applications for BCI technology that are theoretically possible, but which do not exist at this time. If these applications do prove possible, it might not be until a time well into the future. Thus, the ideas described in this paragraph should be considered as hypothetical BCI applications that may or may not come to fruition. For example, BCIs could be used to monitor attention in long-distance drivers or aircraft pilots. BCIs might be used to control robots that function in dangerous or inhospitable situations (e.g., underwater or in extreme heat or cold). BCIs might be used to provide additional control in video games. (Gamers comprise a large and rapidly growing population; they tend to be enthusiastic about trying new technologies and are likely to embrace brain signal control. They might even be enthusiastic subjects for experiments developing new control channels.) In the area of neural art and music, some work has already been done. For example, the BioRadio and cyberPRINT applications have been used to instrument a dancer. Physiological signals, including EEG, have been used to create projected images in real time. The Interactive Brainwave Visual Analyzer (IBVA) uses EEG to create music, and the Georgia State University BrainLab has mapped neural spike recordings to MIDI to create neurally-controlled music. Future applications for incorporating BCI technologies into the arts could include visual arts and musical composition. Thus, there is a wide array of possible future BCI applications that can be conceived of and, perhaps, eventually developed. At the same time, it remains clear that for the present and near future, the primary importance of BCI technology will be in increasing the communication and control capacities of people with severe disabilities [54].

F. Panel 6: STANDARDS—Development and Adoption of Appropriate Standards for Designing BCI Studies and for Assessing and Comparing their Results, both in the Laboratory and in Actual Applications. (Chair—A. Kübler. Panelists—L. Bianchi, J. Huggins, T. Kirby, F. L. da Silva, D. McFarland, J. Mellinger, D. Moran, G. Schalk.)

Panel 6 considered the delineation and adoption of appropriate standards for designing BCI research studies and for assessing and comparing their results. Standard objective methods for evaluating and comparing different BCI systems and approaches are needed. General acceptance and application of objective methods for evaluating translation algorithms, user training protocols, and other key aspects of BCI operations are crucial. Evaluations in terms of information transfer rate and in terms of usefulness in specific applications are both important. Recognition and attention to the issue of standards is essential if BCI research is to continue to progress from simple demonstrations of potentially useful systems to actual realization of efficient and useful communication and control systems.

This panel discussed the development and adoption of appropriate standards for designing BCI studies and for assessing and comparing their results, both in the laboratory and in actual applications. Direct comparisons among different BCI designs would be facilitated if data acquisition and reports of results followed defined and agreed standards. For example, in reporting the information-transfer rate or speed of a BCI, output can be viewed as the output of the BCI itself [commonly measured in bits per unit time (bit rate)] and/or as the output of the application that is controlled by the BCI. Our discussion of standards involved such topics as: quality standards for study designs; standards for the reporting of results; standards specific to BCI design (i.e., standardized file formats, functional modules, and inter-module communication); and related ethical standards.

1) Beyond Bit Rate: Bit rate information certainly provides a starting point for evaluation and comparison among different BCI systems. However, when comparing BCI performance, several other important system parameters also need to be identified and accounted for. For instance, it has been proposed that the number of independently controllable channels (i.e., degrees of freedom) that are available to the user should be taken into account. For each independent channel, the signal's type (e.g., proportional versus binary) and its resolution (bits/sample) need to be identified and measured. Furthermore, evaluation of performance should also specify whether reasonable control can be obtained using a single-trial analysis or whether several averaged trials are needed. In addition, reports of single-trial control need to specify whether the results were achieved offline or online (i.e., real-time control).

2) Application Output as a Standard: Translation algorithms convert the bit rate of a BCI into the output of an application, such as a menu to select letters, words, or icons on a screen, or movement of a wheelchair or other device. This represents the "user communication bandwidth," which is the final goal of the BCI. Thus, the bit rate of a specific BCI itself can be improved by achieving greater user communication bandwidth. One may, for example, improve the efficiency of an application by using strategies to remove redundancies typical of the canonical communication channels (e.g., if one writes HAPPY BIR, it is clear what the sender intends to say, so THDAY does not add any further information). For instance, in the Italian language, relatively few words are used in most communication. De Mauro *et al.* showed that 95% of Italian sentences are constructed using only 300 words [19]. Selecting words instead of letters may, therefore, improve the communication rate per unit time. Assuming a system that generates an output of 30 b/min, this amount of information can be used in different ways: 4.7 b are required to select one among 26 letters, but 8.3 b can represent 315 different symbols. Therefore, selecting a word in a limited dictionary requires less effort than selecting two letters in the English alphabet. In 1 min, either 6.4 characters or 3.6 words might be selected.

Thus, although bit rate is an appropriate measure to compare the signal output of different BCIs, other measures may be more suitable when comparing how efficiently an application can be controlled. If, for example, patients use the BCI to communicate by means of a spelling program, the number of words per unit time may be more appropriate than the bit rate. A time-independent unit of measurement for the efficiency of a BCI and its applications could be the output of the application (e.g., words or icons or switches per unit time) divided by the bit rate of the BCI. Such a measurement accounts for any difference in the output of the BCI and the application. Another index of the feasibility of a BCI and its application could be to what extent it improves the quality of life of the individual user. Questionnaires specifically designed to assess quality of life in terms of communication status and regained autonomy in daily life should be developed and completed by BCI users on a regular basis.

3) Standardization of Hardware: Ideally, BCI hardware outputs should conform to the existing standards for computer input devices. This would allow a BCI to be plugged into an existing system in the same way as any off-the-shelf keyboard or mouse. This avoids the necessity of "reinventing the wheel" by designing specialized applications for each BCI. A wide array of assistive technology devices and software for communication, environmental control, and computer access already exists and most are designed to accept control signals from a wide range of standard input devices. If BCI systems conformed to existing input device standards, then a patient who was losing the ability to move could continue to use a familiar communication system while making the transition from an input device that relied on physical movement (such as a mechanical switch, trackball, or joystick) to a BCI input device. Even BCI systems that require the user to interact with a computer display in order to achieve BCI operation could be designed to provide input that mimicked the input from standard input devices to an application running on a separate computer.

4) Standardization of Recording: Brain signal recordings are another area in which guidelines may be beneficial. In any successful BCI application, the optimal recording site needs to be determined, and the actual source of control (e.g., EEG components as opposed to non-EEG artifacts) needs to be established. This requirement prescribes that initial experiments include all electrode sites that are reasonable for the type of brain signal that is sought (e.g., with P300 potentials, sites might include the area around the center of the vertex) and that are necessary to determine whether or not the recordings are free from artifacts. Once the ideal location has been determined and it has been established that control actually comes from brain signals, the number of recording sites can be reduced to the minimum number needed to extract the brain signal used for control.

5) Ethical Standards: Since users who may benefit most from a BCI are patients with severe and mostly untreatable diseases, ethical issues must be addressed. While full consideration of all these ethical concerns is beyond the purview of this panel's discussion, there are a number of noteworthy issues that must be addressed because they may arise while training patients to use a BCI. First, it is often the case that not all patients who are interested in participation can be accommodated. In this case, a specific BCI lab must formulate guidelines to determine which patients are included, or not included, in training, and under what circumstances and time frames training is terminated. Second, the nature of the support provided by the BCI group and the individual trainers has to be determined. Will the interaction with the user be strictly and exclusively restricted to BCI training, or is the group ready and able to assist in other aspects of the user's daily life with such tasks as writing assessments pertaining to health insurance or psychological treatment? Furthermore, policies may need to be developed for dealing sensitively with the knowledge that a patient may wish to die. It may be difficult to define standards regarding trainer-user interactions because the coping style and situation of each user is different. In any case, it should be made clear at the beginning of BCI training what can be expected of a BCI, the group, and the training personnel, and that BCI training is not a treatment against the disease [52]. In general, it may be most prudent to stress that the patient is providing a service to humanity by participating in the research and thereby minimize the likelihood that the patient will develop unrealistic expectations.

6) BCI2000: Currently, a general-purpose BCI system (the BCI2000) is under development in Dr. Wolpaw's group in Albany together with Dr. Birbaumer's group in Tübingen [20]. This program seeks to provide a standard platform that can compare, optimize, and apply all available brain signals, signal processing methods, and applications. BCI2000 consists of four independent but interacting modules: a) *Source* (signal acquisition and storage); b) *Signal Processing* (feature extraction and translation algorithms); c) *User Application*; and d) *Operator* (process control). Each of the modules implements a different aspect of BCI and does not depend on the specific structure of the other modules, so that one module can be changed without having to change another. BCI2000 can, therefore, be easily adapted to different research or clinical requirements [1]. It is available with full documentation for research purposes at http://www.bci2000.org.

7) Conclusions: Setting standards is becoming increasingly important in the rapidly growing field of BCI research and development. This process inevitably involves a tradeoff between innovation and finding an efficient method to compare systems. A common standard that is cast too narrowly will fail since the technology, study design, applications, and user groups differ widely among BCI systems. Furthermore, these factors are changing rapidly. Since BCI technology is in an early stage of development with many innovative advances underway, only a carefully selected set of standards can successfully describe and compare the wide range of different systems.

G. Debate 1: Choice of Brain Signals for BCI Use: Spikes Versus Field Potentials [Moderator—S. Levine. Speakers—J. Donoghue (spikes), J. Wolpaw (field potentials)]

A wide variety of brain signals could conceivably be used for BCI communication and control. These signals fall into two categories: spikes that reflect the action potentials of individual neurons and field potentials that reflect the combined synaptic, neuronal, and axonal activity of groups of neurons (see [21] for review). Spikes are necessarily recorded near the neurons producing them, and, thus, require implantation of small electrodes within brain tissue. Field potentials can be recorded as EEG from the scalp (in which case, they reflect activity in large areas of brain), from small electrodes within the brain (in which case, they reflect the activity in small immediately adjacent areas of tissue), or from epidural or subdural locations in between these two extremes. In general, the topographical resolution of

[1] BCI2000.org: http://www.bci2000.org.

field potentials is highest for the most invasive electrodes, those within brain, and lowest for noninvasive scalp electrodes. The debate between Donoghue and Wolpaw centered on which of these two categories of brain signals (spikes or field potentials) is most useful for BCI systems.

It is not yet clear which signals can be most useful for BCI systems. Only fragmentary data are available. Sets of spikes can predict limb trajectory and initial studies suggest that they can provide comparable control of a cursor in the absence of actual limb movement (e.g., [22] and [23]). Since they are intimately involved in the control of actual movements, they might provide BCIs that are relatively easy or natural to use. On the other hand, when they are applied to the control of artificial devices, their behavior is likely to change, so that the relevance of their original function in normal motor control to their BCI value becomes less clear (e.g., [23]). The usefulness of intracortical field potentials, which could be comparable to that of spikes (e.g., [24]), remains largely unexplored. A number of EEG signals, including slow cortical potentials, sensorimotor cortex rhythms, and P300 potentials can control simple devices at rates up to 10–25 b/min (see [5] for review) and are capable of multidimensional movement control [25]. The possibilities for further improvements in the use of these noninvasively recorded signals are just beginning to be evaluated. Epidural or subdural recording is less invasive than intracortical recording, and its resolution can be considerably higher than that of EEG. Initial data relevant to the BCI usefulness of these intermediate signals are promising [26], [27].

Intracortical signals, spikes, and/or local-field potentials, may yield the highest information transfer rates (i.e., bit rates). However, these signals require the most invasive methods, and the long-term structural and functional stability of intracortical electrodes is a major unresolved issue. All other things being equal, the least invasive methods are preferable. It may be that some combination of recording methods will prove valuable. Effective exploration of these alternatives must incorporate adequate evaluation of alternative signal processing methods, for these can greatly affect results. In sum, it not yet clear which electrophysiological signals will be most useful. Thorough evaluation of all signal types is needed.

H. Debate 2: Linear Versus Nonlinear Methods for BCI Signal Processing [Moderator—G. Birch. Speakers—K. Müller (linear), C. Anderson (nonlinear)]

BCIs translate brain signals into device commands. Linear and nonlinear methods can be used for this translation and both approaches have been used to date. In this debate, Müller argued in favor of linear methods, while Anderson argued in favor of nonlinear methods. The points they raised are fully discussed in their paper in this issue [43] and are briefly summarized here.

The discussants agreed that the choice of a linear or nonlinear method depends in large part on the nature, size, and other characteristics of the data set and requires a clear conception of the theoretical model being applied to the data. They also agreed on the guiding principle that, all other things being equal, simpler methods are better.

Linear methods require that the data be linearly separable. When a data set meets this criterion, linear methods are usually preferable because linear classifiers tend to be simpler and more robust. While it is certainly useful to validate classifiers derived from a training set of data by testing them on a test set, their value must still be confirmed online. In the presence of strong noise or significant outliers, linear methods may fail. Such conditions frequently exist in physiological data. When regularization of such data is not possible, nonlinear methods (e.g., support vector machines or neural networks) are appropriate, even though they are computationally more demanding. Moreover, when the source of the data is not well understood, nonlinear data transformations may provide a more meaningful description. Thus, nonlinear methods are particularly useful when a problem is intrinsically nonlinear or the data are not robust.

I. Debate 3: Behavioral Versus Cognitive Approaches to BCI Research [Moderator—A. Gevins. Speakers—N. Birbaumer (behavioral), E. Donchin (cognitive)]

In all EEG-based BCIs, the challenge is to develop a mechanism by which the user gains control over the variance in the EEG. The computer's role is to examine this EEG variance and take specific actions depending on the direction in which the variance is controlled. For the last 120 years, psychologists have approached their discipline either as "behaviorists" or as "cognitivists" (recent labels for the approaches described in [28] and [29]). BCI research presents a new class of mind/behavior phenomena and is, thus, a new arena for the continuing debate between the behavioral and cognitive viewpoints. The two differing approaches are reflected in the ways in which these two groups approach the control of EEG variance in designing BCIs. Since the behaviorist's object of study is overt behavior rather than processes that are unobservable, behaviorists have focused on developing effective techniques for the control of behavior, and for assuring (using "operant conditioning" methods) that a person can acquire a specific response. In contrast, the cognitive psychologist tends to view the mind as an information-processing device whose output depends on the relationship between the subject's task, stimuli, and the activation of various cognitive processes. In this debate, Birbaumer presented the case for the behaviorists and Donchin presented the case for the cognitivists.

Birbaumer presented indirect evidence that learning to control EEG features, particularly SCPs, involves implicit/operant learning. In users with excellent SCP control, success was correlated with fMRI-detected activation of (probably inhibitory) basal ganglia structures (putamen/pallidum) and deactivation of supplementary motor areas. These areas regulate cortical excitation thresholds and in their anterior parts, subserve operant learning. On the other hand, even after lengthy training, SCP control does not appear to become automatic: users still need to pay close attention to produce cortical changes. This is confirmed by fMRI evidence for activation of lateral prefrontal structures during SCP-based BCI operation. Cognitive activities such as imaging various scenes during learning or motor imagery do not predict success in SCP control. People who are severely retarded, and, thus, are presumably not capable of elaborate cognitive processes, can achieve excellent SCP control. Data from animals provides additional support for the importance of operant conditioning in SCP control [37].

In contrast, Donchin represented the class of BCIs that relies on differential responses by the subject to fairly structured stimuli. The subject does not have to learn new response patterns but rather processes information within a well-defined task. Brain responses to such stimuli differ as a consequence of different information processing modules that are activated as information is processed. The case used by Donchin as an illustration is the P300-based speller, [30], [31], which relies on the fact that events that force "context updating" in the so-called "oddball paradigm" [32], [33] elicit the P300 component of the ERP. Since this is a virtually ubiquitous response, there is no initial need to train the subjects. The challenge is to develop structured situations in which the relevant stimuli will, in fact, elicit a P300 that the computer can easily detect and interpret. The design of such a BCI requires a detailed task analysis using cognitive process models and a heavy reliance on cognitive psychology as a guide to task design. In the design of such a BCI, Donchin felt that behaviorism provides little depth in the understanding of the human as an information-processing system. From Donchin's perspective, operant conditioning may be a useful tool in the engineering sense in that it facilitates training, but it is not the means for understanding and using the complexity of the human mind which is in itself a rather superb information processing system.

This lively debate was instructive about the history of the behaviorist and cognitivist approaches. It highlighted their implications for the understanding of BCI phenomena and for the design, evaluation, and use of BCI technology.

J. Debate 4: A Standard BCI Framework: Good or Bad? [Moderator—B. Dobkin. Speakers—S. Mason (good), D. McFarland (bad)]

BCI researchers use a variety of terms to refer to BCI system components, their inputs and outputs, their functions, and their interactions. At this early stage in BCI research and development, BCI control has been demonstrated but not yet adequately studied. It is not clear whether adoption of standard benchmarks and terminology would facilitate or stifle continued progress. Since BCI research is driven primarily by the perceived need for human applications [34], this debate was initially formatted as an effort to answer the question: How might standards support or stifle development of BCI applications readily applicable to humans? In his introduction, Dobkin emphasized that BCI researchers will find a more receptive audience for their achievements if they keep clinicians, especially neurologists, orthopedists, neurosurgeons, physiatrists, and rehabilitation personnel abreast of their research in terms that can be understood and can be used to compare devices. Demonstration of the clinical value of BCI is just beginning. The success of clinical trials and the commercialization of devices will depend, in large part, on how physicians and patients come to understand the personal utility of BCI over the course of a fixed or a progressive neurologic disease. It is important that a health care provider who wishes to prescribe a BCI device understand how one black box differs from another, and that he or she can convince insurers of its worth and can make a patient and family comfortable with selection of a particular device and realistic about the purposes and capabilities of BCI technology.

Mason argued that standards are crucial. He emphasized that the development of a common framework affects the quality and efficiency of BCI research, that the development of such a common framework is possible, and that the community should invest effort in the immediate development of a formal framework. He felt that researchers should be proactive on this issue and encourage this framework development in the literature. The field has started to grow rapidly, is receiving increasing media exposure, and will in the future involve many more people. The benefits of defining a standard framework are significant and desirable and the costs (in effort and time) are relatively modest. He argued that the development of an appropriate standard framework would facilitate both continued basic research and successful applications.

Dr. McFarland focused on the fact that BCI research is still in its infancy, and from this reality, he argued that its continued success depends on the exploration of many different signals, signal processing algorithms, and user applications. This comprehensive approach requires flexibility and innovation. Such flexibility and innovation require that investigators be free to conceptualize in many different ways. He illustrated this crucial point by showing a variety of different conceptual diagrams of BCI systems, stressing the vast theoretical and practical differences between these diagrams, and indicating the role of these differences in facilitating progress. Although global standards may be useful in the future when the BCI field moves from mainly exploration to mainly application, the present state of BCI research requires evaluation of many alternative approaches and conceptual frameworks. Formalizing standards at this early stage could stifle such comprehensive evaluation and thereby limit the eventual practical applications of BCI technology.

Mason and McFarland both stressed the importance of promoting such comprehensive evaluations and practical applications. They differed in their views of the usefulness of formal standards serving this purpose at this time.

III. Conclusion

The June 2002 meeting, *Brain–Computer Interfaces for Communication and Control: Moving Beyond Demonstrations*, was the third meeting [35], [36], and the second international one, devoted exclusively to BCI research and development. The participants were neuroscientists, clinical neurologists, systems and rehabilitation engineers, computer scientists, applied mathematicians, physiological and clinical psychologists, and rehabilitation specialists from the U.S., Canada, Europe, and China, involved in BCI research or in fields directly relevant to it (e.g., EEG, signal analysis, neurophysiology, neuroprosthesis development, computer science, human factors). Through research summaries from each of the 38 BCI labs represented, through interdisciplinary topic-oriented discussions, debates, posters, and demonstrations, and through the involvement of many graduate students and postgraduate fellows, this meeting sought to advance BCI research and development.

This second international meeting and the picture it gave of the state of the field is reflected in the differences between this summary article and the corresponding article from the first meeting in 1999 [36]. This new summary is longer and involves more people, both as authors and as participants in panels and debates. Thus, it indicates the rapid growth in the number of people and the number of laboratories involved. More importantly, this new summary is less didactic and more complex than the first. The first was similar to a textbook chapter introducing the BCI field—defining its terms, describing studies to date, and introducing the most important issues, all in a very structured fashion. This new summary is more like a documentary with a central theme. That theme—*Moving Beyond Demonstrations*—focuses on the need to progress from the "gee-whiz" state of simply showing that BCIs are possible, to developing them into a significant new technology with valuable applications. In reflecting and promoting this theme, the meeting displayed the many kinds of current BCI research and engaged the many disciplines essential to progress. The panels provided reasonably representative and comprehensive pictures of current thinking about the basic elements of BCI design and operation, including: the signals used; signal acquisition, processing, and translation; practical applications; and user training and satisfaction. Together, they brought out the factors crucial to progress, including controlled studies, careful comparisons of alternative signals and methods, appropriate applications, careful matches to user groups, and evaluations of long-term clinical benefits. The four debates provided further treatment of crucial issues and illustrated the interdisciplinary nature of BCI research—from neuroscience, to signal processing, to psychological theory, to engineering principles.

The theme *Moving Beyond Demonstrations* can be interpreted in two ways, both important to the current state of the field. First, it emphasizes the need for comprehensive well-controlled studies. In fact, much of the meeting was occupied with the many aspects of this critical requirement. Second, it focuses on the need to make BCIs useful to people with motor disabilities. Their pressing problems are both an opportunity and an obligation for BCI researchers. The future of BCI research will be determined by its response to these two needs.

The first and second international meetings and the differences between them reveal a young, energetic, and rapidly growing research field. By satisfying the highest standards of scientific research and by providing clinically useful applications, BCI researchers can ensure that the field continues to develop, and that this radically new communication and control technology increases the capacity for self-care, entertainment, and productive employment of people with severe motor disabilities.

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