Workshops

BCI Meeting 2005—Workshop on Technology: Hardware and Software

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***Abstract*—This paper describes the outcome of discussions held during the Third International BCI Meeting at a workshop to review and evaluate the current state of BCI-related hardware and software. Technical requirements and current technologies, standardization procedures and future trends are covered. The main conclusion was recognition of the need to focus technical requirements on the users' needs and the need for consistent standards in BCI research.**

***Index Terms*—Brain–computer interface (BCI), specifications, standards.**

I. Introduction

Technology is a fundamental requirement for operation of brain–computer interfaces (BCIs). Indeed, the first demonstrations of brain-actuated control of a computer [1] were made possible by the implementation of online acquisition and processing of EEG signals. Although BCI research and development is becoming a mature and highly interdisciplinary discipline, advances in BCI effectiveness depend heavily on advances in its hardware/software systems.

The aim of a workshop held at the Third International BCI Meeting was to review and evaluate the current state of BCI-related technology and to describe its current and future needs. The workshop was organized into four topic panels whose discussion and conclusions are summarized in Sections II–V. One panel (led by Birch and Yáñez Suárez) discussed the technical requirements of BCI systems focusing on the variety of possible application contexts. A second panel (led by Guger and Mellinger) reviewed technical solutions for each context. The third panel (led by Bianchi and Schmidt) elaborated on the need for technology standardization. The last panel (led by Scherer) highlighted several technology trends.

II. Technical requirements

The goal of this panel was to develop and describe the different technical requirements of BCI systems in different contexts. The technical requirements for BCIs are extremely diverse and depend heavily on the context. For example, the needs of an experimental psychologist for a research tool prompt technical requirements that are different from those of a motor-impaired subject who wishes to use a BCI system as a communication device.

The panel outlined four different target users:

1) researchers (e.g., clinical researchers, neuroscientists, signal processing experts, etc.);
2) technical operators (e.g., caregivers, therapists who are in charge of training someone on BCI operation);
3) end-users (e.g., people with disabilities who rely on the system for communication)
4) casual end-users (e.g., those who use a BCI as an alternative input for entertainment devices).

Cost and benefit of technical requirements vary across these users. At the current stage of BCI development, most of the focus is on the end-user with disabilities. In fact, technical operators are trained with the goal of using BCI for people with impairments, and most researchers focus (at least as a long-term aim) on the improvement of BCI technology for the disabled. While BCI systems could be useful for entertainment, the performance of current BCI devices does not permit practical applications. As a consequence, BCI systems were mainly examined from the perspective of a direct or indirect (research, nursing) application to people with motor disabilities.

Given the degree of disability, the end-user requirements and needs will drive the BCI applications into one or more of the following areas:

- neuroprosthetics;
- robotics/mobility devices;
- environmental control;
- communication.

The control of the applications listed above requires a decreasing communication capacity of the BCI system (e.g., a prosthesis might need more accurate control than a simple word processor). At the same time, improvements in quality of life will be remarkable only if the residual capabilities of the user are comparably low (there is no point in using a brain-controlled speller if one can still type). Fig. 1 depicts the relationship between BCI information transfer rate and end user capabilities. Improvements in BCI technologies allow control of more sophisticated applications, thus increasing the number of people that might benefit from it.

In general terms, the most relevant technical requirements for a BCI device related to the application areas outlined above are as follows.

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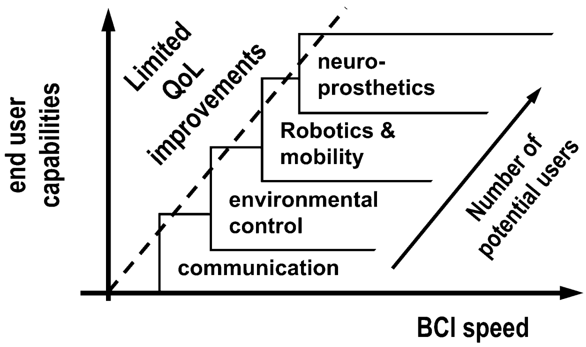

Fig. 1. Applications that may benefit from an input by a BCI system. On the horizontal axis, the speed of information transfer that would make the application controllable; on the vertical axis the degree of residual motor abilities that the user of the application is likely to have. Variety of applications and the effectiveness of a fast BCI will enlarge the size of the population that might benefit from BCI devices.

- *High Information Transfer Rate*: a BCI device should be able to carry information at high speed, relative to the particular application needs, and with a sensible accuracy.
- *Ease-of-Use*: though highly configurable systems are desirable for research prototypes, the devices available for end-user application should need only a reduced set of operations. Moreover, sensors should be designed for simplified placement and the system should be portable when mobility is allowed.
- *Robustness*: while this is not an issue in laboratory experimentation, developers who aim at a real world deployment should be concerned about operability in most environments.
- *On-Demand Operability*: continuous operation of a BCI may induce stress, and the need for another person to turn the system on and off would reduce the potentially gained independence. A comfortable BCI system should include a reliable mechanism to put it into a standby mode and it should perform well in an asynchronous mode while the system is on. This will ultimately exclude the chance that a false positive produces undesirable results.
- *Safety*: as soon as the system is operated by a person with reduced motor abilities, safety is of concern; most current systems are still striving for demonstration of effective operation. Issues of safe operation are yet to be adequately addressed.

The aforementioned desirable characteristics of a BCI must also be considered in the context of other factors such as development effort, invasiveness, training time, cosmesis, affordability, etc. The intended context will drive the decision about priorities. Nevertheless, no matter what the short-term goal, the panel stressed that the long-term focus should be improving the quality of life of the end-user which remains the most promising application for the BCI technology.

III. BCI Technology solutions

This panel outlined the current solutions that several research laboratories and private companies provided to the BCI field.

A. Hardware

Activity of the Central Nervous System can be detected by a variety of techniques. Some rely on the hemodynamic correlates of the brain functions (SPECT, fMRI, NIRS) [2], [3], while others rely on the propagation of the electrical activity (MEG, EEG, ECoG, microelectrode recordings). To date, there is no clear evidence that any one of these signals is decidedly better than others [4]. Techniques that use hemodynamic activity are costly and involve long time-constants; thus, hemodynamic techniques currently have significant drawbacks for effective feedback training. The various techniques have varying degrees of invasiveness: the MEG helmet merely touches the scalp, the EEG is recorded from the scalp with the application of electrode gel, but ECoG grids and microelectrodes must be surgically implanted.

There is also a variety of ways to connect sensors to the computer systems, e.g., by electrical wires, optical wires, or by wireless connections (Wi-Fi, Bluetooth, etc.). Wireless connections are more expensive and need more power, but might prove ultimately to be the method of choice for carrying the flow of information currently involved in BCI practice.

Amplifiers and digitizers are a mature technology, thus should not be considered an open problem. However, since in practice a BCI might be used for a long period of time and battery power supply is often required for questions of practicality, current development efforts should focus on reducing the power consumption. Commercial 24/32-bit digitizers allow for acquisition even in very noisy environments such as those typical for fMRI scanners.

Power supply technology is expected to improve the portability of BCIs. EEG systems rely on batteries, which usually allow an autonomy on the order of hours -- not enough for continuous use. Implanted systems often use inductively coupled power supplies which limits the amount of available electrical current.

Signal processing is performed on a number of platforms. The most common is the PC since programming environments and software components are widely available. Laptops, tablets, and subnotebook computers provide added portability compared to a standard PC. Implementations of BCIs on palmtop PC are also available.

B. Software

The choice of software is most closely linked to the platform that is chosen for the BCI device. In principle, any programming environment and operating system that allows for sufficient feedback latency and jitter might be used for a BCI.

Most devices rely on PC hardware. Offline systems tailored for analysis of recorded data and for experimentation with new algorithms are often implemented in a high-level programming language (e.g., Matlab), allowing for rapid prototyping. Efficiency considerations often imply lower level languages (e.g., C++) when the system is supposed to work in a closed feedback loop.

Communication between the processing units that constitute the BCI is most often provided by functionality decisions internal to the software package. This leaves little space for easy replacement of processing modules, and for integration of units from different packages. Communication protocols like TCP/IP are likely to encourage the interoperability of software modules originally developed by different programmers, provided that they are also compatible in other aspects.

In summary, many technologies still do not meet the requirements of particular BCI applications, especially when the aim is to deploy BCI outside laboratories.

IV. Standards

The goal of this panel discussion was to elucidate the role of technical standards in the development of BCI systems. Technical standards have advantages and disadvantages that need to be considered. Use of technical standards can improve interoperability of components and thereby generally lessen the need for development and use expertise. FDA/CE certification is typically less costly. Technical standards might also provide the foundation to help solve possible future legal disputes arising from BCI development. On the other hand, technical standards might also stifle innovation in any area defined by a particular standard. Therefore, the choice of which areas should be standardized is an important one. For example, certain technical aspects, such as the

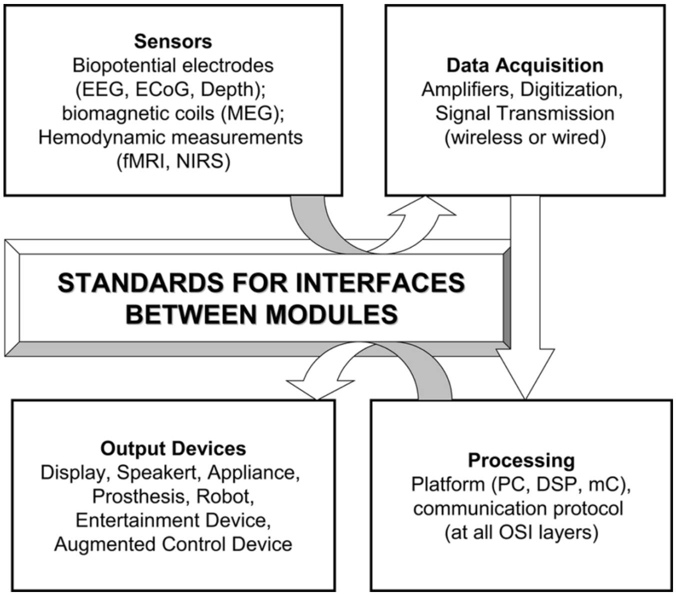

Fig. 2. Several aspects of BCI technology could be standardized. Development of standard nomenclature (abstract standards) is already in progress. Standardized interfaces both at the hardware and at the software level between the modules that constitute a BCI device are needed to facilitate exchange among research groups and also for commercial development.

layout of electrode connectors, are somewhat arbitrary. Because connectors are a mature technology, the definition of a standard for electrode connectors would provide the advantage of standards (i.e., improved interoperability) without being impacted by the disadvantage of that standard (i.e., stifled innovation in the area of electrode connectors). In summary, standards should be chosen so that they specify only the interface between, but not the specific implementation of, particular BCI system components (see Fig. 2).

Several institutions fund standardization processes. In the USA, they include the National Institutes of Health (NIH) [e.g., the National Institute of Child Health and Human Development (NICHD) and its National Center for Medical Rehabilitation Research (NCMRR), and the National Institute for Biomedical Imaging and Bioengineering (NIBIB)]; and; in the European Union, the European Committee for Standardization (CEN).

Successful standards should fulfill particular requirements. They should be based on a common model that can describe most of the applications in the area defined by the standard. Particular components of that standard should be interchangeable and independent (so different versions of each can be used without changes anywhere else in the system). The standard should facilitate interaction among researchers. It should be practical so that it can facilitate diffusion and should not be covered by intellectual property protection such as patents.

Several areas for standardization were also identified: 1) the elements of a BCI that include logical design, software design, and hardware design; 2) BCI terminology (such as dependent/independent BCIs or synchronous/asynchronous BCIs); 3) measurement of BCI performance with metrics such as information transfer rate, mutual information, error rate, and delay/jitter; and 4) definition of a common file format and common test datasets to enhance interaction among different laboratories.

In summary, it was concluded that, at least in some areas of BCI research, technical standards would facilitate progress, and that the BCI community should form a technology standardization committee to drive this process.

V. Future Trends

The goal of the last panel was to identify and examine the trends that will govern future BCI research and development. The first trend identified concerned sensor optimization. Several converging developments, such as new sensor types [e.g., near infrared spectroscopy (NIRS) [7], capacitively coupled non-contact electrodes [8], electrocorticography (ECoG)], miniaturization [9] (using BioMEMS [10] and nanotechnology), and biological response control for implanted electrodes (using, for example, drug delivery systems [11]), indicate that it may be possible to create sensors that deliver high signal fidelity, that can provide stable long-term recordings, and that are also clinically safe.

The second trend identified was the continually improving performance of BCI hardware components and BCI systems. Hardware is expected to continue getting smaller with yet increased computational power, and to require less power despite this increase in performance. BCI systems are expected to follow a general trend towards pervasive computing [12], i.e., that they become increasingly incorporated in people's daily lives and that they will increasingly incorporate intelligent user interfaces that may exhibit context-sensitive behavior.

The third trend was the greater social acceptance of BCI use as a result of increased clinical use, improvements in ease-of-use, and increasingly unobtrusive appearance of BCI systems, as well as the attention of the mass media.

The fourth trend identified was the growing consensus that BCI research is a highly interdisciplinary field. As a result, interdisciplinary collaborations are required for success in BCI research and development. Input is needed from clinical, engineering, neuroscience, psychology, and other fields. Intergroup and interdisciplinary collaborations are required for further progress in BCI development.

In summary, this last panel concluded that the performance of current BCIs and the identified trends for the future indicate that BCI systems are well on their way toward actually improving peoples' lives.

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BCI Meeting 2005—Workshop on Clinical Issues and Applications

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***Abstract*—This paper describes the outcome of discussions held during the Third International BCI Meeting at a workshop charged with reviewing and evaluating the current state of and issues relevant to brain–computer interface (BCI) clinical applications. These include potential BCI users, applications, validation, getting BCIs to users, role of government and industry, plasticity, and ethics.**

***Index Terms*—Application, brain–computer interface (BCI), ethics.**

I. Introduction

Consideration of clinical requirements and issues is crucial to the successful implementation of the brain–computer interfaces (BCIs) currently under development in laboratories throughout the world that may enable people with severe physical disabilities to communicate, to operate robotic prostheses, and even to operate wheelchairs using signals recorded from the brain [1]. The aim of this workshop, which was held at the Third International BCI Meeting, was to discuss issues critical for implementation and validation of BCI applications, to review and evaluate the issues that affect clinical use of BCIs, and to describe the needs of patients who could benefit from this technology. The sessions were chaired by Dr. Donoghue and Dr. Kübler and included a diverse mix of participants including: rehabilitation clinicians (neurologists, physiatrists); psychologists; engineers; neuroscientists; industry representatives. Seven major topics were considered: potential BCI users, applications, validation, plasticity, getting BCIs to users, role of government and industry, and ethics. These are discussed in Sections II–VIII.

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II. Potential BCI Users

The overarching goal of brain–computer interface (BCI) research is to develop technologies that will benefit people with disabilities, to improve their independence and ability to direct their daily activities, and potentially to restore lost function [2]–[4]. As with any nascent technology, it is important to identify initial target populations for BCI systems. The form of a desired BCI may depend on a number of factors related to the user's physical condition and requirements, as well as to the user's individual preference [1].

Potential beneficiaries of assistive or rehabilitative BCI technology can be classified either by disease, injury, or functional impairment. Diseases can be broadly divided into two categories: progressive and nonprogressive. Progressive conditions include neuromuscular diseases (e.g., amyotrophic lateral sclerosis (ALS) and muscular dystrophy) in which muscle use is typically lost over time, potentially leading to a full loss of movement capability ("locked-in" condition), whereas nonprogressive conditions include stroke, traumatic brain injury, spinal cord injury, and amputation [5]–[10]. Functional impairments include partial or total paralysis and communication impairment which may also entail varying abilities to process sensory feedback. The needs of these different groups of potential users may differ profoundly; and for those with progressive disorders they may change substantially over time. Thus, it seems most effective to focus on addressing the level of functional loss rather than targeting particular diseases.

III. Applications

Since a BCI is a device that translates signals from the brain and transforms them into a useful output with no use of muscles, the most obvious applications involve those that provide assistive technology that enable movements or communication in order to improve the quality of everyday life for severely disabled people [11]–[14]. Although there appears to be a lack of documented information about what the desired applications within the community of potential users are, the most obvious applications appear to be those that restore communication (e.g., word-processing or restoring speech capabilities); those that restore some form of mobility (e.g., maneuvering wheelchairs); those that use environmental controls (e.g., thermostats, television, power beds); those that replace or restore motor control (such as robots or prosthetics); and those that restore self-feeding and grooming.

Although the BCI research community has not yet established agreed-upon priorities for these various assistive technologies, most current BCI research and development efforts focus on restoring or maintaining communication [3], [15], [16].

Within the BCI community, there is also the intention to develop systems that can restore or replicate movement. The most desired outcome would be reanimating a paralyzed limb [17], but, short of that, brain-controlled prostheses that attach to a limb or brain-controlled robotic prostheses that act as a proxy for a paralyzed limb are also desirable [18].

In addition to assistive technologies, BCIs may also have value in neurorehabilitation of severely disabled people by reinforcing use of damaged or diseased neural pathways [19], [20]. For example, such applications would include those that use a stroke survivor's brain signals to move a virtual arm, which may eventually lead to increased ability to move a real arm [21]. Biofeedback in the form of auditory and visual