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BCI-for-Communication-and-Control

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***Abstract*- Advances in cognitive neuroscience and brain imaging technologies have started to provide us with the ability to interface directly with the human brain. This ability is made possible through the use of sensors that can monitor some of the physical processes that occur within the brain that correspond with certain forms of thought. Researchers have used these technologies to build brain-computer interfaces (BCIs), communication systems that do not depend on the brain's normal output pathways of peripheral nerves and muscles. In these systems, users explicitly manipulate their brain activity instead of using motor movements to produce signals that can be used to control computers or communication devices. Human-Computer Interaction (HCI) researchers explore possibilities that allow computers to use as many sensory channels as possible. Additionally, researchers have started to consider implicit forms of input, that is, input that is not explicitly performed to direct a computer to do something. Researchers attempt to infer information about user state and intent by observing their physiology, behaviour, or the environment in which they operate. Using this information, systems can dynamically adapt themselves in order to support the user in the task at hand. BCIs are now mature enough that HCI researchers must add them to their tool belt when designing novel input techniques. In this introductory chapter to the book we present the novice reader with an overview of relevant aspects of BCI and HCI, so that hopefully they are inspired by the opportunities that remain.**

***Index Terms*- EEG, Brain-Computer Interface, Human-Computer Interaction, Pervasive Computing, Augmented Brain-Computer Interface, ABCI, Opportunistic BCI, Opportunistic State Detection**

I. INTRODUCTION

Any natural form of communication or control requires peripheral nerves and muscles. The process begins with the user's intent. This intent triggers a complex process in which certain brain areas are activated, and hence signals are sent via the peripheral nervous system (specifically, the motor pathways) to the corresponding muscles, which in turn perform the movement necessary for the communication or control task. The activity resulting from this process is often called motor output or efferent output. Efferent means conveying impulses from the central to the peripheral nervous system and further to an effector (muscle). Afferent, in contrast, describes communication in the other direction, from the sensory receptors to the central nervous system. For motion control, the motor (efferent) pathway is essential. The sensory (afferent) pathway is particularly important for learning motor skills and dexterous tasks, such as typing or playing a musical instrument. A BCI offers an alternative to natural communication and control. A BCI is an artificial system that bypasses the body's normal efferent pathways, which are the neuromuscular output channels. A BCI must have four components. It must record activity directly from the brain (invasively or non-invasively). It must provide feedback to the user, and must do so in realtime. Finally, the system must rely on intentional control. That is, the user must choose to perform a mental task whenever she/he wants to accomplish a goal with the BCI. Over the past five years, the volume and pace of BCI research have grown rapidly. In 1995 there were no more than six active BCI research groups, now there are more than 20. They are focusing on brain electrical activity, recorded from the scalp as electroencephalographic activity (EEG) or from within the brain as single-unit activity, as the basis for this new communication and control technology.

A. Modules Of BCI

a. Source Module

The source module digitizes and stores brain signals and passes them on without any further pre-processing to signal processing. It consists of a data acquisition and a data storage component. Data storage stores the acquired brain signal samples along with all relevant system in a data file. The documented file format consists of an ASCII header, followed by binary signal sample, and event marker values.

b. Signal Processing Module

The signal processing module converts signals from the brain into signals that control an output device. This conversion has two stages: feature extraction and feature translation. In the first stage, the digitized signal received from the sourcemodule is subjected to procedures that extract signal features (e.g., firing rate of a cortical neuron etc.). In the second stage, a translation algorithm translates these signal features into control signals that are sent to the user application module. Each of the two stages of signal processing consists of a cascade of signal operators, each of which transforms an input signal into an output signal.

c. User Application Module

The user application module receives control signals from signal processing and uses them to drive an application. In most present-day BCIs, the user application is presented visually on a computer screen and consists of the selection of targets, letters, or icons. User feedback could also be auditory or haptic. Selection is indicated in various ways. Some BCIs also give interim output, such as cursor movement toward the item prior to its selection. Each of these applications could be realized with BCI2000.

d. Operator Module

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

II. BRAIN-COMPUTERS INTERFACE: ESSENTIAL FEATURES

A BCI is a device that can decode human intent from brain activity alone to create an alternate communication channel for people with severe motor impairments. More explicitly, a BCI does not require the "brain's normal output pathways of peripheral nerves and muscles" to facilitate interaction with one's environment. A real-world example would entail a quadriplegic person controlling a cursor on a screen with signals derived from individual neurons recorded in primary motor cortex (M1) without the need for overt motor activity. It is important to emphasize this point: a true BCI creates a completely new output pathway for the brain.

As a new output pathway, the user must have feedback to improve how they alter their electrophysiological signals. Similar to the development of a new motor skill (for example, learning to play tennis), there must be continuous alteration of a person's neuronal output. The output should be matched against feedback from the intended actions such that the person's output (swinging a tennis racket or altering a brain signal) can be tuned to optimize his or her performance toward the intended goal (getting the ball over the net or moving a cursor toward a target). Thus, the brain must change its signals to improve performance, but the BCI may also be able to adapt to the changing milieu of the user's brain to further optimize functioning. This dual adaptation requires a certain level of training and a learning curve—both for the user and the computer. The better the computer and the user are able to adapt, the shorter the training required for control.

There are 4 essential elements to the practical functioning of a BCI platform

1) Signal acquisition, the BCI system's recorded brain signal or information input;

2) Signal processing, the conversion of raw information into a useful device command.

3) Device output, the overt command or control functions administered by the BCI system.

4) Operating protocol, the manner in which the system is altered and turned on and off. All of these elements act in concert to manifest the user's intention to his or her environment.

Signal acquisition is some real-time measurement of the electrophysiological state of the brain. This measurement of brain activity is usually recorded via electrodes. These electrodes can be either invasive or noninvasive. The most common types of signals include EEG, electrical brain activity recorded from the scalp; ECoG, electrical brain activity recorded beneath the skull; field potentials, electrodes monitoring brain activity from within the parenchyma; and "single units," microelectrodes monitoring individual neuron action potential firing.

In the signal-processing portion of the BCI operation, there are 2 essential functions: feature extraction and signal translation. The first function extracts significant identifiable information from the gross signal; the second converts that identifiable information into device commands. The process of converting raw signal into one that is meaningful requires a complex array of analyses. These techniques can vary from the assessment of frequency power spectra, event-related potentials, and cross-correlation coefficients for analysis of EEG and/or ECoG signals to directional cosine tuning of individual neuron action potentials. The impetus for these methods is to determine the relationship between an electrophysiological event and a given cognitive or motor task. For example, after recordings are made from an ECoG signal, the BCI system must recognize that a signal alteration has occurred in the electrical rhythm (feature extraction) and then associates that change with a specific cursor movement (translation). As mentioned above, it is important for the signal processing to be dynamic such that it can adjust to the changing internal signal environment of the user. In terms of the actual device output, this overt action is accomplished by the BCI. As in the previous example, this action can result in moving a cursor on a screen; other possibilities are choosing letters for communication, controlling a robotic arm, driving a wheelchair, or controlling some other intrinsic physiological process such as moving one’s own limb or controlling the bowel and bladder sphincters.

An important consideration for practical applications is the overall operating protocol, which refers to the manner in which the user controls how the system functions. The “how” includes such things as turning the system on or off, controlling what kind of feedback is provided and how fast, the speed with which the system implements commands, and switching between various device outputs. These elements are critical for BCI functioning in the real world application of these devices. In most current research protocols, the investigator sets these parameters; in other words, the researcher turns the system on and off, adjusts the speed of interaction, and defines very limited goals and tasks. The user must be able to do all of these things by her- or himself in an unstructured applied environment.

III. Brain Imaging Technologies

There are two general classes of brain imaging technologies: invasive technologies,in which sensors are implanted directly on or in the brain, and non-invasive technologies, which measure brain activity using external sensors. Although invasive technologies provide high temporal and spatial resolution, they usually cover only very small regions of the brain. Additionally, these techniques require surgical procedures that often lead to medical complications as the body adapts, or does not adapt, to the implants. Furthermore, once implanted, these technologies cannot be moved to measure different regions of the brain.While many researchers are experimenting with such implants (e.g. Lal et al. 2004), we will not review this research in detail as we believe these techniques are unsuitable for human-computer interaction work and general consumer use. We summarize and compare the many non-invasive technologies that use only external .While the list may seem lengthy, only Electroencephalography (EEG) and Functional Near Infrared Spectroscopy (fNIRS) present the opportunity for inexpensive, portable, and safe devices, properties we believe are important for brain-computer interface applications in HCI work.

A. Electroencephalography (EEG)

EEG uses electrodes placed directly on the scalp to measure the weak (5–100 μV) electrical potentials generated by activity in the brain (for a detailed discussion of EEG, see Smith 2004). Because of the fluid, bone, and skin that separate the electrodes from the actual electrical activity, signals tend to be smoothed and rather noisy. Hence, while EEG measurements have good temporal resolution with delays in the tens of milliseconds, spatial resolution tends to be poor, ranging about 2–3 cm accuracy at best, but usually worse. Two centimeters on the cerebral cortex could be the difference between inferring that the user is listening to music when they are in fact moving their hands. We should note that this is the predominant technology in BCI work, as well as work described in this book.

B. Functional Near Infrared Spectroscopy (fNIRS)

fNIRS technology, on the other hand, works by projecting near infrared light into the brain from the surface of the scalp and measuring optical changes at various wavelengths as the light is reflected back out (for a detailed discussion of fNIRS, see Coyle et al. 2004). The NIR response of the brain measures cerebral hemodynamics and detects localized blood volume and oxygenation changes (Chance et al. 1998).Since changes in tissue oxygenation associated with brain activity modulate the absorption and scattering of the near infrared light photons to varying amounts, fNIRS can be used to build functional maps of brain activity. This generates images similar to those produced by traditional Functional Magnetic

Resonance Imaging (fMRI) measurement. Much like fMRI, images have relatively high spatial resolution(<1 cm) at the expense of lower temporal resolution (>2–5 seconds), limited by the time required for blood to flow into the region.In brain-computer interface research aimed at directly controlling computers, temporal resolution is of utmost importance, since users have to adapt their brain activity based on immediate feedback provided by the system. For instance, it would be difficult to control a cursor without having interactive input rates. Hence, even though the low spatial resolution of these devices leads to low information transfer rate and poor localization of brain activity, most researchers currently adopt EEG because of the high temporal resolution it offers. However, in more recent attempts to use brain sensing technologies to passively measure user state, good functional localization is crucial for modeling the users' cognitive activities as accurately as possible. The two technologies are nicely complementary and researchers must carefully select the right tool for their particular work. We also believe that there are opportunities for combining various modalities, though this is currently underexplored.

IV. Applications Of Bci Technology

A. *Beyond Medical Applications*

- **Device control-** Research on BCIs to assist users lacking full limb development has matured to the point that such users are already benefiting, even though the devices offer limited speed, accuracy, and efficiency.

  Nonmedical device control is more problematic. Users with full muscular control cannot benefit as easily because a BCI lacks the bandwidth and accuracy to compete with a standard input device, such as a mouse or keyboard. Introducing a shared control scheme would enable the user to give high-level, open-loop commands while the device takes care of low-level control.

  Additional control channels or hands-free control could benefit users such as drivers, divers, and astronauts, who must keep their hands on controls to operate equipment. Brain-based control paradigms could supplement other forms of hands-free control, such as a voice command or eye movement.

- **User-state monitoring-** Future interfaces must be able to understand and anticipate the user's state and intentions. Automobiles could alert sleepy drivers, or virtual humans could convince users to stick to their diet.

  BCIs might also be useful in neuroscientific research. Because they can monitor the acting brain in real time and in the real world, BCIs could help scientists understand the role of functional networks during behavioral tasks.

- **Evaluation-** Evaluation applications can be either online or offline. The former continuously provide evaluations, in real or near real time; the latter provide evaluations only once, after the experimental study is finished. Neuroergonomics and neuromarketing are two application subareas.

- **Training and education-** Most training aspects relate to the brain and its plasticity - the brain's ability to change, grow, and remap itself. Measuring plasticity can help improve training methods and individual training regimens.

- **Gaming and entertainment-** Over the past few years, companies such as Neurosky, Emotiv, Uncle Milton, MindGames, and Mattel have released numerous products. Most developers are convinced that BCIs will enrich the gaming and entertainment experience in games tailored to the user's affective state - immersion, flow, frustration, surprise, and so on.

- **Cognitive improvement-** A common nonmedical application involving a BCI is neurofeedback training, in which operant conditioning alters brain activity to improve attention, working memory, and executive functions.

  The line between medical and nonmedical neurofeedback applications is likely to be thin, but a nonmedical application might be the optimized presentation of learning content.

- **Safety and security-** Safety and security EEG alone or combined EEG and eye movement data from expert observers could support the detection of deviant behavior and suspicious objects. Also, image inspection might be faster than is possible with current methods.

V. The Future Of BCIs: Problems And Prospects

Brain-computer interface research and development generates tremendous excitement in scientists, engineers, clinicians, and the general public. This excitement reflects the rich promise of BCIs. They may eventually be used routinely to replace or restore useful function for people severely disabled by neuromuscular disorders; they might also improve rehabilitation for people with strokes, head trauma, and other disorders.

At the same time, this exciting future can come about only if BCI researchers and developers engage and solve problems in 3 critical areas: signal-acquisition hardware, BCI validation and dissemination, and reliability.

A. Signal-Acquisition Hardware

All BCI systems depend on the sensors and associated hardware that acquire the brain signals. Improvements in this hardware are critical to the future of BCIs. Ideally, EEG-based (noninvasive) BCIs should have electrodes that do not require skin abrasion or conductive gel (ie, so-called dry electrodes); be small and fully portable; have comfortable, convenient, and cosmetically acceptable mountings; be easy to set up; function for many hours without maintenance; perform well in all environments; operate by telemetry instead of requiring wiring; and interface easily with a wide range of applications. In principle, many of these needs could be met with current technology, and dry electrode options are beginning to become available (eg, from g.tec Medical Engineering, Schiedlberg, Austria). The achievement of good performance in all environments may prove to be the most difficult requirement.

Brain-computer interfaces that use implanted electrodes face a range of complex issues. These systems need hardware that is safe and fully implantable; remains intact, functional, and reliable for decades; records stable signals over many years; conveys the recorded signals by telemetry; can be recharged in situ (or has batteries that last for years or decades); has external elements that are robust, comfortable, convenient, and unobtrusive; and interfaces easily with high-performance applications. Although great strides have been made in recent years and in individual cases microelectrode implants have continued to function over years, it is not clear which solutions will be most successful. ECoG- or local field potential-based BCIs might provide more consistently stable performance than BCIs that rely on neuronal action potentials. Nevertheless, it is possible that major as yet undefined innovations in sensor technology will be required for invasive BCIs to realize their full promise. Much of the necessary research will continue to rely primarily on animal studies before the initiation of human trials.

B. Validation and Dissemination

As work progresses and BCIs begin to enter actual clinical use, 2 important questions arise: how good a given BCI can get (eg, how capable and reliable) and which BCIs are best for which purposes. To answer the first question, each promising BCI should be optimized and the limits on users' capabilities with it should be defined. Addressing the second question will require consensus among research groups in regard to which applications should be used for comparing BCIs and how performance should be assessed. The most obvious example is the question of whether the performance of BCIs that use intracortical signals is greatly superior to that of BCIs that use ECoG signals, or even EEG signals. For many prospective users, invasive BCIs will need to provide much better performance to be preferable to noninvasive BCIs. It is not yet certain that they can do so. The data to date do not give a clear answer to this key question.126 On the one hand, it may turn out that noninvasive EEG- or fNIR-based BCIs are used primarily for basic communication, while ECoG- or neuron-based BCIs are used for complex movement control. On the other hand, noninvasive BCIs may prove nearly or equally capable of such complex uses, while invasive BCIs that are fully implantable (and thus very convenient to use) might be preferred by some people even for basic communication purposes. At this point, many different outcomes are possible, and the studies and discussions necessary to select among them have just begun.

The development of BCIs for people with disabilities requires clear validation of their real-life value in terms of efficacy, practicality (including cost-effectiveness), and impact on quality of life. This depends on multidisciplinary groups able and willing to undertake lengthy studies of real-life use in complicated and often difficult environments.

Current BCIs, with their limited capabilities, are potentially useful mainly for people with very severe disabilities. Because this user population is relatively small, these BCIs are essentially an orphan technology: there is not yet adequate incentive for commercial interests to produce them or to promote their widespread dissemination. Invasive BCIs entail substantial costs for initial implantation, plus the cost of ongoing technical support. Although the initial costs of noninvasive BCI systems are relatively modest (eg, $5,000-$10,000), they too require some measure of ongoing technical support.

Clear evidence that BCIs can improve motor rehabilitation could greatly increase the potential user population. In any case, if and when further work improves functionality of BCIs and renders them commercially attractive, their dissemination will require viable business models that give both financial incentive for the commercial company and adequate reimbursement to the clinical and technical personnel who will deploy and support the BCIs. The optimal scenario could be one in which BCIs for people with severe disabilities develop synergistically with BCIs for the general population.

C. Reliability

Although the future of BCI technology certainly depends on improvements in signal acquisition and on clear validation studies and viable dissemination models, these issues pale next to those associated with the problem of reliability. In all hands, no matter the recording method, the signal type, or the signal-processing algorithm, BCI reliability for all but the simplest applications remains poor. Brain-computer interfaces suitable for real-life use must be as reliable as natural muscle-based actions. Without major improvements, the real-life usefulness of BCIs will, at best, remain limited to only the most basic communication functions for those with the most severe disabilities.

Solving this problem depends on recognizing and engaging 3 fundamental issues: the central role of adaptive interactions in BCI operation; the desirability of designing BCIs that imitate the distributed functioning of the normal CNS; and the importance of incorporating additional brain signals and providing additional sensory feedback.

Brain-computer interfaces allow the CNS to acquire new skills in which brain signals take the place of the spinal motor neurons that produce natural muscle-based skills. Muscle-based skills depend for their acquisition and long-term maintenance on continual activity-dependent plasticity throughout the CNS, from the cortex to the spinal cord. This plasticity, which generally requires practice over months or years, enables babies to walk and talk; children to learn reading, writing, and arithmetic; and adults to acquire athletic and intellectual skills.

The acquisition and maintenance of BCI-based skills like reliable multidimensional movement control require comparable plasticity (eg, as described by various investigators. Brain-computer interface operation rests on the effective interaction of 2 adaptive controllers, the CNS and the BCI. The BCI must adapt so that its outputs correspond to the user's intent. At the same time, the BCI should encourage and facilitate CNS plasticity that improves the precision and reliability with which the brain signals encode the user's intent. In sum, the BCI and CNS must work together to acquire and maintain a reliable partnership under all circumstances. The work needed to achieve this partnership has just begun. It involves fundamental neuroscientific questions and may yield important insights into CNS function in general.

Brain-computer interface performance is also likely to benefit from distributed control. For BCIs, the distribution would be between the BCI's output commands (ie, the user's intent) and the application device that receives the commands and converts them into action. The optimal distribution will presumably vary from BCI to BCI and from application to application. Realization of reliable BCI performance may be facilitated by incorporating into the application itself as much control as is consistent with the action to be produced, just as the distribution of control within the CNS normally adapts to suit each neuromuscular action.

The natural muscle-based outputs of the CNS reflect the combined contributions of many brain areas from the cortex to the spinal cord. This suggests that BCI performance might be improved and maintained by using signals from multiple brain areas and by using brain signal features that reflect relationships among areas (eg, coherences). By allowing the CNS to function more as it does in producing muscle-based skills, this approach could improve BCI reliability.

Using signals from multiple cortical and/or subcortical areas might also resolve another obstacle to fully practical BCIs. In current BCIs, the BCI rather than the user typically determines when output is produced. Ideally, BCIs should be self-paced, so that the BCI is always available and the user's brain signals alone control when BCI output is produced. Brain-computer interfaces that use signals from multiple areas are more likely to be sensitive to the current context and thus may be better able to recognize when their output is or is not appropriate.

Finally, current BCIs provide mainly visual feedback, which is relatively slow and often imprecise. In contrast, natural muscle-based skills rely on numerous kinds of sensory input (eg, proprioceptive, cutaneous, visual, auditory). Brain-computer interfaces that control applications involving high-speed complex movements (eg, limb movement) are likely to benefit from sensory feedback that is faster and more precise than vision. Efforts to provide such feedback via stimulators in cortex or elsewhere have begun. The optimal methods will presumably vary with the BCI, the application, and the user's disability (eg, peripheral inputs may often be ineffective in people with spinal cord injuries).

VI. CONCLUSION

A BCI allows a person to communicate with or control the external world without using the brain's normal output pathways of peripheral nerves and muscles. Messages and commands are expressed not by muscle contractions but rather by electrophysiological phenomena such as evoked or spontaneous EEG features (e.g. SCPs, P300, mu/beta rhythms) or cortical neuronal activity. BCI operation depends on the interaction of two adaptive controllers, the user, who must maintain close correlation between his or her intent and these phenomena, and the BCI, which must translate the phenomena into device commands that accomplish the user's intent. Present-day BCIs have maximum information transfer rates #25 bits/min. With this capacity, they can provide basic communication and control functions (e.g. environmental controls, simple word processing) to those with the most severe neuromuscular disabilities, such as those locked in by late-stage ALS or brainstem stroke. They might also control a neuroprosthesis that provides hand grasp to those with mid-level cervical spinal cord injuries. More complex applications useful to a larger population of users depend on achievement of greater speed and accuracy, that is, higher information transfer rates. Future progress hinges on attention to a number of crucial factors. These include: recognition that BCI development is an interdisciplinary problem, involving neurobiology, psychology, engineering, mathematics, computer science, and clinical rehabilitation; identification of the signal features, whether evoked potentials, spontaneous rhythms, or neuronal firing rates, that users are best able to control; the extent to which this control can be independent of activity in conventional motor output and sensory input channels; the extent to which this control depends on normal brain function; identification of the best feature extraction methods and the best algorithms for translating these features into device control commands; development of methods for maximizing each user's control of these signal features; attention to the identification and elimination of artifacts such as EMG and EOG activity; adoption of precise and objective procedures for evaluating BCI performance; recognition of the need for long-term as well as short-term assessment of performance; identification of appropriate applications; proper matching of BCI applications and users; close attention to factors that determine user acceptance of augmentative technology; and emphasis on peer reviewed publications and appropriately conservative response to media attention. With adequate recognition and effective engagement of these issues, BCI systems could provide an important new communication and control option for those with disabilities that impair normal communication and control channels. They might also provide to those without disabilities a supplementary control channel or a control channel useful in special circumstances.

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