The I of BCIs: Next Generation Interfaces for Brain–Computer Interface Systems That Adapt to Individual Users

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Abstract. Brain-computer interfaces (BCIs) have advanced rapidly in the last several years, and can now provide many useful command and control features to a wide variety of users--if an expert is available to find, assemble, setup, configure, and maintain the BCI. Developing BCI systems that are practical for non-experts remains a major challenge, and is the principal focus of the EU BRAIN project and other work. This paper describes five challenges in BCI interface development, and how they might be addressed with a hypothetical easy BCI system called EZBCI. EZBCI requires a new interface that is natural, intuitive, and easy to configure without expert help. Finally, two true scenarios with severely disabled users highlight the impact that EZBCI would have on users' lives.

Keywords: Brain-computer interface; Brain-machine interface; BCI; BMI; expertise; nonexpert; interface; adaptive; reliability; usability; flexibility; assistive technology; smart homes; realworld; EZBCI.

1 Recent Progress and Emerging Challenges

The principal goal of brain–computer interface (BCI) research has been providing communication to persons with motor disabilities so severe that they prevent communication through other means. Hence, the main focus of many research groups has been addressing fundamental challenges, such as getting a BCI to work at all [1], [2], [3], getting it to work outside of the laboratory [4], [5], [6], or getting it to work with patients [7], [8]. Indeed, the very theme of the second international BCI conference in 2002 was "Moving Beyond Demonstrations."

Helping patients should and will remain very important. Due to the success of BCI research so far, however, the most helpful research directions are changing. It is no longer so impressive to demonstrate that a simple BCI might allow one specific function, most of the time, for some patients, as long as a PhD student from the local BCI research lab can find, assemble, customize, and maintain the BCI system. The goal of proving that a BCI can provide a function to a user has been attained; the next challenge is getting any BCI to reliably provide any function for any user.

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The reader is assumed to have a basic familiarity with BCIs; reviews can be found elsewhere [9], [10], [11]. Recent developments include:

Different BCI approaches have been further investigated with severely disabled users in home and other real world environments [12], [13], [14], [15], [16].

Crucial parameters have been identified and explored [17], [18], [19], [20], [21], [22], [23], [24].

New BCI applications have been validated, such as control of a robotic arm [24], [25], neural prosthesis [6], [26], mobile humanoid robot [27], Smart home [28], and virtual [15] or real [29], [30] wheelchair;

BCIs have proven useful as communication systems for broader user groups than previously recognized [14], [31], [32].

BCI have been explored as tools for rehabilitation of stroke, psychopathy, autism, addiction, and attentional disorders [9], [33], [34], [35], [36], [37].

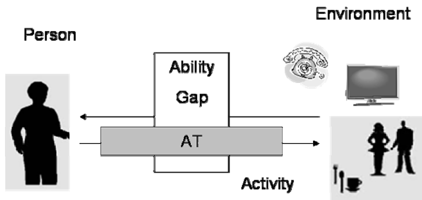
New software tools within the BCI2000 framework have greatly reduced the time and inconvenience of developing and using new BCI applications [38].

The promising possibility of combining multiple BCIs has begun to be addressed [9], [31], [32], [39], [40].

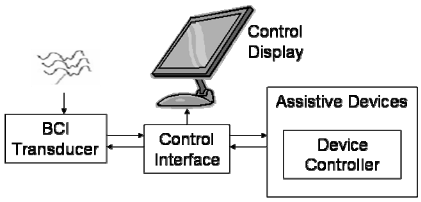
More realistic, immersive interfaces have been used with different BCI systems [3], [15], [41]. Leeb and colleagues compared an immersive VR environment to a conventional, mundane setting and found that the VR environment yielded reduced training time, fewer errors, and more motivated and happy subjects.

Despite this piecemeal progress, BCI systems are still predominantly inflexible, difficult to use, unreliable, and unavailable to nearly all people who need them. They are seen primarily as research tools with limited practical function that might only be useful to some people with very severe physical disabilities. BCIs are typically accessible only via research laboratories that are seeking research subjects, and expert assistance is necessary for initial configuration, daily operation, maintenance, and updating. BCIs would be far more practical to much larger populations if they could easily identify and adapt to the needs, desires, and abilities of each individual user and operate effectively each day with little or no oversight. That is, what users need most are not additional laboratory studies or offline simulations, but working BCIs--ideally suited to each user--that operate reliably in home environments with minimal support.

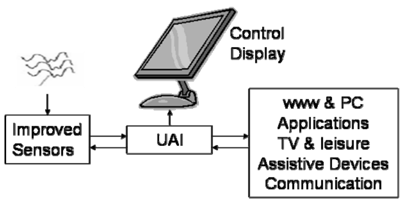
Figure 1 below highlights the challenges and potential solutions inherent in developing a BCI system that is practical for nonexperts. The term “EZBCI” is hereby introduced to describe this hypothetical easy BCI system. Panel A shows an individual who wishes to interact with the environment. The person can receive information from the environment, but is not able to reciprocate or control the environment. Assistive Technology (AT) tries to bridge this ability gap by restoring the ability to send messages or commands. Panel B shows how modern BCI systems bridge this gap. The user’s EEG activity is translated into signals that might control a monitor or device. These systems only exist in laboratories, require expert assistance, and allow control of only individual devices. Panel C shows how EZBCI will address the need for a practical BCI that can control many applications.



a) The ability gap that AT tries to address.



b) Emerging BCI solution in laboratories.



c) Desired solution in an EZBCI system.

Fig. 1. Panel A shows the ability gap facing many users that assistive technology addresses. Panels B and C show how conventional BCIs and a hypothetical EZBCI system bridge this gap. The acronym "UAI" refers to the Universal Application Interface, discussed in the text. This figure is adapted from [42], which itself adapted a figure from [43].

Figure 2 below presents a more detailed representation of how EZBCI must address four accessibility gaps in modern BCIs. The panel on the left presents the current accessibility of BCI components. Four accessibility gaps are represented by the image of the scientist wearing the ubiquitous white lab coat. These reflect tasks that currently require expert assistance. The leftmost gap reflects the need for a trained caretaker to prepare the subject for each session of BCI use. An expert must also identify and purchase the correct equipment. The second accessibility gap is signal processing: an expert is needed to configure relevant parameters. The third accessibility gap is applications: even with expert help, users can only use the application developed by a local research group. The fourth accessibility gap, in operating protocol, has two components. First, users do not have any choice of mental strategy, and second, expert help is required to provide even limited customization of stimulus parameters. The third and fourth gaps have question marks to reflect that, even with expert help, very few applications and operating protocols are available.

The panel on the right depicts accessibility after EZBCI is developed. The first accessibility gap requires a much easier setup process. The necessary equipment must be easy to purchase from established European manufacturers without expert help. Instead, an untrained caretaker could apply the cap to users with severe disabilities, and other users could setup the system without help. The second accessibility gap requires providing software that identifies and implements the correct parameters and enables improved performance even in noisy or unstable settings. The third and fourth accessibility gaps are addressed through the Intuitive Universal Interface (IUI) discussed in more detail below.

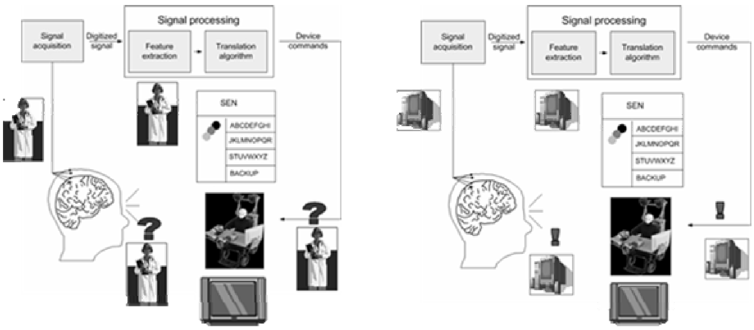


Fig. 2. BCIs today and tomorrow. The left panel shows the four accessibility gaps that currently impair BCI accessibility, and the right panel shows how this would change with the development of a practical BCI system such as the hypothetical EZBCI.

Two recently funded projects within the EU aim to improve BCIs by addressing these challenges. The TOBI (Tools for Brain-Computer Interaction) project, developed by Jose Millán and colleagues across twelve institutions, has identified four application areas where BCI assistive technology can make a real impact for people with motor disabilities:

Communication & Control

Motor Substitution

Entertainment

Motor Recovery

The BRAIN (BCIs with Rapid Automated Interfaces for Nonexperts) project, developed by the author and colleagues in seven institutions, has three RTD goals:

New sensor systems to detect brain activity without requiring electrode gel

Automated software to determine the best signal processing parameters and BCI approach for each user

An Intuitive User Interface (IUI) that allows users to easily switch between applications

BRAIN and TOBI are only two examples of projects aimed at developing better interfaces or other components for BCIs. The text, ideas, and figures used here are meant to present major challenges in BCI research rather than issues specific to any grant proposal or research team. The author and colleagues hope that this article and associated discussion provide new contacts, ideas, and collaborations.

While improved sensors, signal processing tools, and rehabilitation are important, this article focuses primarily on issues relating to the interface component of BCIs. There has been relatively little attention to HCI issues within BCI research, especially during early BCI research efforts, since attention was focused on simply getting a BCI to work. The work that has been done has focused on issues like the role of feedback or the timing of stimulus presentation [3], [44], [45]. Important questions (and hence challenges) within BCI interface development remain:

1. How can a single integrated BCI system allow users to control a variety of applications and smoothly switch between them?

Modern BCIs allow users to spell, control a robot, move a mouse, or other tasks, but not switch between them. A BCI designed for web browsing may be of little value to a disabled user who wants to move a wheelchair, pour a drink, adjust her bed, or play music. It is increasingly easy to develop interfaces that allow a myriad of devices to control almost any application. For example, protocols such as X10, Zigbee, or UPnP are often used to allow people to control smart home devices through conventional or assistive communication systems [46].

2. Can interfaces be designed that accept input from different BCI approaches? For example, could an interface designed for an ERD BCI accept input from an SSVEP BCI? What if the user wishes to use more than one approach to control an interface, which is possible in a “hybrid” BCI system [9], [31]?

Although BCI2000 can allow different types of BCI approaches to control the same application, this opportunity has been mostly ignored. Only one study has even compared different BCI approaches within users, and this work used different interfaces [10]. A Universal Remote Control (URC) system or Windows driver need not even know what type of BCI produces an input signal.

3. How can BCI interfaces adapt to the needs, abilities, desires, and usage histories of individual users?

Ideally, BCIs should be adjustable via three means. First, BCIs should try to learn what’s best for each user and adapt accordingly. Second, BCIs should allow users to manually configure the system as desired. Third, it should also be easy for friends, family, carers, or other third persons to make adjustments based on user requests.

4. How can BCIs incorporate HCI concepts designed around low bandwidth input?

One article proposed combining a BCI with DASHER [47], but did not do so. The Hex-O-Spell BCI system developed by the Berlin group [48] is an excellent but rare example of a novel and straightforward interface developed specifically for BCIs. Automated error correction is another technology that has only begun to be explored with BCIs [49], [50]. No BCIs work with the T9 text entry system, advanced word or sentence completion (such as in the WordsPlus software system developed with eye trackers), or other potentially helpful HCI innovations. Again, some of this functionality is possible in BCI2000, but has not been explored.

5. How can BCIs best exploit the graphical user interface (GUI) concept?

Identifying and launching applications or sending specific commands should seem easy and natural. Interfaces should be easy to customize so users can attain goals easily and have the information they need without feeling overwhelmed.

2 Building an Intuitive Universal Interface (IUI) for BCIs

Many companies and research groups have spent tremendous resources over many years to develop conventional operating environments that are straightforward, intuitive, flexible, and easy to learn, use, and customize without expert help. If the five questions above were rephrased around a Windows operating system, considerable progress would be apparent. Users can very easily control different applications and switch between them. Control is possible via a keyboard, mouse, trackball, voice control, or various assistive devices such as an EMG, eye tracker, or sip-and-puff switch. Users can manually customize various parameters and/or allow Windows to adapt to common actions, such as by placing commonly selected applications in the Start menu. Windows offers support for persons using low bandwidth interfaces in various ways. The GUI has come a very long way.

Similar progress is needed within BCI research before BCIs can mature as a practical means of communication--for disabled or healthy users. Figure 3 below presents the IUI, which aims to address these five challenges within BCI systems.

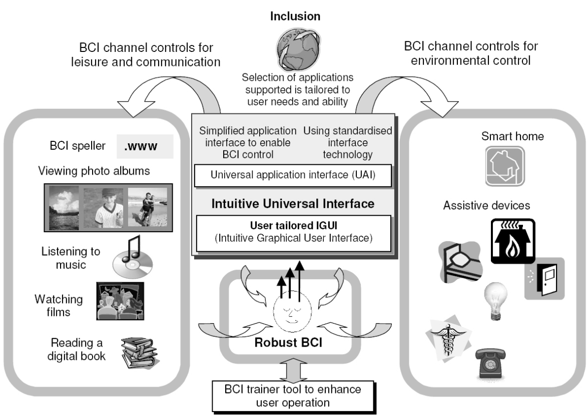


Fig. 3. The Intuitive Universal Interface (IUI) includes a front end called the Intuitive Graphical User Interface (IGUI) and back end called a Universal Application Interface (UAI). Dr. Gaye Lightbody from the University of Ulster developed this figure for the BRAIN grant.

The front end of the IUI is the Intuitive Graphical User Interface (IGUI). The IGUI will include one consistent, familiar display that allows users to perform certain tasks or switch applications. The IGUI will use a flexible architecture and display that adapts itself to each user's abilities, desires, and needs, and/or can be modified by the user. Some users may dislike cluttered displays, while others might prefer displays with information such as the ambient temperature, battery power of medical or other devices, any noisy or bad electrodes, or activity present on security cameras. The IGUI will adapt to each user's abilities by increasing image sizes for those with poor vision, prompting users with memory deficits, providing a BCI trainer if desired, etc.

Addressing these varied user needs requires allowing customization of the applications needed, the sequence of the operations used for control, and the interface. The IUI should support a plug and play type interface and methodology that will support such customization with limited effort and no outside support.

The back end is called the Universal Application Interface (UAI) and will translate the user's requests into meaningful commands to different applications. The UAI will use established wired and wireless interface technologies. By using these well developed standards, the IUI will open up a world of new devices without extensive new development. The IUI must minimize work for the user, who will typically be unfamiliar with BCIs and may present other challenges such as mild dementia, poor computer literacy, poor vision, or limited patience.

The IUI should recognize and integrate relevant context. The IUI, like any good interface, should not allow users to open a window or door that is already open, turn on a light that is already on, move a wheelchair into a wall, launch a movie that is already playing, or navigate toward a clearly erroneous URL. This context awareness requires bidirectional communication between the UAI and other applications.

Unlike prior BCIs, the IUI will accept input from different BCI approaches. A user who has poor SSVEP activity, finds flickering lights annoying, could instead use ERD activity for control. Users could also combine different BCI approaches to improve usability, bandwidth, or accuracy [9].

The IUI will not exist in isolation. On the contrary, progress in related challenges such as improved sensors or signal processing could greatly affect the options available within the IUI. Further, these technologies should be integrated with the IUI, tested across different target user groups, and revised based on their feedback.

3 How the IUI Would Improve Realworld BCI Scenarios

How would the IUI change the BCI usage experience from the user perspective? Consider the status quo along the five challenges above:

1. An expert is required to get even one application working. Adding another application requires expert help, possibly from a different research group. To switch between applications, an expert or trained user must change numerous parameters and re-launch the BCI system.
2. No BCI can accept input from more than one BCI approach, nor a combination of them, nor a combination of BCI and other input.
3. Customizing a BCI interface also requires an expert.
4. BCIs do not use helpful technologies common in other low bandwidth interfaces.
5. Most BCIs have a simple, clunky interface that requires instruction.

Below are two true stories of recent efforts to provide BCIs for patients, followed by hypothetical improvements that could result from EZBCI. Again, emphasis is placed on interface improvements:

Dr. A is in his early 50s and runs a neuroscience research lab. He has late stage ALS, with some remaining gaze control. Experts at the Wolpaw lab developed a P300 speller that the patient has used for about 2-6 hours per day for over two years. The Wolpaw lab gave him the necessary hardware and a license to BCI2000 software. The Wolpaw lab identified the processing parameters, and provides periodic support. Dr. A requires a caretaker to assist with daily electrode cap preparation and cleaning. Although Dr. A can use an eye tracking system, he prefers the BCI because it is easier to use, faster, and produces less fatigue [14].

One day, Dr. A informed the Wolpaw lab that his system was no longer working. An expert was sent to fix the problem. It turned out that Dr. A had unintentionally sent a combination of key strokes that caused the display to shift beyond the range of the monitor. Hence, whenever the system was launched, no display was visible. The expert repaired this problem and the system worked again.

While this is a modern BCI success story, there is much room for improvement. With EZBCI, assistance would still be needed with cap preparation due to the patient's motor disabilities. However, this process would be much faster and easier, and feasible for an untrained career. Software would automatically find the best parameters. The IUI would not allow unwanted functions such as repositioning the display. Dr. A would be able to easily customize his speller, such as by changing the number of items in the display (the BCI's vocabulary), speed or intensity of flashes, or size of the letters. He could incorporate word or sentence completion. He might add new selections to the speller matrix such as commonly spelled phrases, and/or the system could automatically develop and periodically propose such suggestions.

Most importantly, Dr. A. would also be able to control other applications, either with a similar interface or a different IGUI that he could customize. For example, if Dr. A liked the P300 speller, he could have a similar system in which the classic "Donchin matrix" contained not letters or words but commands to a smart home device, wheelchair, or movie player. Or, he could choose a different type of display to control these devices, perhaps with P300 and/or other activity. Some of this functionality is currently available within BCI2000, but only via expert help.

Mr. B was a stockbroker living near Atlanta, Georgia. In March 2005, he was mostly locked in due to ALS and had moderate gaze control. He was very active via a gaze based spelling system called WordsPlus, and traveled to the US Congress and successfully pushed for Medicare changes to aid severely disabled patients. In spring 2005, his gaze control rapidly declined. He contacted Prof. Melody Moore through friends in the local assistive technology community. Prof. Moore and colleagues (including the author) developed an SSVEP BCI system that allowed Mr. B to send about 4 bits per minute via a 1D cursor movement system. This system was used for testing within the lab and could not allow meaningful communication. Work with Mr. B halted when the author left the lab.

The IUI would have allowed Mr. B to perform useful tasks with his BCI, instead of only validating the possibility of future functionality. There were no other fundamental challenges to overcome with Mr. B. He could generate a signal and effect control, but no tools existed to translate those control signals into meaningful outputs. BCI users who can move a cursor in one dimension can select letters or other items from a menu [14], control bed position or make other medical requests [52], control a wheelchair [30], or perform other tasks.

In conclusion, the BCI research community has attained some important early goals, such demonstrating proof of concept and validating BCIs as practical communication tools for patients who need them. Emerging challenges include reducing the demand for expert assistance and improving customizability and flexibility. The proposed suite of next generation BCI interface and application control tools, called IUI, would allow nonexpert users to control a variety of applications via a friendly, intuitive, and adaptive display. The IUI could greatly expand the usability and flexibility of any existing BCI system and thereby help develop BCIs into practical communication and control systems. These interface developments, combined with improvements to other components of BCIs, could move the EZBCI system from a hypothetical proposal to an available, complete communication system for severely disabled users and much broader groups.

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