Interface Design Challenge for Brain-Computer Interaction

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Abstract: Great things can be achieved even with very low bandwidth. Stephen Hawking has been able to break new ground in theoretical physics just by twitching his hand and cheek. Jean-Dominique Bauby was able to write a best-selling memoir by blinking one eyelid. By reading and decoding "brain-waves", the field of brain-computer interfacing (BCI) is poised to open up the possibility of such expression, even for people who can no longer move a single muscle. A BCI still requires an HCI front-end to be of practical use, but many currently-used HCIs do not adequately address limitations on the typical target user's input (e.g., limited eye movement leading to poor spatial vision) or output (e.g. variable delays, and false positives/negatives, in "pressing the button"). In this symposium, BCI experts will present their view of the challenges arising from these limitations. The HCI community is invited to participate in a competition to provide the best solutions.

Keywords: brain-computer interfacing (BCI), electroencephalography (EEG), human-computer interaction (HCI), human factors, spelling, augmentative and alternative communication (AAC), assistive technology, competition

1 Introduction

Brain-computer interfacing (BCI) is a field of research which aims to develop the means for a person to communicate, or to issue a control signal, without using muscles or peripheral nerves [44]. Control signals are instead interpreted directly from activity in the cerebral cortex, measured via surface electrodes on the scalp (EEG), via electrodes implanted inside the skull on or in the cortex, or via some other brain imaging technique. The BCI user's communication or control intentions are then decoded from the signals. Bypassing the peripheral output channels makes the technology attractive as a potential tool for rehabilitation following stroke or brain injury, or for neuroprosthetics that replace lost function: for example for people who have amputated limbs, who have spinal cord injuries, or who are paralyzed as a result of disease [45, 42, 6]. Cases at the most extreme end of this spectrum of disability tend to attract the most attention in BCI: many studies focus on its applicability to people with advanced amyotrophic lateral sclerosis (ALS), a fast-progressing degenerative motor-neuron disease. Within a few years, ALS may lead to a “locked-in” state (LIS) [34] where only a very small number of individual muscles (typically eye muscles) can be moved voluntarily, and it may then progress beyond this to what has been termed the “totally locked-in” state (TLIS) [3, 21], in which no voluntary movement control remains at all (this latter state holds a particular interest for BCI researchers, since alternatives to BCI become unfeasible). In such a condition, restoration of efficient communication with other people and with one’s environment becomes a high priority.

The locked-in state holds a fascination for the research community and the public alike. It is well-known that, with the appropriate method of augmentative and alternative communication (AAC), a surprising amount can be accomplished with low bandwidth. Nobel-prize-winning physicist Stephen Hawking, and best-selling author Jean-Dominique Bauby are two well-known cases in point [2]. BCI promises to go one step further, perhaps by improving further the range expression available to locked-in users, and perhaps by widening the category of people who can make use of AAC, even to include the totally-locked-in.

BCI strategies generally fall into two broad categories: self-actuated BCI and stimulus-driven BCI [24]. In self-actuated BCI, the user chooses when to start, and when to stop, performing a certain mental task or operation. Performing the mental task causes a measurable change in the strength of certain brain signals: usually the power of certain oscillations increases or decreases, at particular frequencies and spatial locations that are dependent on the task and on the individual. A common example is motor imagery: imagining making movements with one’s hand, for example, leads to fluctuations in the power of signals that are measurable from the motor and pre-motor cortical areas of the brain, which can in turn be used as a continuous control signal [25, 33]. By contrast, a stimulus-driven BCI relies on the brain’s response to a particular stimulus, delivered at a time decided by the computer [11, 28]. To use the interface, the user directs his or her attention to the stimulus he or she wishes to select: the BCI then depends on measuring the difference between the brain’s response to relevant, attended stimuli and its response to irrelevant, unattended stimuli. Often the useful responses are in the form of event-related potentials (ERPs) which are brief deflections in the EEG lasting less than a second.

BCIs, whether they are stimulus-driven or self-actuated, elicit signals that have a low signal-to-noise ratio [30]. This effectively limits the communication performance of BCIs [35]. The current state-of-the-art in BCI control is still noisy enough that, generally, the utility of a BCI system to any one given user has not yet surpassed that of the conventional assistive technology available to the same user [4, 35]. The avenues that have tried to address this limitation all entail certain problems. For example, brain-signals recorded closer to the neural source, via invasive neurosurgical techniques [22, 18, 43, 9], are of higher signal-to-noise ratio, but obtaining them entails increased risk and cost [16]. Another avenue is to elicit signals of higher signal-to-noise ratio using better-designed stimuli and tasks [5, 13, 29]. However, these refinements (in common with the original design of the BCIs in question) are optimized specifically to elicit clearer brain signals, and do not explicitly address ease-of-use or obey the demands of conventional human factors. BCI performance may therefore also be limited by the error-prone behavior of the user in attempting to deal with a poorly-designed HCI in noisy conditions [27]. As an alternative to these approaches, BCIs might stand to improve their utility by improving the usability of their HCI front-ends.

2 Example: ERP-based spelling

The most widely-explored paradigm for BCI spelling is the stimulus-driven Donchin matrix speller [11, 10]. Letters are arranged in a grid on screen, and a subset of the letters (usually one row or one column) is highlighted at any one time. During a sequence of such highlighting events, the relevant, attended stimulus tends to cause larger ERPs than the unattended stimuli. The BCI can infer the desired character by determining the row and column that produced the largest ERP. The sequence of highlighting events will typically be repeated many times in order to overcome the inherently low signal-to-noise ratio. Although it does form the basis for the most comprehensive trials to date of BCI in target users' homes [37, 41, 31, 21, 38], its treatment in the BCI literature has been largely as a research tool rather than a practical AAC device. Its design was motivated more by the necessary conditions for eliciting and measuring changes in ERPs, and less by usability concerns. This holds also for many subsequent refinements [e.g. 17, 23, 19, 26, 39] which changing aspects of the arrangement of the stimuli in space and time, to increase the brain signals' signal-to-noise ratio or the robustness with which letters are encoded.

The usability gap is particularly clear when we consider the users who stand to benefit most from BCI, namely those people on the LIS/TLIS border and beyond, whose paralysis has progressed far enough to impact their ability to direct and focus their gaze, resulting in poor spatial vision. Two recent studies [8, 40] independently confirmed that the high performance reported in the standard laboratory settings with healthy users depends heavily on ERP components that are only generated when users fix their gaze precisely on the target letter. Both studies show, however, that the system can be used at a lesser level of performance without target fixation, since the P300 ERP itself does not depend on this (though it remains an open question how well a paralyzed person with poor spatial vision could deal with the practical demands of locating and attending to their desired letter within a dense visual array). One of the studies [40] showed that, by rearranging the stimuli spatially into a radial layout, and temporally into a two-step hierarchy, the system became more resistant to the limitations of poor gaze control. This is an excellent example of the impact of improved HCI design in BCI. Consideration of users' limited vision has also led to speller designs even less dependent on spatial vision [1] and entirely based on auditory stimuli [14, 20, 36].

3 Self-actuated BCI spelling

The improved HCI mentioned in the previous section, called Hex-O-Spell, had previously made its debut in BCI as one of the few self-actuated spelling systems, driven by motor imagery [7, 29]. Other interesting user interfaces have also been used in conjunction with self-actuated BCIs, such as Dasher [12], and a similar information-theoretic approaches to spelling [32], although there has been little opportunity to assess their performance in the target user group. Another reason for the under-representation of self-actuated BCI in communication is that there is a larger variance in people's native ability to control them [15]. Stimulus-driven BCIs have a greater tendency to be usable "out of the box," where self-actuated BCI may require more user training to be accessible to all users. This is one area in which better HCI design may be valuable: to better reinforce a user's learning of the control signal. A related, and also valuable, design goal is to adapt better to variations in users' level of control. Adaptation to a range of proficiency levels is important in three contexts: on first use (to cope with variation in levels of control between individuals); during use (to cope with fatigue); and over longer timescales (to adapt to a given user's improvement in control as their repeated use of the interface allows them to learn).

4 Symposium and competition

Our symposium at HCI 2011 will present the HCI challenges faced by the field of BCI, as seen through the eyes of BCI experts. It will also launch a competition into which the HCI community is invited to enter to meet these challenges: to design a better BCI-driven interface for communication. Provisionally, the competition it will consist of two independent streams, each with its own prize:

1. The design stream: entrants will submit two-page white-papers to us, provisionally by November 2011, detailing their design for a better HCI front-end to a brain-computer interface and explaining the design elements that best serve the target population. A prize will be awarded for the best idea, in the opinion of the judges.

2. The implementation stream: by the later provisional deadline of mid-February 2012, entrants will submit an actual implementation, built within a rapid-development software framework that we make available. This will allow us to test the effectiveness of the entrants' design in coping with a noisy input signal. The input signal will be triggered by the user making a mouse movement at the appropriate times, as dictated by the interface's stimuli. The resulting signal will emulate a slow ERP or a brief burst of self-actuated brain activity. Design of the interface's auditory and/or visual stimuli, and their arrangement in space and time, and the decoding of the sequences of input signals into arbitrary English text, will be the entrants' challenge. Error-correction and predictive spelling will be encouraged. Finalists will be chosen according to the judges' assessment of how well the designs meet the needs of the target user group. A time-limit will then be chosen for each finalist according to a "handicap"-like system, with the aim of

leveling the playing-field between designs that meet different degrees of limitation on the user's sensory input. Naturally we expect auditory-only interfaces to be slower than those that require vision, but we nonetheless wish to ensure that a design that is useful to any subgroup of the target population has a chance of winning. A "spell-off" event will then be held for the finalists, at which the entrants will be required to use their interfaces to spell a given sentence in English: the winner will be finalist who has the largest number of (correct letters - incorrect letters) on the screen at the end of their allotted time period.

Details of the prize money, exact deadlines, and further rules will be posted on: http://bcimeeting.org/HCI2011Challenge/

5 Design challenges for a BCI

In conclusion, we envisage that that the ideal HCI-for-BCI should:

1. cope with a noisy input signal (entailing many false positives and false negatives in selection) which may become noisier or more infrequent as the user tires;
2. allow efficient and robust error correction;
3. integrate prior knowledge about the task to be performed (for example predictive selection) in an intuitive and accessible way;
4. adapt to wide range of user proficiency levels between users, and within the same user from hour to hour and from day to day.
5. promote user behavior that leads to learning and improvement in BCI control;
6. be accessible to users whose vision is poor, or perhaps even to users who are functionally blind.

We look forward to the participation and the ideas of the HCI community. We expect that this competition will further enhance the non-muscular communication options available to people with severe motor impairments.

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