Brain Computer Interfaces: Psychology and Pragmatic Perspectives for the Future

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Abstract. Whilst technologies, such as psychophysiological measurements in general and electroencephalograms (EEG) in particular, have been around and continually improving for many years, future technologies promise to revolutionise the emerging Information Society through the development of brain-computer interfaces and augmented cognition solutions. This paper explores critical psychological and pragmatic issues that must be understood before these technologies can deliver their potential well. Within the context of HCI, we examined a sample (n = 105) BCI papers and found that the majority of research aimed to provide communication and control resources to people with disabilities or with extreme task demands. However, the concepts of usability and accessibility, and respective findings from their substantial research literatures were rarely applied explicitly but referenced implicitly. While this suggests an increased awareness of these concepts and the related large research literatures, the task remains to sharpen these concepts and to articulate their obvious relevance to BCI work.

1 INTRODUCTION

The concept of the brain computer interface (BCI) presents some startling possibilities for enhanced communication and accessibility: BCIs have the potential for helping individuals with severe communication and control problems due to disability or extreme circumstances, as well as giving anybody who requires or desires non-traditional human-to-system communication tools additional input/output channels. The notion of BCI may be simple, but the underlying science is complex. Hence, an effective application of BCI necessitates an adequate appreciation of the underlying science. For this reason, this paper sets out to consider the psychology and rehabilitation engineering underlying BCI.

An effective BCI system is based on the following three axioms: (1) It is possible to take sensitive and reliable measurements of aspects of human brain activity on a non-invasive basis; (2) These aspects of human brain activity can be controlled systematically and dependably by the individual; (3) These measurements of human brain activity can be readily used to control or communicate with interactive systems or to communicate with other people [1]. These are the specific requirements for effective BCIs. In addition, we suggest that there are at least three generic requirements that apply to any communication and control systems: Functionality [2], i.e., does it support important, useful and desirable tasks? Usability [3], i.e., is the system too difficult to use? and Accessibility [4] i.e., are there any barriers that prevent or disadvantage users when using the system?

This paper is structured in four sections to present and discuss (a) important psychological factors for BCI, (b) practical factors for BCI, (c) the implications of BCIs for the future of Human Computer Interaction and (d) a futuristic BCI vision.

2 PSYCHOLOGICAL FACTORS FOR BCIs

We propose that any consideration of psychophysiological measurements must include the rigorous scrutiny and interpretation of these measurements in a human centred context. This includes a popular measurement approach for BCI, the scalp-recorded electroencephalographic measurement (EEG). EEG refers to the placement of electrodes on the head of a human or animal in order to measure the electrical consequences of brain behaviour. The conventional view of BCI is that EEG will enable severely disabled individuals to communicate with and control their environments through control of screen displays, prosthetic devices and robotic systems. This conventional view is changing, however, particularly as are the results of the emerging psychological and pragmatic issues. The following four factors provide not an exhaustive but comprehensive set of psychological considerations for analysis.

They are (a) the types of cognitive function reflected in the EEG, (b) the nature of feedback and the modalities involved, (c) the types of intended users and (d) the types of tasks and environments chosen.

The first consideration is that different patterns of the brain activity may be mapped to respective cognitive functions. If so, then different aspects of the EEG may reflect different functions to a greater or lesser extent. One of the most obvious areas is that of motor – related EEG. Since voluntary movement control already exists as an internal control system in humans, it is natural to use voluntary movement-related potentials (VMRPs) to drive a BCI [5]. Thus it is possible to detect actual index finger flexions in an individual's EEG records. Furthermore, imagined voluntary movements with able-bodied persons can be reliably detected and measured [6]. This opens some major opportunities for individuals with significant psychomotor impairments.

Perceptual and cognitive brain processes can also be detected. We know from primate studies that decision making involves at least two general phases of neural processing, namely the depiction of sensory information and the accumulation of evidence from decision-related regions. Recent research [7] deployed a cued paradigm plus single-trial analysis of electroencephalography (EEG) and found temporally specific components related to perceptual decision making. They then went on

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to conduct further analyses of their EEG recordings to understand their analyses of fMRI data collected for the same behavioural task to identify the cortical locations of these EEG components. They found evidence of a cascade of events associated with perceptual decision making that takes place in a highly distributed neural network. Of particular importance is activation in the lateral occipital complex supporting the view that perceptual persistence is a mechanism by which object-based decision making in the human brain takes place.

In addition to EEG and FMRI, consider event related potentials (ERPs). These are electrophysiological responses to internal or external stimuli, including perceptions or thoughts. Event-related potentials (ERPs) are seen in the electroencephalogram (EEG). Since ERPs may be used to measure brain activities associated with human related information processing, they may be able to indicate variations in cognitive load [8] [9]. The measurement of ERPs in a laboratory setting is relatively easy, but much more difficult in the real world, due to all manner of uncontrollable factors such as eye movements, switching of attention, continuous as opposed to discrete sensory inputs. [10]. These researchers reported a range of techniques that they could produce significant single trial ERPs in such circumstance, leading to the generation of useful averaged evoked potentials (AEPs) over multiple trials. They were able to locate the spatial origins of these ERPs. Finally they were able to observe minute by minute changes in cognitive load and overload, using (back-propagation) neural networks to do so.

A second psychological factor is the nature of the feedback given to the individual using the BCI. In particular, choosing the modality for feedback is perhaps the most obvious choice. It is often assumed that the feedback modalities of choice are visual, auditory or their combination. However, researchers [11] have reported a system that uses vibrotactile biofeedback to supply haptic information. They found that six, healthy, young, male participants could use a mu-rhythm based BCI within a motor imagery paradigm to control the position of a virtual cursor. The cursor position was shown visually as well as transmitted haptically by varying the intensity of a vibrotactile stimulus to the upper limb. The six subjects operated the BCI in a targeting task, receiving only vibrotactile biofeedback of performance. They were able to control the BCI using only vibrotactile feedback with an average accuracy of 56% and as high as 72%. The results of this study show that vibrotactile feedback works as a possible feedback modality to operate a BCI using motor imagery.

A third psychological issue is the choice of intended users. Whilst much of the above work has been conducted with the support of non-disabled participants, these are often tests of the feasibility and practicality of the proposed methods. The authors often state their aims are to be to assist individuals with high levels of disability, particularly psychomotor disabilities. However, we can also be disabled by our circumstances and by the excessive demands that tasks place on us. In particular, cognitive overload occurs when the information throughput of our tasks / circumstances become too high or complex for us to cope [12]. In such cases, augmented cognition through modality specific input scheduling is a potential solution. If BCI is a progressively more viable option, as current research suggests, then BCI can provide another communication channel as a basis for augmented cognition. The difference between augmented cognition and BCI approaches is in the intent of the user. In the former the system senses user state and engages task dependent mitigations to optimize performance; conversely, the later accepts deliberate, intended, cognitively articulated input from the user. For example some researchers [13] state their research question as "How can BCI be used to assist neurologically healthy individuals in specifically demanding tasks?"

A fourth psychological consideration is the choice of tasks and context of use that are chosen. Many of these studies make use of simple tasks such as the control of screen cursors to demonstrate the impressive potential of BCI; few of the studies have based their insights on an analysis of user requirements. Future BCI investigations require the systematic evaluation of user requirements to improve the user-sensitivity of the chosen designs of such BCI systems. Where individuals have substantial psychomotor deficits, any opportunity to communicate and control the environment appears to be beneficial, but, as science moves on, these individuals may wish to enhance their quality of life through the control of screen displays, prosthetic devices, robotic systems etc. If so, the consideration of more user sensitive design could be beneficial. However, BCI is likely to be beneficial to a wider range of intended users and beneficiaries. Individuals with reduced sensory, psychomotor or cognitive attributes may also benefit and would surely want more than the basic functionality of BCI based control of simple systems. However, the increasing work on augmented cognition demonstrates that there will be individuals who are working in high information or high stress environments and could use BCI communication (active or passive) to indicate a need for changes in the task / information configurations that they must face. Considering all these potential, intended users, it is clear that the tasks and environments supported by BCI will soon need to become much more enriched and interactive than at present. Of course, the tasks / environments must not only be functionally enriched, they must also be perceived as positive and welcoming. In the past, assistive technology has sometimes proved to be functionally valuable but aesthetically inadequate. People with disabilities and indeed all potential users may be discouraged from using unattractive technology that seems to stigmatise its users. If this argument is correct, then the BCI systems of the future must be acceptable to intended users in the gestalt of a sophisticated industrial design that meets functionality needs and user requirements whilst affording usability, accessibility, aesthetics and personae.

In summary, we have proposed four psychological factors that are of practical importance to BCI developments and applications. They are all important if BCI methods are to be effectively understood and applied. The following four factors are of highest face validity. They are; (a) the types of cognitive function reflected in the EEG, (b) the nature and modalities used for feedback, (c) the types of intended users and (d) the types of tasks and environments chosen. However, these factors have been chosen on the basis of face validity. How can such factors be identified on a more conceptually robust basis, without creating cognitive overload for the BCI scientist or practitioner? Elsewhere, it has been suggested that nine factors can be used to capture the essentials of human cognition. Research [12] has proposed nine factors that have been validated by two, large sample validation studies. Those nine factors are (from a user perspective); input processing, feedback management, executive functions, working memory, long term memory, emotions and motivations, mental modelling, out put and learned, complex output sequences. Episodic memory has also been suggested as an extra factor, but it has been argued by leading researchers [14] that this is best seen as part of working memory.

3 SOME PRACTICAL ASPECTS OF BCI

BCI can be seen from a number of distinct perspectives. Above we considered a psychological perspective and the nature of the psychological processes involved. Here, we look at BCI from the perspective of rehabilitation engineering.

Traditionally, EEG has been the measurement of popular choice and, within that, EEG related to the motor cortex and thus to psychomotor processes. As discussed above, simple psychomotor responses (e.g. finger flexions) are feasibly detected in an individual's EEG. This would be helpful for an individual with limited movement to control a system with minimal physical effort. In addition, improving technology now allows for the cortical electrophysiological correlates of imagined movement (e.g. imaginary finger flexions) to be detected and that is much more promising for people with severe limitations. There are a significant number of ways to extract measurements from an EEG record, of which the event-related potential (ERP) or evoked potential (EP) and the averaged evoked potential (AEP) are perhaps the best known. However, current and recent work shows how many variations of this theme are possible and so the race is on to determine the most effective options.

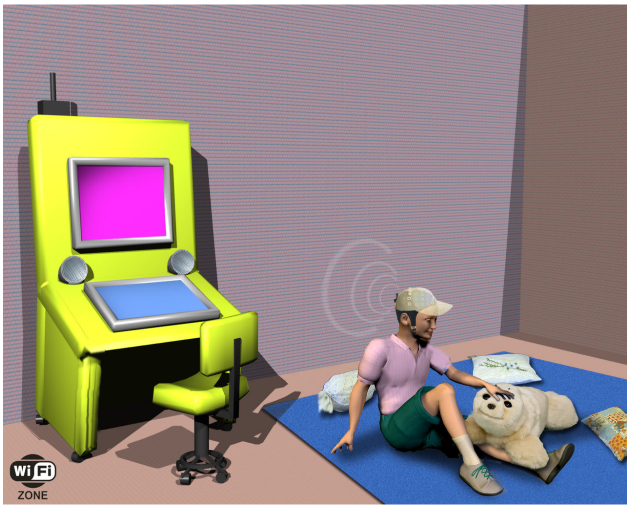
Continuing the focus on evoked potentials and averaged evoked potentials (AEG), researchers [15] explored the measurement of the P300 component of the human EEG, with a new and unsupervised algorithm for P300 estimation, thus improving the raw EEG records. They proposed and tested a new method to detect the P300 potentials in the human EEG by a P300 based BCI. The results were favourable to this new approach over a selection of older methods.

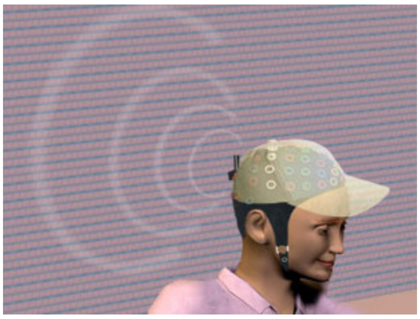
Other researchers [16] explored the use of flash onset and offset visual evoked potentials (FVEPs) to activate a BCI system. Flashing stimuli displayed on a screen are used to produce onset and offset FVEPs when the users looks at them. By shifting their visual attention to different items, users can produce strings of letters or numbers with which to communicate or to control useful systems. They also produced averaged evoked potentials from their data, including the differences between the N2 and P2 peaks and the N1 and P1 peaks. In two experiments with five subjects in two experiments, they found an accuracy level of 92.18%, showing that the onset and offset FVEP-based BCI can achieve a high information transfer rate. In contrast, other researchers [17] explored steady state visual evoked potentials (SSVEPs) with overlapping stimuli that can evoke changes in SSVEP activity without the need for shifting gaze. They found that half of their subjects could achieve a suitable level of control of a BCI. Though further work is needed to improve this percentage, the authors argued that this method might be very suitable for severely disabled users.

One way to improve the effectiveness of EEG based BCIs is to develop more advanced measures. Some researchers [18] explored the use of energy density maps derived from EEGs in ten healthy volunteers, comparing two real as well as between two imaginary movements. They were able to identify the most discriminative features based on statistically significant differences between the energy density maps. They concluded that these types of analyses could provide a larger number of command signals to control the external systems via a BCI. In addition, researchers [19] explored the potential of machine learning methods for compensating for the high variability in EEG data when analyzing single-trials in real-time. They concluded that such methods contributed to the creation of cleaner data and thus more effective BCI systems.

Of course, there is no need to use EEG measurements in isolation. It can be put to joint use with the respiratory heart rate response, induced by brisk inspiration [20]. They investigated the ways in which a BCI could be turned on or off by the user. They found that ten healthy subjects were able to switch on and use a steady-state visual evoked potential-based (SSVEP) BCI using one ECG (electrocardiogram) and EEG channel, after only 20 min of feedback training. In addition, the subjects made very few false positive errors. On this basis, the combination of EEG and ECG promises to be very useful in the future. A further methodological improvement is based on the concept of the "quasi-movement" [21] defined as voluntary movements that have been minimised as to be virtually undetectable, making them rather like imagined responses. In fact, quasi-movements are consistent with the proposed continuity between real and imagined movement. They found that in healthy subjects quasi-movements work well in brain-computer interface, being associated with significantly smaller classification errors when compared conventional imagined psychomotor responses. It is also feasible to consider the potential role of near-infrared spectroscopy (NIRS) for BCI [22]. They concluded NIRS that instruments are only small-scale and can be used to make noninvasive measurements. They were able to show that they could measure regional cerebral blood flow effectively by NIRS during a tapping task (preferred hand) and reported methods to evaluate NIRS measurements by use of an artificial neural network.

So far, we have assumed that the BCIs will be based on hard-wired systems. This is a reasonable assumption given current experience of wired and wireless Internet interfaces. However, wireless systems offer potentially greater flexibility given a suitable wireless environment. Thus it is important to consider wireless BCIs. Thus wireless systems for BCIs could make use of subcutaneous transmitters with little loss of signal strength! [23]. Such wireless systems can be strengthened further by the effective use of compact, operational amplifiers that require little power and can support implantable systems [24]. Such an amplifier has only a power consumption of only 736 nW and a chip area of only 0.023 mm2. Another, non-invasive option is the application of wireless principles to EEG using an electrode cap with a wireless link. A study of the Armoni Project [25], using non-invasive criteria, designed an EEG cap that made the EEG system become invisible to the wearer (see graphics pictures below).





3 BCI IMPLICATIONS FOR HCI

The brain computer interface (BCI) should be the instantiation of access "par excellence". Current work, as discussed above, has established the feasibility, in principle, of communication and system control through a BCI. It is clear that a range of psychophysiological measures can be used either singly or in combination. Intended users range from individuals with virtually no disabilities to those individuals with severe psychomotor impairments. BCIs can also be used by individuals facing cognitive overload or inappropriately high stress levels. Such systems can now be set to detect such problems and provide cognitive augmentation through task or information sharing. For example, a task can be carried out jointly by a system and a person. Alternatively, the person could take one task and the system could be given another task. It is also increasingly possible to identify those aspects of human cognition that are reflected in different components of the EEG. This would allow BCIs to focus on the most relevant cognitive functions, perhaps capturing the most accessible or usable. Whilst visual feedback is the most common form, as discussed above, BCIs can use a range of different modalities to guide the user. Finally, it is important to add that powerful data analysis methods can be used to extract the maximum informational value from psychophysiological data with consistency and reliability.

The above summary demonstrates the successes of current BCI research and development and points to their use to solve accessibility problems, particularly for people with severe psychomotor deficits, but also much more widely. However, it is remarkable when we considered a large sample (n = 105) of BCI related papers, very few made reference to, or use of, the extensive research literatures covering universal accessibility or usability. Yet these should be central to the development of this field. This is undoubtedly due to the current state of the art and the necessary focus upon demonstrating validity and feasibility.

However, such systems are not themselves immune to usability and accessibility problems. Whilst these two topics are much too big to be discussed in depth here, some simple links can be suggested. Usability is defined in terms of the level of task difficulty that a system requires. There are many experts on usability, but for our focus on BCI, references to the work of Nielsen [3] and Shneiderman [26] will have to suffice. The point is that there are simple ways to conduct usability evaluations for interactive systems. Accessibility is defined here as the lack of barriers between a system and a user that would otherwise degrade or prevent the effective use of system.

Universal accessibility is equally large as a topic. Here the work of [27] can be singled out. The accessibility of an interface depends on at least four factors: the technology platform, the intended users, the tasks and the context of use. All of these four factors have been discussed above, but their contributions to accessibility need a more explicit treatment. For a system to be truly accessible, it can also be said that depends on (a) the chosen hardware, (b) the quality of the connection, (c) the users' ability to perceive incoming information and feedback, (d) the making of appropriate responses with sufficient ease, (e) cognitive accessibility i.e. the ability to navigate efficiently (with few errors) and to comprehend the information given and (f) the achievement of their objectives through the use of an interactive (BCI) system [28]. If BCI research and development can achieve these twin goals of usability and accessibility, then BCI promises to become a mainstream technology and a substantial contributor to the global Information Society.

A new application of BCI is discussed by the Armoni Project [25]. The low levels of motivation that people with intellectual disability often experience during long periods of their daily life when they are without adequate cognitive, sensory and motor stimulation is an aggravating circumstance that can have a detrimental impact on their moods [29], their well-being and, therefore, their quality of life. These cognitive, sensory and motor decrements can be mitigated by systems based on ICT technologies, using feedback with indicators based on BCI (Brain Computer Interaction), EEG pickups of the real-time emotion states of the users of such a system.

To meet these needs, a BCI related PC station has been constructed, which can be assembled in groups of two, three or four unit's ensembles. BCI (Brain Computer Interaction) techniques are used, with technically advanced and conventional peripherals, as well as state-of-the-art software with auto-adaptive capacities. They are designed for dependent-disabled people and allows access to and interaction with more than 100 activities, with systems that, from the point of view of the user, are significantly: easy to use, accessible (according to the different degrees of disability), cognitively interesting for all types of people considered here, recreationally funny, easy to learn and to use for learning, rehabilitation and maintenance activities.

There is a substantial amount of research that demonstrates emotional monitoring in people with EEG [30], with evoked emotions [31], cerebral laterality-emotion and EEG [32], recognition of emotions [33], emotion assessment [34]frontal EEG asymmetry as a monitor of emotions [35] and depression measured through EEG [36]. This development of an appropriate EEG methodology, allows for a baseline to be established for each user, in terms of his/her emotions plus the map of the EEG, particularly of the ventromedial frontal zone of the human brain cortex [37].

All this feedback, coming from standard peripherals, as well as from advanced systems, particularly the EEG cap, can be formally processed. BCI provides an objective and real time interaction and supplies us with feedback relating to the mental state of the cortex of the user through real-time evaluation of the correlative EEG, with order-disorder states of the brain (polarity of emotion and probably intensity, [38], and customized emotion performance and identified for each user by therapist in institutions. State-of-the-art BCI (Brain Computer Interaction) technology, and the specific case adopted here of BCI by EEG (electroencephalogram), has developed systems that are very focused on the ability to control peripheral elements and devices (for example, moving a cursor, moving a wheelchair etc). The Armoni project immerses the user in a new perspective, focussing on the emotional personal state of the user, capturing it in the mainframe computer of the stimulation station through wireless based EEG (This has been supported by clinical trials).

4 THE FUTURISTIC VISION OF BCI

Imagine a situation in which you are working in your home study. You notice that the room temperature is slightly too high, so you turn your gaze to the temperature display and think it down a few degrees. The room cools to a more acceptable level. Your next task is to send a package to a colleague by 3Dmail. You had prepared the package the night before, so all you have to do is to think yourself through the process. A copy of the package goes and you are rewarded by feedback in the form of a brief passage from Mozart. Suddenly, you find that you have a home visit from a colleague, a rare treat these days. You both exchange archived information via your systems and exchange pleasantries. She shows you her new system, which is not based on the familiar hat system but on subcutaneous units, set almost flush the skull. You make a cognitive note to explore the options sometime, but not sometime soon. You both agree that sometimes it is nice to get out.

Later, you inspect your news feeds, filtering out those items that do not accord with your religious views. This reminds you to switch on your background prayer mode. You notice the item in which some criminals have adapted their BCIs so that they can control other peoples' robots and wireless enabled property and down load it for immediate inspection. Before you have a chance to read, you receive a handwritten, hence highly secure text message from your daughter saying that she is on the intercontinental bus and needs you to send some credits as she is over-extended

This view of BCI future may be in turn, attractive or repellent, depending on your world view, but in the nearer future, we can surely look forward to BCIs that make usable, accessible contributions to universal accessibility.

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