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Article information:

To cite this document: Maurice Mulvenna, Gaye Lightbody, Eileen Thomson, Paul McCullagh, Melanie Ware, Suzanne Martin, (2012),"Realistic expectations with brain computer interfaces", Journal of Assistive Technologies, Vol. 6 Iss: 4 pp. 233 - 244

Permanent link to this document:
http://dx.doi.org/10.1108/17549451211285735

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Peer-reviewed paper

Realistic expectations with brain computer interfaces

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The BRAIN consortium would like to acknowledge all the people who participated in the field tests in Northern Ireland and Spain. The research leading to these results has received funding from the European Community's Seventh Framework Programme under grant agreement no. 224156.

Abstract

Purpose – *This paper describes the research underpinning the development and evaluation of a brain computer interface (BCI) system designed to be suitable for domestic use by people with acquired brain injury in order to facilitate control of their home environment. The purpose of the research is to develop a robust and user-friendly BCI system which was customisable in terms of user ability, preferences and functionality. Specifically the human interface was designed to provide consistent visual metaphors in usage, while applications change, for example, from environmental control to entertainment and communications.*

Design/methodology/approach – *The research took a user centred design approach involving representative end-users throughout the design and evaluation process. A qualitative study adopting user interviews alongside interactive workshops highlighted the issues that needed to be addressed in the development of a user interface for such a system. User validation then underpinned prototype development.*

Findings – *The findings of the research indicate that while there are still significant challenges in translating working BCI systems from the research laboratories to the homes of individuals with acquired brain injuries, participants are keen to be involved in the deign and development of such systems. In its current stage of development BCI is multi-facetted and uses complex software, which poses a significant usability challenge. This work also found that the performance of the BCI paradigm chosen was considerably better for those users with no disability than for those with acquired brain injury. Further work is required to identify how and whether this performance gap can be addressed.*

Research limitations/implications – *The research had significant challenges in terms of managing the complexity of the hardware and software set-up and transferring the working systems to be tested by participants in their home. Furthermore, the authors believe that the development of assistive technologies for the disabled user requires a significant additional level of personalisation and intensive support to the level normally required for non-disabled users. Coupled with the inherent complexity of BCI, this leads to technology that does not easily offer a solution to both disabled and non-disabled users.*

Originality/value – *The research contributes additional findings relating to the usability of BCI systems. The value of the work is to highlight the practical issues involved in translating such systems to participants where the acquired brain injury can impact on the ability of the participant to use the BCI system.*

Keywords *Health care, Computer applications, Special purpose computers, Brain, Brain computer interface, Steady state visual evoked potential, Usability, Configuration, Personalisation*

Paper type *Research paper*

Introduction

Hundreds of thousands of people across the world are unable to interact effectively with other people, assistive devices, or information and communication technologies due to disabilities and functional impairments. Persons with traumatic brain injuries (for more

DOI 10.1108/17549451211285735

details, see www.brainline.org/landing_pages/categories/abouttbi.html) (Holder, 2005), spinal cord injury, or who have suffered a stroke are examples of groups who are often excluded. Communication is a fundamental need that is empowering to the individual's recovery and participation in society. The challenge of technology-enhanced rehabilitation is to develop a system that allows for individual users' preferences to be accommodated, in this case in a user interface that does not depend upon their impaired movement ability. Brain-computer interface (BCI) systems possibly uniquely offer the promise to address this need, and they have emerged as plausible alternatives for offering communication and control to physically disabled people (Wolpaw *et al.*, 2002; Allison *et al.*, 2007; Future BNCI, 2012).

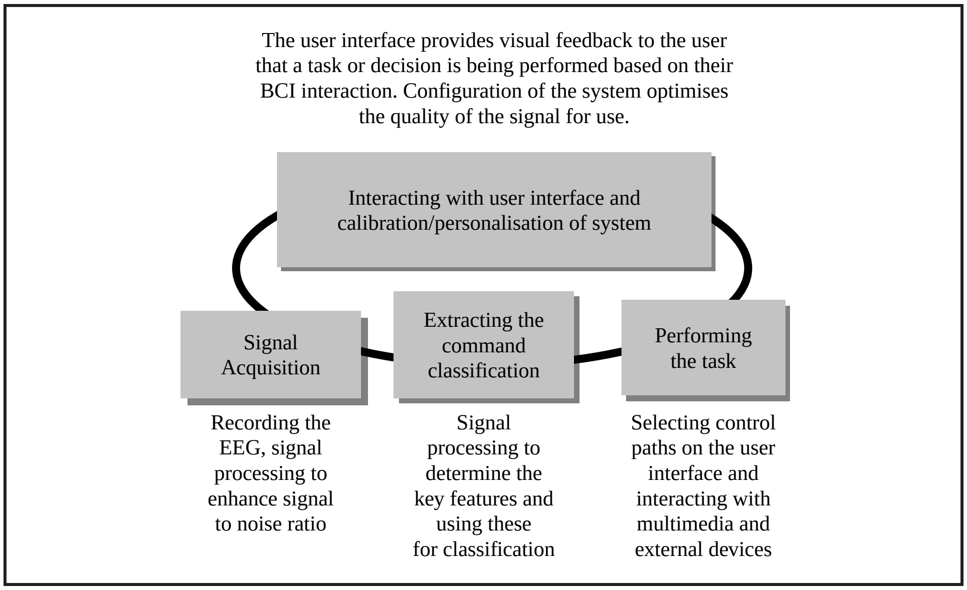
Availability, lower cost, portability and convenience make the electroencephalogram (EEG) the dominant choice in non-invasive monitoring. The EEG is typically recorded using an array of electrodes positioned around the scalp of the user. This forms the input to a computerised system from which desired actions may be performed (Figure 1).

Despite numerous endeavours, a practical and convenient BCI system that can be used in everyday situations still poses a challenge. Besides the known issues of time-consuming and difficult setup (e.g. positioning the electrodes and applying conductive gel to obtain a proper signal), fast, easy and accurate personalisation, customisation, and calibration of such a system to a particular user is a big hurdle for practical application of the technology. A convenient calibration procedure is among the main challenges to be addressed in order for successful user adaptation of BCI to be achieved.

There has, however, been some evidence of success for long-term home use of BCI as reported by Sellers *et al.* (2010). In this paper they report the progress over two and a half years of independent use of a P300-based BCI for a particular user with amyotrophic lateral sclerosis (ALS). They highlight the key challenges faced by enabling such independent use, such as difficulty of use by non-technical personnel, limited applications, user-configurability issues and sustained and manageable support long term. They have endeavoured to improve upon these key issues and report some success. Careful selection of a potential user was undertaken; Vaughan *et al.* (2006) highlight six criteria used in determining a suitable candidate for long-term BCI use, ranging from the user's underlying condition to their support network of carers, family and friends.

Birbaumer (2006) gives a valuable overview of the progress of invasive and non-invasive BCI at that time, which is still relevant mostly today. Birbaumer *et al.* (2003) investigated slow

Figure 1 Main components of a non-invasive EEG-based BCI system



cortical potentials (SCP) for control and showed some positive outcomes in terms of long-term use for ALS patients. They trained 32 patients in its use but they report that long training sessions were needed. They also reported the persistent need for professional attention and continuous technical support. Only one patient showed potential for independent home use.

A joint project investigated the comparison of SCP-BCI, sensorimotor rhythm (SMR) BCI and P300-based BCI working with seven ALS (pre-locked in state) patients. BCI-SMR and P300 showed some positive use after 20 training sessions but the SCP-based BCI required further training. They comment on the factors against widespread non-invasive BCI use, stating that long training times still often result in high error rates. Furthermore, they highlight the disparity between BCI efficacy for healthy users and the patients within their studies. Healthy users were able to achieve a level of control over a number of sessions whereby; the patients needed 20 sessions to achieve a 70 per cent accuracy using SMR BCI (Kübler *et al.*, 2005).

Neuper *et al.* (2003) provide a case study for BCI use of a severely paralyzed patient using event-related desynchronization and event-related synchronization (ERD/ERS) based BCI for verbal communication. The BCI was established within the patient's home (clinical) setting and training was performed over several months. Technical assistance was also provided on-line. An average spelling accuracy of 70 per cent was achieved.

The literature highlighted in this introduction aims to give some overview of the complexity involved in providing successful BCI for the individual. Some key repeating issues are present such as the technical complexity of the BCI system, the need for strong carer and family support, the need for training, on-going technical support, and the BCI accuracy disparity between users. The latter is also highlighted by Allison and Neuper (2010a), stating that there is no ''universal BCI''.

The desire to promote domestic BCI use is evident (Future BNCI, 2012; Brain Communication Foundation, 2012) but the challenges are significant. As such, BCI deployment to the home environment to date has been carefully focussed possibly centred on an individual user or a small group of users, perhaps often with a defined neurological condition. Brain-computer interfaces with rapid automated interfaces for nonexperts (BRAIN) aimed to develop a framework and BCI system that would support a more wide spread deployment to the disabled user in their own domestic setting.

The paper describes the research work undertaken, describing the selected BCI paradigms used, and the development of a user interface for the BCI system. The findings indicate the complexity in setting up the BCI systems outside of a lab environment and the difference in efficacy of use between disabled and non-disabled participants, and both issues are examined in the discussion section. The paper concludes by highlighting the challenges to successful BCI deployment and indicates some possible areas for future research.

BRAIN research project

The work presented in this paper was part of a European funded project called BRAIN. The primary aim of the research was to promote inclusion by developing, integrating, and testing technology that makes real world BCI systems more flexible, usable, reliable, and accessible (BRAIN Project, 2012).

We believe that the underlying technology and software that facilitates BCI is at an early and evolving stage of development. However, recent endeavours to promote commercially viable BCI systems (Intendix, 2012; eMotiv, 2012) support the investment of effort for development in future BCIs (Future BNCI, 2012).

The research hurdles that limit BCI adoption are varied and encompass challenges in signal acquisition, signal processing, configuration of the system for individuals and support for the breadth of applications to be used. Figure 1 shows the key components of a typical BCI system.

Nam *et al.* (2009) report that BCI's lack of acceptance could be a consequence of a lack of understanding of the usability of BCI systems. Finding the right opportunities to make BCI usable and accessible offer the potential to turn BCIs into practical assistive technologies that can help users interact with family, carers as well as home-based technologies including assistive devices, home appliances, or computer and internet technologies, A key challenge to this is to minimise the work in deploying BCI systems successfully for users and their supporters.

In order to facilitate this, a European consortium of academic (Universities of Bremen, Ulster and Warsaw) and industrial partners (TMSi, Telefonica, and Philips) and a non-government organisation (The Cedar Foundation) working for people with disabilities collaborated, with each focusing on a key target area for improvement. While the ambition of the project overall required research advances in signal acquisition, processing, interfacing with home-based applications, etc. this paper reports on engagement with disabled and non-disabled users as participants trialling the research prototypes developed in the project, describing the development of the user interface to the BCI system, for the steady-state visual evoked potential (SSVEP) paradigm and discussing the findings. This BCI paradigm is described in the next section.

BCI paradigms

Core to the BCI setup is the software that utilises the electrical activity of the brain. There are a few approaches that may be considered. These are referred to as the BCI paradigms, and BRAIN set out to evaluate these. Two paradigms explored were: SSVEP; which uses variable frequency flashing lights to evoke the EEG, and ERD/ERS which uses cued imagined movement to generate the EEG. The SSVEP paradigm is discussed within this paper and used in the research and by participants for assessment of engagement and for evaluation. The following section describes SSVEP.

SSVEP paradigm

Steady-state visual evoked responses use a flashing or flickering stimulus, generally small lights placed around a monitor (typical useable range 5-48 Hz, at 2 Hz intervals, with >25 Hz considered as high frequency (HF) SSVEP), which the participant looks at. In doing so this activates an electrical response in the participant's EEG that matches the chosen frequency. Signal processing algorithms and classification procedures map designated responses to a desired task to enable the participant to make a selection; for example, to open the door. By using a number of differing flashing objects, decision paths can then be supported by the participant focusing in on a particular action of interest that represents the activity that they want to do. There are limitations on the number of usable frequencies in SSVEP due to the user's susceptibility to the paradigm in terms of differentiated response in the EEG and other physical and mental activity, e.g. movement artefact, environmental conditions. The issues relate to the strength of the SSVEP signal and how each person reacts to the different frequencies.

These factors impact on the user interface development, where the architecture has to facilitate the user interface to react to individual SSVEP capabilities as well as to personal capabilities. The benefit of this paradigm is that the user requires minimal training and the paradigm can potentially support multiple frequencies depending on the responses of the user to the flashing stimuli. Within the project a target of four distinguishing frequencies was aimed for to enable a four-way decision-navigation possible.

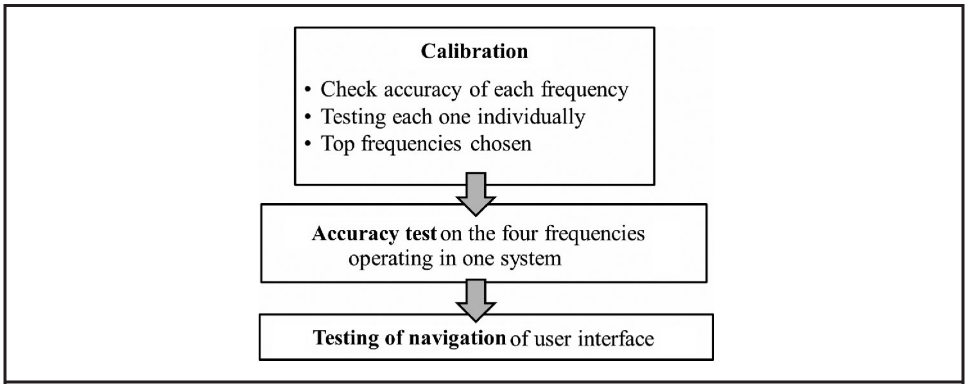
Using SSVEP an initial calibration process was performed to determine the best frequencies of operation for a particular participant. These frequencies were then used to set up the conditions of operation for the BCI system. The objective was to make the system more suitable for widespread end-user deployment and more usable for the non-expert. The key stages are shown in Figure 2.

SSVEP paradigm – the variations

a) High frequency SSVEP (30-48 Hz)

In its first phase, the research focused on HF-SSVEP-based BCI (Garcia-Molina and Mihajlovic, 2010; Durka *et al.*, 2009). Keeping the frequencies used in the range of 30-48 Hz produced an SSVEP interface that was more comfortable and less tiring for the user as the flashing component produces less irritation. This provided significant scientific challenge to

Figure 2 Key stages of SSVEP user calibration and testing



overcome as it becomes more difficult to differentiate between the higher frequencies than it does with the lower frequency SSVEP.

The aim was to automate the calibration for the HF-SSVEP. However, this proved to be a complex issue particularly with the disabled user due to general lower accuracy rates. Progress was made by sequencing through a range of frequencies and choosing the optimal top four. However, even at the second stage of the testing process (Figure 2 – accuracy test) it became evident that there was a disparity between accuracy for the disabled user and the user with no brain injury.

b) HF with phase discrimination

As a result of such difficulties the project investigated an alternative phase-based SSVEP algorithm to allow classification to be discriminated based on the dominant frequency alone (Garcia-Molina and Mihajlovic, 2010).

c) Low frequency SSVEP

Whilst development continues on the phase-based SSVEP, user trials continued using an existing low frequency SSVEP algorithm within the consortium that had previous success in larger users trials for healthy users in Hannover Messe with 86 users, in 2010 (Volosyak *et al.*, 2011; Allison *et al.*, 2010b).

Human interfaces for BCI

Much of the research in BCI systems initially focuses on the significant and fundamental technical challenges with signal acquisition and processing. However, while these remain imperative, there is now an opportunity to consider user perspectives more strongly. Another area where opportunities arise is in considering the breadth of applications that need to be controllable in the user's environment in order for a BCI system to make a significant potential impact on the quality of life for the user. These are two areas in which our research focused in order to provide steps towards a more holistic solution that is of value to users and supports the European policy area of social inclusion. The interfaces considered in this project are explained in the following paragraphs.

Smart home and universal interface systems have been developed with other assistive technologies (Bond *et al.*, 2006; Martin *et al.*, 2006) and BCIs that allow limited control of household electronic devices have also been validated and a demonstration of smart homes issues via virtual reality has been proposed (Holzner *et al.*, 2009) but a complete BCI for control of home devices or other applications is not available in 2012. Many users are also excluded because they are elderly, uncomfortable with computers, or have various different limitations. The visual interface and key technologies that integrate with the BCI components are important to achieve a system that is inclusive, user friendly and is accessible to wide range of user groups.

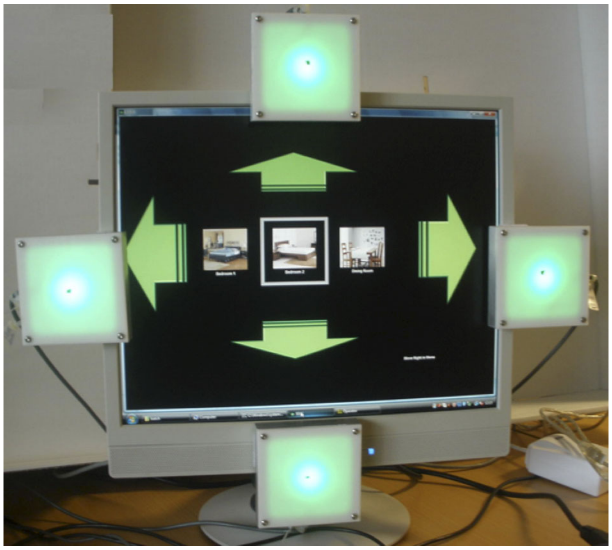
In the research, a component key to accessibility and usability was the intuitive graphical user interface (IGUI) that is customisable to the needs of the user. The IGUI was developed and tested with regard for creating an experience that is easy, enjoyable, and rewarding for users with different disabilities and limitations. The IGUI is customisable according to the user's abilities, stated preferences, and BCI paradigm selected.

The IGUI offers a bridge from the BCI platform used in our research (BCI2000, 2012; McCullagh *et al.*, 2010) and a universal application interface (UAI) (McCullagh *et al.*, 2011) to common home-based interface technologies (such as X10 and UPnP) allowing users to control any of the devices using these well-established protocols. The smart home and the communications and entertainment package that were developed incorporated components of several systems that have already been developed for non-BCI interfaces. These included applications to help users monitor and interact with electronic devices, access consumer services, information, and communication tools via the internet. Typical tasks undertaken by participants were to navigate and switch on light in the dining room; choose a film, play it and subsequently stop it; and choose an icon to show feelings, for example, ''I want to eat''.

The IGUI module provides a graphical menu display which co-ordinates its operation with visual stimuli in the form of light emitting diodes (LED) in line with the SSVEP protocol. Each of these four LEDs relate to an arrow on the interface (Plate 1).

The combined operation of the LEDs with the menu icon display provides the user with the means by which they can communicate and control the operation of the IGUI. The BCI paradigm offers the user a restricted ability to operate a command interface due to the low bandwidth communication associated with this technology. With reference to this a minimum desirable interface had been identified which requires four command options. Where possible the IGUI offers the user an ability to navigate through a list of menu items (left or right), select a menu item (down), or exit a menu item (up). Therefore, the SSVEP operation was adapted to provide a four-way choice mechanism. The means of achieving this is dependent upon the measured user capability. Based on a number of set-up parameters, each user's display and the architecture behind it, it can be generated automatically.

Plate 1 Photograph showing IGUI with SSVEP LEDs



The initial design of the interface was influenced by a user study and questionnaire. From a developmental aspect there were several areas of consideration in the design of a practical and intuitive user interface. First, how will the user interface vary in appearance and operation for different BCI paradigms if needed, and second, how will the user interface for a given paradigm remain intuitive for each of the variations in application? Namely, how can a user interface both support the switching on of a light and the control of a media player using the same fundamental control?

The left and right arrows act to rotate the images within the centre of the screen to reflect the location of the user, i.e. in which room are they aiming to control devices. The down arrow allows the user to enter the desired location or enter into the controls for the particular chosen application, or activate a particular control. The up arrow allows the user to step back up through the command hierarchy. Once the room has been chosen, the user interface will replace the images of the locations with images of applications, for example, lights, heat, etc. This same extensible structure is used to control media devices. This is optimised through three forms of BCI command from the BCI system. Binary command signals from the BCI system enable discrete decisions to be made, such as entering a particular location, or switching on a light. But for the media player this is not an intuitive approach. A continuous analogue command is extracted from the BCI system, which enables a more suitable control of, for example, volume of a media device (McCullagh *et al.*, 2010).

User engagement methodology

The development approach (Lightbody *et al.*, 2010) was to include participants with a disability and those without to help inform the design. An ethical framework was developed for the project and ethical approval provided by the University of Ulster[1].

Two groups of users in two countries were identified and recruited. In Northern Ireland, disabled participants with acquired brain injury were recruited, while in Spain, participants without movement disabilities were recruited.

In Northern Ireland the Cedar Foundation was the research partner working locally in partnership with people with disabilities including brain injury. Cedar convened workshops and surveyed the user needs of their tenants in supported smart housing. The participants were keen to take part in the project and were interested in the BCI development. Those participants interviewed face-to-face expressed an appreciation of the value of the BCI system and a sense of satisfaction of being involved in the development process. Only one participant was unsure if they would use the technology, all the others were keen to try it. Within this group Cedar identified a lead user who was more closely involved in the project. Initial investigations involved five disabled users who were residing within Cedar's supported smart housing (of which one was the lead user). Later studies involved a wider group of participants ($n = 20$) with a broad heterogeneity of brain injury and physical disability.

In Spain, the research partner Telefonica recruited healthy subjects who participated in user sessions at their site. A total of 23 people participated in the final sessions. The quantitative research was conducted by focus groups of seven to eight participants each and the quantitative part was gathered from surveys delivered to users. The results of the user survey influenced the design of the user interface, and the target applications. For the final user validation, a protocol was developed to gather user perspectives and record functional efficacy on pre-determined tasks.

Findings from the user trials

Within an established ethical framework, user involvement commenced with a preliminary workshop to provide project information to interested participants. During this they were invited to participate in the research and provided with an information sheet. Further discussions with the users followed, with those still interested signing consent forms.

In the trials, the efficacy of the SSVEP paradigm was evaluated for users with and without brain injury.

Initially a range of frequencies was investigated for each user. From the optimal frequencies, four were chosen for navigation with each flashing LED assigned to an arrow. However, some complexities in this process were uncovered.

The high-level findings from initial evaluations were that the detection of SSVEP is considerably better for healthy users than for Cedar tenants. The median area under curves (AUCs)[2] for healthy users was 0.93, while the median AUCs for Cedar tenants are 0.72.

Participants in this experiment included 11 Cedar tenants (five males, six females, mean age 37.9 ± 9.7) and 17 controls from a healthy population who could be available at the Cedar location (ten males, seven females, mean age 41.3 ± 10.8).

In general, only a few frequencies are suitable for BCI operation in the HF range. This leads to the problem that a high accuracy may be achievable for independent frequencies but this accuracy does not translate when multiple frequencies are being used as stimuli. In other words difficulties arise in differentiating between responses from multiple flashing LEDs. This problem is compounded when fewer suitable frequencies can be supported. Thus, to increase the number of possible stimuli and consequently the information throughout, one can think of several solutions including: use a single frequency of stimulation but modulate the phase of each stimuli; and encode more than one frequency on a single target (Zhu *et al.*, 2011).

We observed a significant variability for different stimulation frequencies with each participant.

In the testing of a integrated final prototype with healthy participants ($n = 23$) in Spain, the results in general show that 53 per cent of participants could finish all of the three tasks presented to them, 17 per cent were able to complete only the first task, 4 per cent were able to complete the first two tasks and 26 per cent could not complete any of the tasks. The most positive result of this experiment was the high rate of success for these subjects able to use the integrated system. The issue where most of the users were either completely able or unable to use the system requires further work to understand.

Whilst results with the participants in Spain were encouraging, the results with Cedar participants were disappointing and highlighted that significant technical development and fine-tuning would be required to enable this SSVEP paradigm to support people with acquired brain injury.

In summary, a high accuracy for a particular frequency did not necessarily relate to a high accuracy in navigation. A dominant frequency could lead to a misclassification of other frequencies. The results showed great difficulty in achieving a four-way decision path required to navigate the IGUI. Work to enhance the algorithms to enable more accurate differentiation between decision paths was undertaken (Zhu *et al.*, 2011) and in parallel user studies continued with a lower frequency SSVEP algorithm (Volosyak *et al.*, 2011).

Given that the research consistently highlighted that users with acquired brain injury provided lower accuracies as compared to those users without brain injury it is conceivable to suggest that emphasis should be placed on the intelligence behind the user interface and supported applications; including more context aware technology (Zander and Jatzev, 2012; Millán *et al.*, 2010), for example, to minimise the choices to the user dependent on activity in progress. The consequence of this would be to facilitate BCI system navigation with fewer actuating frequencies but using those that provide greater accuracy, promoting a more robust and usable system.

Discussion

While the research undertaken successfully developed a working BCI system that supported a selection of BCI paradigms enabling the control of a range of domestic and multimedia applications (e.g. video player, control of lights, fan, and introduced icon-based communication), the system could not compensate the lower accuracies achieved for the participants with brain injury, therefore failing on the overall aim for social inclusion for users with disabilities. There were several reasons for this outcome.

Trials showed that users with brain injury systematically achieved lower BCI accuracies than their non-disabled counterparts. Ware *et al.* (2010) demonstrate that there is a divide between acceptable user accuracy for an interface and the accuracy actually achieved by the user. Attempts were made to reduce the number of frequencies used within the system thereby reducing the decision choices available for the interface. This was still not successful in providing a robust system, capable for use by non-experts, possibly due to the increased number of elements within the decision path to reach the desired command.

Furthermore, the disabled users were considered within the project as a homogeneous group. The goal of the project had been to mechanise the calibration process for the BCI system to a level that the individual characteristics of the user could be supported without expert intervention. However, clearly this is not the case. There are examples of successful long-term use of BCI for the disabled user (Sellers *et al.*, 2010), but what seems clear from the literature is that such systems are uniquely customised for particular users with expert assistance available.

Other factors such as concentration, perception, movement, fatigue, and cognitive load of the interface all influence the use of the BCI system. In all electronic assistive technology there is a level of expert intervention at initial setup (e.g. Dynavox EyeMax for eye-tracking), and with the added complexity of the BCI system it seems realistic to expect a similar if not more involved setup process.

One of the major factors is the lower BCI accuracy for the users with brain injuries. It could be that, alternative tailored BCI paradigms could offer the accuracies required for operation, but just consider how best to operate BCI under these conditions? Effort is needed to develop the surrounding system to the BCI with inbuilt intelligence, a concept of ‘‘shared autonomy’’ as voiced by Millán *et al.* (2010). Context aware information (Martin *et al.*, 2007) could be included or hybrid BCI established (Pfurtscheller *et al.*, 2010; Allison *et al.*, 2012). The specific needs of the disabled user have to be investigated further and the BCI system designed accordingly.

Conclusions

The need for home-based technical solutions to support the inclusion of people with acquired brain injury grows year on year – both as medical advances ensure people survive trauma and there is a move away from acute care into the home environment. From a practical view point it is obvious from the research and evaluation of the BCI system that to be useable in a domestic environment the system needs considerable rationalisation, including hiding the complexity of the various items of the equipment from the user, reducing the bulkiness of the equipment and reducing the wiring involved. Furthermore, with respect to wheelchair users the equipment would have to be of a size to be portable and with no dependency on a mains power supply. Concerning the use of LEDs for stimulation the participants found this acceptable. One participant needed help to maintain the position but was able to rest her head. This is not possible with her current form of assistive device, which is a Dynavox system where she controlled a pointer using her mouth and consequently smooth movement is difficult.

The overhead and logistics of removing the technology from its initial laboratory setting to a second technical team and thence to the Cedar environment was considerable. This demonstrates that the tasks involved in ensuring that the technology is transferable and usable should not be underestimated. This includes provision of accurate technical documentation, provision of technical support and ensuring that all technology is freely available. Furthermore, for use in a domestic setting a considerable amount of end-user training support would be required. This would include devising dedicated training documents and provision of ongoing technical support.

In terms of the challenges that lie ahead for the research, a general one is to develop an interface that remains intuitive to a broad range of users for the diverse range of applications expected to be made available for use. The key challenges to be tacked for BCI systems to be more successful in the mainstream can be enumerated as:

- *Portability*. Ensuring that systems work as well in the field as in the research lab.
- *Mobility*. Ensuring that systems can work at home, work, in wheelchair, etc.
- *Configuration*. Ease of calibration or configuration of these complex systems encompassing initial setup and subsequent use.
- *General efficacy*. Ensuring that BCI systems work as well for brain-injured people as for non-disabled users.
- *General applicability*. Ensuring that BCI systems integrate more easily into a broad range of different types of home-based automation and assistive technologies.
- *Deployment*. Enabling easier deployment of systems by users and their support staff.

Each of these challenges requires significant research effort across different technical domains in order make progress and help build BCI systems that are more usable by a broader population of people. However, the most significant challenge identified in our research is that of achieving general efficacy of use of BCI systems. It is unfortunate that those people with acquired brain injury who may potentially receive maximum benefit from using BCI systems are those identified in our research as a group who systematically achieved lower accuracies than non-disabled participants. Our research identifies that BCI systems need to be able to compensate for this lower efficacy of use by those with brain injuries. As the nature of the injury may directly affect the quality of the BCI signal for a brain-injured user, the compensation by the BCI system needs to be capable of being individually configured for that user.

This individually configured compensation may be viewed as a form of personalised shared autonomy and indicates that more research is required on so-called ‘‘smarter’’ BCI systems using hybridization and intelligent control (Allison *et al.*, 2012).

Notes

1. University of Ulster Ref: REC/09/0034.
2. AUC, where curve is receiver operating characteristic curve – AUC is measure of operating performance and is a good indicator of the detectability of the SSVEP at the stimulation frequency.

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