Adaptive Personalisation for Researcher-Independent Brain-Body Interface Usage

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Abstract

In this case study, we report what we believe to be the first prolonged in-situ use of a brain-body interface for rehabilitation of individuals with severe neurological impairment due to traumatic brain injury *with no development researchers present*. We attribute this success to the development of an adaptive cursor acceleration algorithm based on screen tiling, which we combined with an adaptable user interface to achieve inclusive design through personalisation for each individual. A successful evaluation of this approach encouraged us to leave our Brain-Body Interface in the care settings of our evaluation participants with traumatic brain injury, where it was used with support from health care professionals and other members of participants' care circles.

Keywords

Neurorehabilitation, Brain-Body Interfaces, Brain-Computer Interfaces, Cyberlink™, Assistive Technology.

ACM Classification Keywords

H5.2. User Interfaces, Input Devices and Strategies.

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CHI 2009, April 4 – April 9, 2009, Boston, MA, USA

ACM 978-1-60558-247-4/08/04.

Introduction

Brain-body interfaces (BBIs) do not depend on the brain's normal output pathways such as speech or gestures, but instead use electrophysiological signals from the brain. This makes them suitable for usage by individuals with traumatic brain-injuries that may rule out all other forms of communication.

Diagnostics and measurements of brain injuries have progressed with new techniques such as Functional Magnetic Resonance Imaging (fMRI) [8], but rehabilitation usage by members of the care circle without researcher support is more demanding than usage in laboratory or controlled clinical settings. BBIs enable individuals with traumatic brain injury to communicate, recreate or control their environment, but these novel technologies are unknown to the typical care circles for brain injured individuals [15-18]. Thus while we still see annual news reports on individuals controlling computers with their brains [17] (which our research group have achieved with individuals with traumatic brain injury in their care settings for almost a decade [12]), there is no guarantee that novel BBI usage in research settings will translate into usable technologies in the usage contexts where they are of most value as the only viable form of communication and environmental control. In this case study we report what we believe to be the first prolonged in-situ usages of a BBI *without development researchers present* in the rehabilitation of individuals with severe neurological impairment.

There are two types of BBIs, namely *invasive* (signals obtained by surgically inserting probes inside the brain) and *non-invasive* (electrodes placed on body).

Invasive Brain-Body Interface devices

Various protective tissues, the skull, blood flow and other brain matter between the scalp and area of the brain generating the signal can distort the bio-potentials drawn from the outside of the scalp. Hence invasive electrodes can give better signal to noise ratio and obtain signals from a single or small number of neurons [15, 16]. This is an extreme response to the problem of noisy signals from BBIs. While this may ultimately restore motor control over limbs to individuals with severe neurological impairment (perhaps indirectly via BBIs for wheelchair control), for general communication and environmental control, it is best avoided due to the costs and risks associated with surgery.

Non-Invasive Brain-Body Interface Devices

Brain activity produces electrical signals that can be read by electrodes placed on the skull, forehead or other part of the body (the skull and forehead are predominantly used because of the richness of bio-potentials in these areas). Algorithms then translate these bio-potentials into instructions to direct a computer, giving people with brain injury a channel to communicate. Various research groups have developed non-invasive BBIs using approaches such as Electrooculography (EOG), Electroencephalography (EEG), Electromyography (EMG), Magnetic Resonance Imaging, Slow Cortical Potentials (SCP), Electrocochleography (ECoG), Neuroprosthetic signals and low-frequency asynchronous switches [15, 16].

The Growth of Brain-Body Interface Research

Research has been carried out on the brain's electrical activities since 1925. Brain-body interfaces, also called brain-computer interfaces (BCIs), provide new

augmentative communications channels for those with severe motor impairments. In 1995 there were no more than six active BCI research groups. By 2000 there were more than 20, and now more than 30 actively research BBIs [45]. The cost, size and complexity of many research systems obstruct evaluation with participants outside research laboratories. Thus most BBI evaluations have been laboratory exercises (Tables 1 and 2), albeit with some encouraging results. However hospitals and nursing homes can be reluctant to explore BBI usage, with ethical issues associated with gaining informed consent from adult brain injured

patients, plus concerns over litigation. However, such concerns only become active when BBIs can actually be used in care settings. Much research has only involved able-bodied use in laboratory settings, which may not generalise to use by people with traumatic brain-injury in their typical care settings. Many existing BBIs need complicated setups and extensive computer analyses (often impossible via real-time algorithms). They also mostly have user interfaces with fixed configurations. Tables 1 and 2 support our claim for the first prolonged researcher-independent use of BBIs in everyday rehabilitation and care settings.

Dates	Researcher/ Research Group	Brain-Body Interfaces	Participants	Outcome
1997 - 1999	Craig and his team	Alpha wave based	21 able-bodied and 16 disabled	95% able and 93% disabled success rates, used eye closure to switch devices [9, 10].
1997 - 2000	Kostov and Polak	EEG based	1 able-bodied and 1 disabled	70 - 85% success in moving a cursor in real-time [28, 29, 30].
1991 - 1998	Wolpaw and team	EEG based	5 able-bodied	41 - 90% success in moving a cursor around a screen [34, 47, 48].
1990	Keirn and Aunon	EEG based	5 able-bodied	90% success in choosing 1 of 6 letters [24].
1990	Barreto and team	EEG and EMG based	6 able-bodied	Moving a cursor around a screen and also mouse clicks. Success rate not given [3].
1990	Knapp and Lusted	EEG, EMG and EOG based	1 disabled	Move a cursor. No other data available [33].
1996	Knapp and Lusted	As 1990	6 able-bodied	65% success in hitting a target on screen [2].
1999 - 2002	Doherty and team	EEG, EMG and EOG based	3 disabled	60% success in hitting on screen target [11].
1994	Pfurtscheller and team	EEG, EMG and EOG based	4 able-bodied	50% success in extending a bar on screen [23].

Table 1. Summary of non-invasive Brain-Body Interfaces

Dates	Researcher/ Research Group	Brain-Body Interfaces	Participants	Outcome
1999	Pfurtscheller and team	EEG, EMG and EOG based	4 able-bodied	87% success in extending a bar on screen [38].
2001	Pfurtscheller and team	EEG, EMG and EOG based	3 able-bodied	70 - 95% success in extending a bar on screen [39].
1988 - 2000	Donchin and team	P300 based	10 able-bodied and 4 disabled	Able-bodied selected 6 - 8 letters per minute while disabled selected 3 per minute [12].
1998 - 2003	Bayliss and Bollard	P300 based	5 able-bodied	50 - 90% success in completing virtual driving [4, 22].
1999 - 2003	Birbaumer and team	SCP based	5 disabled	75% success in using the developed spelling device [6, 41].
2003 - 2007	Birbaumer and team	EEG, fMRI, SCP based	5 able-bodied and 6 disabled	Average one letter per minute [6].
2002 - 2007	Birch and Mason	LF-ASD Based	5 able-bodied and 2 disabled	78% able and 50% disabled, success in producing signals [7].
2002 - 2007	Cheng and team	SSVER based	13 able-bodied	62% success in sending information to a computer [5].
2003 - 2007	Weiskopf and team	fMRI based	No data available	No data available [46].
2000 - 2008	Akoumianakis and team	Adaptive user interfaces and interface agents based	No data available	No data available [1].
2004 - 2008	Navarro	Bluetooth based	No data available	No data available [37].

Table 1 (continued): Summary of non-invasive Brain-Body Interfaces

Dates	Researcher / Research Group	Brain-Body Interfaces	Participant	Outcome
1999 - 2000	Kennedy and team	EEG and EMG based	5 able-bodied and 2 disabled	78% able and 50% disabled, success in producing signals [25, 26, 27].
1999 - 2007	Levine and team	ECoG based	13 able-bodied	62% success in sending information to a computer [32].
2005 - 2007	Birbaumer and team	ECoG based	No data available	No data available [31].
2004 - 2007	Stanford University	Neuroprosthetic Based	No data available	No data available [21].
2002 - 2007	Tsinghua University	Motor Functions Based	No data available	No data available [36].

Table 2. Summary of invasive Brain-Body Interfaces

Inclusive Design of BBIs

Our research goal was an inclusive interface that can be personalised for individual needs for use outside of research laboratories. The main challenge was the inconsistent control of the cursor caused by 'irrelevant' electrooculargraphic (EOG), electro-myographic (EMG) and electroencephalographic (EEG) signals being picked by the BBI. These bio-potentials have a low voltage range of micro volts to mini volts, which makes control of a cursor difficult due to unwanted 'noise'.

An Interaction Design Approach

The basic design solution chosen to address these challenges to calculate the directions of travel and 'push' the cursor towards the intended target through discrete tiles that could direct cursor movement [20].

Rather than try to improve signal processing algorithms or hardware designs to reduce noise, we took an *interaction design approach* that would combine pushing the cursor in the intended direction using an approach called 'discrete acceleration' with personalisation to match individual capabilities. This would reduce the impact of noise and consequent erratic involuntary movement of the cursor on an individualised basis, by providing users with a fixed set of customised targets that best matched their capabilities and needs [20]. An example of a resulting user interface is shown in Figure 1.

Schlunbaum [43] distinguished between an *adapted* user interface (adapted to the end user at design time),

an *adaptable* user interface (end user themselves may change) and an *adaptive* user interface (interface that changes its characteristics dynamically at run time which is used in this phase). Schneider-Hufschmidt and his colleagues [44] argue that adaptability increases usability. This research aimed to add adaptable features to an adaptive user interface to allow a better match between device demands and user capabilities. This had to be achieved with minimal training time, and allow reconfiguration of the interface at any time.

Figure 1. An example user interface showing targets (dark blue, labelled), tiles (mauve speckled) and gaps between them (yellow)

An Adaptive User Interface

Our BBI followed Masliah and Milgram's recommendation of a goal-directed process as a means of communication via assistive technology [35]. Our BBI combined a 'Starting Area', targets, tiles, and gaps

between them (Figure 1). A 'Starting Area' and a target provided the end points for goal-directed navigation.

A practice program was used to setup targets for each individual BBI user on the basis of individual performance during a practice session [20]. This provided an initial configuration of the interface that was matched to an individual's ability. The targets appeared on the screen at random. There were twenty-four targets to hit if possible (Figure 2), the fastest to reach targets were chosen for the individual interface. The number of targets to be used in the interface was set by the carer. The target test can be re-run at any time to improve user performance.

Figure 2. Target Practice Interface

An Adaptable User Interface

Once an initial target layout has been created, this can be further personalised. The interface can also be fully configured manually for users with the most severe

brain injuries who cannot carry out a target test. Here, a carer decides where to place targets.

Figure 3. Personalising the interface

Further flexibility is provided by adaptable dimensions, fonts and colours, which can cater for colour blindness and other visual impairments [19]. Tile dimensions, dwell times, label fonts and colours can be configured by carers. Figure 3 shows a dialog box for setting timing parameters. Figure 4 shows the target configuration dialog, Figure 5 the starting area configuration, and Figure 6 configuration of actions associated with targets (this requires some low level hardware expertise and is researcher-configured). The BBI capabilities illustrated in Figure 6 extend effective interaction for some users to tasks beyond simple communication. Once the target test has been completed, each target can be used for a range of

purposes, i.e., target text to audio communication, control via a computer port of an external device, or launching a computer application [20]. Together, these dialogs allow personalisation to suit individual needs and abilities. Target Caption text (Figure 6) is converted to speech output when a target is hit. This gives a voice to a brain injured user to say “Yes”, “No”, “Thanks” or any text entered by a carer or researcher.

Figure 4. Configuring targets

Figure 5. Configuring starting area

Figure 6. Window for configuring individual targets

Figure 6 shows that a string of binary (8 bits) can be sent to a parallel port to switch devices on/off using the 'Send Message to Port' capabilities. Devices attached to parallel port read the binary string sent to it and respond accordingly. This supports capabilities such as switching on devices such as a TV, Radio, or CD player. Also, any application installed on the laptop can be launched by entering the file name and the location. The application requested will be launched on the screen and will be displayed for a pre-configured time, which enables a user to view sites such as news sites or sports sites. Thus as well as communicating, our BBI users can switch devices or launch computer applications [16, 20].

Summative Evaluation

Reinhold and team state [41] that BCI systems have to convey information as quickly and accurately as needed for individual applications, have to work in most environments, and should be available without the assistance of other people (self-initiation). There are various challenges associated with the characteristics of people with traumatic brain injury such as individual, disabilities and abilities, effect of medication on individual participants, attention span of an individual and emotions and frustrations when research was being carried out. The BBI developed in this research was designed to provide sufficient flexibility to address these challenges through personalised timings, target dimensions and other interface features to cater for the needs of each participant. This flexibility was intended to provide opportunities for grounded evidence-based performance-improving personalisation by carers, parents/guardians and any support staff. Members of brain-injured individuals' care circles have better knowledge of them than researchers. We thus hoped

that this knowledge could be well utilised when configuring interfaces manually or using the adaptive target setup.

We needed to evaluate whether the developed BBBI was inclusive and could be used by any brain-injured user, unless comatose or suffering adverse effects of daily medicine intake. The approach chosen was to design, develop, evaluate and optimise using able-bodied participants and then evaluate an optimised version with brain-injured participants.

There were three iterations of the design before arriving at the one illustrated in Figures 1-6 above. Final evaluations with brain-injured participants were carried out at Holy Cross Hospital (Surrey, UK) and Castel Froma nursing home (Leamington Spa, UK). Both these institutes are rehabilitation centres for brain-injured individuals. The formal evaluation lasted from September 2004 to September 2005 [16]. Previous formative evaluations had been carried out as part of exploratory research in Delhi (11 able-bodied and 19 disabled participants, July/August 2002), with a Focus Group in Milton Keynes (5 able-bodied participants, January to July 2003) with evaluation and optimisation in various homes in Surrey (10 able-bodied participants, July/August 2004) [16]. These formative evaluations provided the evidence for the suitability of the design reported in [18-20]. The evaluations and subsequent usage described here have only recently been partially reported in the first authors' PhD thesis [16].

The interface program was configured by the researcher or a carer. Figure 7 shows a setup that could be used by brain-injured participants without any

researcher or brain-computer interface expert present. An external 19 inch LCD screen was placed in front of the participant, running an interface program written in MS Visual C++. The apparatus was easy to setup using laptop computer and a non-invasive Brain-Body Device called, Cyberlink™. The three electrodes of the BBI were placed on the forehead of the participant using a head-band (Figure 8). This whole set-up fitted on a table that can be placed close to participants. Bio-potentials from the BBI were fed into a laptop computer, which faced away from the participant, in order for the researcher or a carer to launch and configure the interface as required. From this point onwards, brain-injured individuals were able to use the system without any further configuration.

Figure 7. Evaluation Set Up

Figure 8. Cyberlink™ with electrode head band

Consent was obtained from the institutes to work with ten nonverbal brain-injured participants. Hospital staff, parents and guardians evaluated each BBI before consenting to evaluations with brain-injured participants at their premises. After the first two visits, five out of the ten participants were chosen (Table 3). The other five had severe visual impairment, which prevented them from using the BBI, hence they could not participate in the evaluation.

Part. No	Institute	Gender/ Age	Clinical Diagnosis	Additional Information
45	Holy Cross	M38	Locked-in syndrome	Non-verbal, can respond by thumb occasionally
46	Holy Cross	F61	Severe cerebral haemorrhage, brain stem injury	Non-verbal
47	Holy Cross	M45	RTA, Diffuse axonal brain damage	Non-verbal. Can use a foot switch but it takes a lot of effort from the participant
48	Holy Cross	M60	Brain stem injury	Non-verbal
49	Castel Froma	M32	Traumatic Brain Injury	Non-verbal

Table 3. Details of the participants used for summative evaluation and subsequent independent usage

The evaluation was carried out to establish whether brain-injured participants could give consistent answers using the BBI developed in this research. At first, data from each disabled participant was collected once or twice a week (Wednesday and/or Fridays), depending on the availability and health of the participants. Data collection sessions lasted twenty minutes to one hour, with one or more breaks as needed for each

participant. The number of targets ranged from two to six depending on severity of disability. Data recorded were: percentage of targets reached to indicate correct answers, behaviour of participant, any reconfiguration of interface, changes in medication, duration of visit, and other input devices used, as participant 47 could use a foot switch. This gave an opportunity to double check the answers given by the user interface [20].

Also, encouraging feedback was received from the locked-in syndrome participant (45, Table 3), who used his thumb to indicate approval.

Participants had a 75% success rate for consistent answers within the preset time configured for their interface. As there was always an opportunity to try again, we could claim 100% consistency when communicating using our BBI. Discrete acceleration with personalisation was thus shown to improve performance relative to previous usage of BBIs in care settings (e.g., [12]).

Independent Usage

As a result of a successful formal evaluation, a decision was made to leave the BBI on-site for independent usage with no researcher present at the Holy Cross Hospital for three weeks in a month, and for one week every month at Castel Froma for independent usage by the carers and medical staff. This independent usage study lasted for seven months, confirming that our BBI could be used independently.

Two research collaborators have provided email feedback [9, 14] in support of our claims of independent usage and have agreed to its use in research publications. A speech therapist at Holy Cross from 2002-06 has confirmed [14] that our BBI:

“is a simple portable idea that didn't require Paul's [first author's] presence and was left at the hospital without him being there to set-up, configure or use. Paul left the kit at the hospital for carers/guardians to use it in my absence.”

A mother of one participant [9] forwarded a document that summarised her experiences with her son 'J':

“ I have enjoyed the trial period I had with Cyberlink™.

I have had no difficulty using it once shown - except for a few email exchanges - and a 32" screen on the wall close to [J] gives him the chance of seeing the games and what he is trying to do - e.g. he was able to make the 'Grow Game' work ... and wasn't worried by the contact probes attached to his head by the headband - no different to a sweat band!

[J] managed to do this after a very short time and seemed to enjoy it with the recent smiles he has been giving us.

It is easy to carry as it is only a laptop plus head band and small amplifier.

It is something I would love to continue using with [J] as it is so easy to use and doesn't appear to create any problems.”

Since this study, there was further independent usage with 'J'. Adaptations were made to improve cursor visibility. 'J' has not survived to evaluate this improved function, nevertheless this option will be evaluated and added to the adaptable personalisation capabilities of our BBI to meet a wider range of individual needs and will help up to improve personalisation for cursor visibility with future users.

Participant	Used text to audio	Launched applications	Switched devices
46, 49	Yes	No	No
45, 47, 48	Yes	Yes	Yes

Table 4. Evaluation Results (consistent answers and independent usage)

Table 4 summarises the independent usage achieved. All five participants could communicate using the Cyberlink™. They could use the Cyberlink™ according to their specific capabilities via their personalised interface. Communication took the form of asking participants various questions connected with their day to day tasks, e.g., Do you want the CD player on? Do you want the curtains closed? Would you like a bath? Are you tired? How many targets do you see in the screen? Several participants had problems with their eyesight and were greatly encouraged by audio feedback that enhanced their experience by converting target button labels to speech output.

Participants 46 and 49 were only able to use the interface to communicate using a two target Yes or No interface, due to the severity of their brain injury. As Table 4, shows, the other three participants (45, 47 and 48) could launch applications such and switch devices. Participant 47 had days where he wanted to be left alone, which reduced his recorded success rate. However, on his good days, he used the BBI to communicate, switch devices and launch applications. Participants 45, 47 and 48 had television and music systems in their room and showed interest in doing

more with the interface than other participants. The ability of these three participants to do more than communicate demonstrated the superiority of a personalised inclusive user interface that can expand or shrink the number of targets to match an individual's capability. These participants used the interface to control devices, and also launch applications such as an Internet browser with a home page suitable for unattended reading, e.g., a non-scrolling sports page that automatically refreshed as news was updated. The browser closed after a pre-configured period (e.g., 45 or 60 minutes). This let a participant read web pages of interest for a suitable period.

Subsequent and Current Work

Further research on independent usage has been carried out after the completion of the above study. Such studies have to be time limited for several reasons. We do not have the resources to leave current equipment in place for lengthy periods due to its expense. Also, permanent usage would require institutional support. Current research is focused on creating BBIs that can convince care institutions of their value. Although some health professionals and care circle members are convinced of the usability and value of our BBI, formal adoption as a therapeutic rehabilitation device will require evidence that we currently have neither the resources nor the professional credentials to be able to provide. Also, there are ethical issues arising from creating dependencies that we cannot support, i.e., we are unable to provide constant timely and effective hardware and software support to a geographically dispersed group of participants. Consequently, we cannot yet let our BBI become a fixed, permanent and indispensable part of people's daily routines.

A further challenge to longitudinal research here is the frailty of participants with traumatic brain-injury, which is often associated with impaired immune systems and thus high susceptibility to infection. Participants 45, 46 and 49 have died since the formal evaluation.

A related study on independent usage has been conducted with a group of eight visually impaired participants in Colombo, with a success rate of 80% in correctly answering a question on first attempt. These participants were able to use their forehead muscles (EMG via Cyberlink) to say Yes or No to the questions that were being asked. The researcher sent the interface system and studies were conducted by a colleague of the researcher without the development researcher present [18]. Further research is needed in support of this user group.

A current study is being carried out with a new recent participant who is not only able to use the interface described in this paper, but also pick individual letters and make short sentences using onscreen keyboard developed as a by product of the research reported above [16]. This participant enjoys hearing books read to him, he was also scrabble player and enjoyed painting. Although accessible applications for these activities exist for some categories of impairment, none have been developed for traumatic brain injury. Currently applications are being developed to cater for this user, building on existing work (e.g., letter selection for scrabble). As with the ongoing work with 'J', during development and use of new applications, we may encounter further needs for adaptable personalisation to complement adaptive aspects of our BBIs.

To make the BBI systems available at minimum cost, two new devices for gathering brain waves are being considered for future work in conjunction with low cost laptops and displays (where prices have dropped considerably since our formal evaluations). Two devices being considered are the *NIA* (Neural Impulse Actuator) and Emotive Systems' *Neural Games Controller* headset. As well as bringing down the costs of purchase, we need to ensure that the systems are reliable and can be used without regular developer intervention, as well as allowing sufficient personalisation capabilities as we extend the functionality of our BBIs.

Conclusion

A BBI was left at the premises of Holy Cross Hospital and Castel Froma nursing home for independent usage without the development researcher present. Carers were able to use it as part of their routine communication with the severely impaired individuals. The carers had a routine list of questions written and kept in participants' rooms, which were used for communicating with the participants at various times of the day without the researcher being present. All five brain-injured individuals able to participate in this research could use our BBI to varying degrees to communicate and control applications. This demonstrated the inclusivity of the adaptable adaptive user interface, excluding only participants who were comatose or adversely affected by daily medicines.

As a result of this successful formal evaluation, we left our BBI for use by two participants over periods of several months. This confirmed that we have developed a portable BBI that can be used in the field outside the laboratory environment to carry out

independent usage for daily routine communications. We continue to develop this BBI further in a range of settings, and hope to be able to collaborate with health care professionals to develop and validate a system that is suitable for institutional adoption.

Acknowledgements

We are grateful for the support following institutes for allowing access and providing a research base: Vimhans Delhi, Mother Theresa's Mission of Charity Delhi, Holy Cross Hospital Surrey and Castel Froma, Leamington spa.

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