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Usability and Performance Measure of a Consumer-grade Brain Computer Interface System for Environmental Control by Neurological Patients

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Abstract

With the increasing incidence and prevalence of chronic brain injury patients and the current financial constraints in healthcare budgets, there is a need for a more intelligent way to realise the current practice of neuro-rehabilitation service provision. Brain-computer Interface (BCI) systems have the potential to address this issue to a certain extent only if carefully designed research can demonstrate that these systems are accurate, safe, cost-effective, are able to increase patient/carer satisfaction and enhance their quality of life. Therefore, one of the objectives of the proposed study was to examine whether participants (patients with brain injury and a sample of reference population) were able to use a low cost BCI system (Emotiv EPOC) to interact with a computer and to communicate via spelling words. Patients participated in the study did not have prior experience in using BCI headsets so as to measure the user experience in the first-exposure to BCI training. To measure emotional arousal of participants we used an ElectroDermal Activity Sensor (Qsensor by Affectiva). For the signal processing and feature extraction of imagery controls the Cognitive Suite of Emotiv's Control Panel was used. Our study reports the key findings based on data obtained from a group of patients and a sample reference population and presents the implications for the design and development of a BCI system for communication and control. The study also evaluates the performance of the system when used practically in context of an acute clinical environment.

Keywords: stroke, rehabilitation, brain-computer interface, electroencephalography, emotiv EPOC

1. Brain—Machine Interface: Closer to Therapeutic Reality?

Brain Computer Interface (BCI) systems are considered one of the innovations that can potentially change the management of disability for the human race. Global interest in the use of BCI in neurorehabilitation and the ethical challenges stemming from that encompasses a diverse group of professionals [1]. BCI systems establish a direct link between a brain and a computer by transforming some measurable neurophysiological signals into computer commands for devices such as computers, switches or prostheses [2-6] without the use of any motor control by users [7- 8]. The clinical use of BCI consists mainly of application to patients with substantial deficits in communication and motor function [4, 9-10]. Studies have shown that the use

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of BCI systems aid faster recoveries in patients with both mental and physical traumas when compared to those who undergo traditional rehabilitation methods [11-12]. In BCI systems signals from the brain can be measured by detecting an electric field (electro-encephalo-graphy-EEG, electro-cortico-graphy –EcoG etc.) or a magnetic field (magneto-encephalo-graphy - MEG), functional magnetic resonance imaging (fMRI) and several other ways [13-14]. Amongst the various methods EEG has proven to be a better choice for use in the clinical environment and in real-time systems due to its portability and lower cost [15]. Several studies indicate that patients with severe motor disabilities require alternative means of communication and surface EEG signals can be used effectively to interact with the outside world by operating external devices [6, 16- 18].Thus BCI has importance particularly in the context of the rehabilitation of severely limited patients. One of the objectives of our study was to investigate the viability of low cost BCI systems to assist neurologically disabled patients, we have chosen an EEG based BCI system for our study which is relatively inexpensive and non-invasive.

Consumer-grade non-invasive BCI systems are available in user-friendly styles such as baseball caps [19] headbands [20] and headsets [21] and provide both an easy setup process and freedom of postures for users; this makes the application of BCI systems in both healthcare and the entertainment industry much easier than ever. In this paper, we will investigate the use of a consumer-grade BCI system as an assistive technology device for communication and control for patients with neurological conditions. The study was part of a collaborative research program between the University of Kent and East Kent Hospitals' University NHS Foundation Trust, both in the UK. Participants involved in this HCI research study were patients on the neuro-rehabilitation unit at the Kent and Canterbury Hospital. Study participants had been diagnosed with a range of neurological conditions (e.g. Acute Brain Injury, Multiple Sclerosis, Motor Neuron Disease, Cerebral Palsy, Stroke). An equivalent number of healthy participants were recruited as controls.

The remainder of the paper has been organised as follows: Participant demographics and apparatuses used in the system are described in Section 2 followed by a description of the experimental procedure in Section 3. Section 4 reports the results. Section 5 concludes the paper.

Table 1 Demographics of participants

Participant	Gender	Age	Neurological Condition
Patient 1 (P1)	Female	74	Right Brain Stroke
P2	Male	67	Multiple Sclerosis
P3	Male	48	Multiple Sclerosis
P4	Female	22	Cerebral Hemorrhage
P5	Male	45	Multiple Sclerosis
Control 1 (C1)	Male	37	-
C2	Male	27	-
C3	Male	26	-
C4	Male	25	-
C5	Male	43	-

2. Participants and apparatuses

The study was piloted with two participants; data from these two pilot sessions was not included in the analysis. Ten participants took part in the usability sessions; five controls and five patients with neurological conditions with different kinds of lesion(s) e.g. discrete & diffuse, static vs progressive & diagnostic diversity e.g. MS, Stroke. The inclusion criterion for patients was that the patient must not have had prior experience in using BCI headsets so as to measure the user experience in the first-exposure to BCI training and to evaluate the learnability and usability of these BCI systems. Participant Demographics are listed in Table 1. The research was conducted after approval from the ethics committee of the University of Kent.

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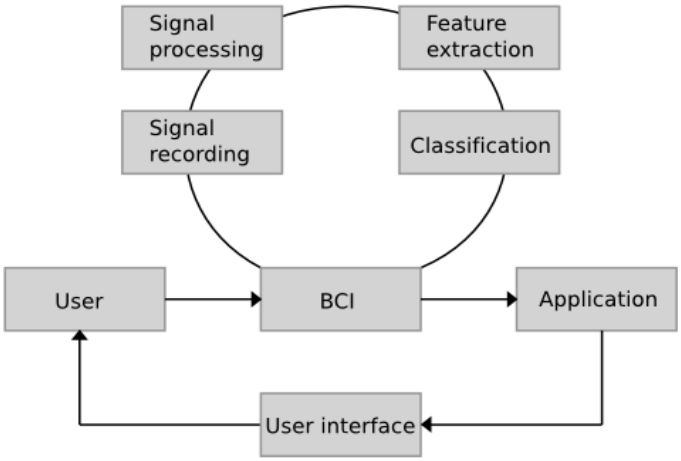

Fig. 1 A BCI application system adapted from [22]

Although various types of systems exist, Fig. 1 shows a typical non-invasive EEG BCI system which was used in the study. The system consists of several core components with specific functions [22]:

- Signal recording to capture the EEG
- Signal processing, which removes noise and artefacts from the EEG
- Feature extraction, which identifies EEG features relevant to the context of application
- Classification, which involves training a computer algorithm with a subset of the extracted features and using the trained classifier to classify the rest of the data. This component provides an interpretation of the raw EEG signals
- Activation of the chosen application, e.g. a radio, television, video player
- Feedback to the user, which in turn reinforces the process. The implementation of a BCI system in a particular context (e.g. in neurorehabilitation) normally involves both an application and a user interface. While a BCI system transforms EEG signals into an appropriate output to control the selected application (e.g. electronic devices or computers), the activation of the application converts these control signals into feedback (i.e. stimuli such as audio, visual or haptic), through a user interface.

The usability sessions involved measuring emotional arousal of participants with ElectroDermal Activity Sensors manufactured by Affectiva, the Qsensor [23] is shown in Fig. 2(a). The Qsensor is comprised of electrodes for measuring temperature, electro dermal conductance (in microsiemens), and an accelerometer (measuring acceleration in G) with sampling rates of 2,4,8,16, and 32 Hz. The dimensions of the wrist-worn band are 14.7mm × 56.6mm × 31.8mm (h ×l × w) and weighing 22.7grams. The EEG was measured by the Emotiv EPOC EEG headset [24] with 16 sensors as shown in Fig. 2(b). The Cognitive Suite of Emotiv's Control Panel software was used for the signal processing and feature extraction of imagery controls that were used in the session for navigating to the right, navigating to the left, and the action of pushing as shown in Fig. 2(c). Video logging of the training session was conducted using Techsmith Morae's Recorder [25].

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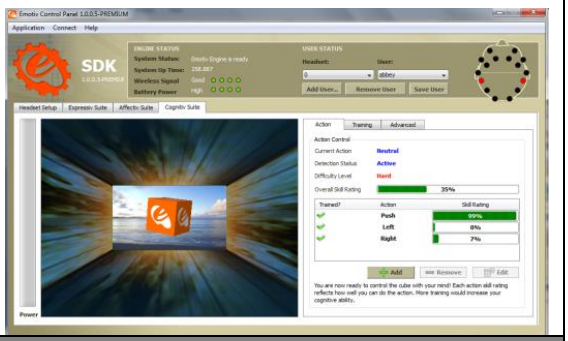
(a)Qsensor	(b) Epoch Headset	(c) Video Logging of BCI Training
		
Measures of Emotional Arousal	Brainwave Activity	Accuracy levels of training the BCI system to navigate left, right and to push

Fig. 2 Experimental apparatus used in the usability sessions

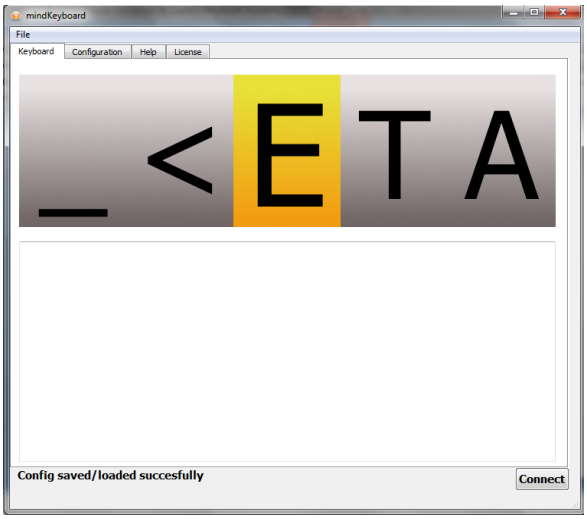
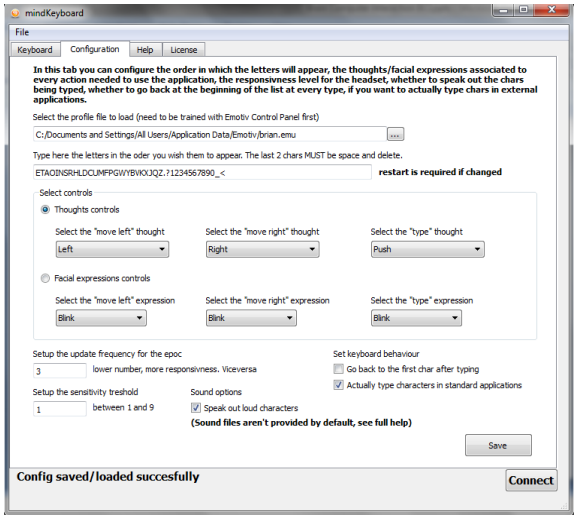
Typing Screen with Horizontal Navigation	Configuration Screen for Though Control
	
Alphabet arranged in order of frequency of occurrence. Back space and space keys depicted with "<" and "_" symbols.	Configuration set to thought control by default; facial expression used to validate if patients fail to initiate any typing control with imagery.

Fig. 3 Brainwave typing interfaces

3. Procedures

The study and the Informed Consent Form (ICF) received approval from the Ethics committee of the University of Kent. All patients were screened for eligibility; e.g. patients with epilepsy and user of other neuro-stimulators or pacemakers were ruled out. Participants were tested individually. The procedure for conducting the usability evaluation sessions for the BCI system is depicted in Fig. 4. Sessions started with a brief overview of the study's objectives and obtaining informed consent. Following that, the Qsensor bracelet was setup with Electro Dermal Activity (EDA) sensors placed on the inner part of the participant's wrist. Time was allocated for the EDA sensors to warm up until the indicator showed a blinking green light. The demographic questionnaire was presented to participants; patients who needed assistance in completing the demographic questionnaire were presented with each question verbally and they either answered directly or via their caregiver; responses were noted accordingly. After completion of questionnaire, the fitting of EPOC headset proceeded by hydrating the 16 sensors and adjusting the placement of the sensors on the participant's scalp. The Emotiv Control Panel's Headset Setup panel was used to ensure that sufficient quality of readings were obtained from all 16 sensors. The fit was adjusted so that the rectangular

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compartments at the front ends of the headband sat comfortably just superior and posterior the participant's ears. The headset was tilted so that the two lowest, front-most sensors were symmetric on the forehead and positioned 5 – 6 cm above the participant's eyebrows. The headset was fine-tuned by gently sliding the headset in small increments until an ideal fit had been achieved and measured by observing the sensor readings on Emtoiv's control panel.

Procedure
0:00 Briefing - Overview of the study and the session
0:02 Consent form
0:05 Qsensor Setup; Adjusting the wristband; Check for the blinking **green** light
0:07 Demographic Questionnaire
0:10 Launching Morae Recorder; test recording for 15sec; Start recording
0:12 Wearing the Epoc headset; fitting/adjusting 16 sensors
0:15 Launch Control Panel
0:16 Create User Profile; Add User
0:17 Engine Status; check that all sensors have **green** readings
0:25 Training
- Training Neutral state of mind
- Add action Push then train; min 50% (skip to EmoKey if 80+%)
- Add action Left then train; min 50%
- Add action Right then train; min 50%

0:45 Save profile
0:50 Launch MindKeyboard
- Select profile from config tab
- Open the keyboard tab
- Ask participant to Navigate Left & Right
- Ask participant to type hello

1:10 Open EmoKey; Load Mapping push; Open app (video player);
- Connect to Control Panel
- Ask Participant to think "push" to activate key press
- Ask participant to repeat the action 3 times to ensure that activation of the 'push' button did not occur by chance

1:15 End; Switch off headset + Remove Qsensor
1:17 SUS survey & 12pt scale

- Close Morae
- Save & Close the Emotiv sw

1:25 Debriefing

1:30 End

Fig. 4 Experimental procedures

Video logging of the screen interaction was conducted using Morae Recorder [24]. Participants started with the Cognitive suite of the Emotiv control panel to train the device to recognise their EEG patterns during periods when they were imagining right and left movements and the 'push' action button as depicted in Fig. 2(c). The training started with training on patterns for a neutral state of mind, followed by the 'Push' action, then 'Right' or 'Left' depending on the handedness of the participant. When the accuracy level of the first command, 'push' reached the 95-100% the participant proceeded to the next step to test controlling an application with this command. The command was to 'Push' the maximize button on a virtual video player launched with the Emotiv EmoKey application. Following that, training resumed with the navigation buttons, 'Right' and 'Left'. When the training time reached 30minutes or the accuracy reached 50% for both navigation directions, the participants proceeded to the typing application. The Mind Keyboard (an Emotive app) was used for this phase of the experimental evaluation and the participants were requested to type the five-letter word 'hello' by navigating horizontally in the alphabet listing with the 'right' and 'left' imagery movements and selecting the letter with the 'PUSH' command. Interfaces for this segment of the BCI usability evaluation is depicted in Fig. 3.

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4. Results and Discussion

In this section we present the key findings of the research project with a discussion of the measurements examined for patients and controls and their implications for the design and development of BCI systems for communication and control.

4.1. Proficiency with assistive technology

Participants recruited for this study had a range of neurological conditions. The research study's sample is described with IDs of C1-C5 for controls and P1-P5 for patients with neurological disorders. Table 2 lists the self-reported comfort-level of participants with technology in general. Participants in the Patients' group ranged in age between 22 and 74 years (Mean = 51.2 years; Standard Deviation = 20.4 years). Participants in the control group ranged in age between 26 and 43 years of age (Mean = 31.6 years; Standard Deviation = 7.99 years). Participants were requested to self-report their comfort level of technology on a scale ranging from 1 to 5 with values of one indicating 'uncomfortable using technology' and five indicating 'very comfortable'. Since the training of BCI control depends on imagery of navigation in the right and left directions, the participants were requested to indicate their handedness. All participants in the control group and two participants in the patients' group were right-handed, and consequently started the imagery training in the right direction. Three participants with neurological disorders were left-handed and started their imagery training in the left direction. No significant differences in self-reported comfort-levels with technology were found between the two experimental groups; thus the sample was believed to be homogenous with regards to proficiency with technology.

Table 2 Technology background of participants

P/C	Session Date	Comfort Level	Handedness
P1	Jul 16, 2012	3	Right-handed
P2	Aug 3, 2012	3	Right-handed
P3	Aug 3, 2012	3	Left-handed
P4	Aug 6, 2012	2	Left-handed
P5	Aug 7, 2012	5	Left-handed
		M= 3.2 (SD = 1.1)	
C1	Jul 12, 2012	3	Right-handed
C2	Jul 12, 2012	3	Right-handed
C3	Jul 17, 2012	4	Right-handed
C4	Jul 17, 2012	5	Right-handed
C5	20 Jul, 2012	3	Right-handed
		M= 3.6 (SD = 0.89)	

Participants' backgrounds with technology ownership and usage of assistive technology were examined. Participants in the control group all reported owning at least one computer, using the Internet daily and regularly using a word processor for typing. None of the reference population reported using assistive technologies for reading or writing. In contrast, participants in the patient group all reported owning a computer, less than half reported using the Internet on a daily basis or using a word processor for written correspondence. Two out of the five participants reported using assistive technologies for reading and writing. Details are shown in Table 3.

Table 3 Assistive Technology Usage

Participant	I own a computer	I use the internet daily	I use a word processor to complete most of my written correspondence	I use assistive technology for my writing/reading
vP1	Yes	No	No	No
P2	Yes	Yes	Yes	Yes
P3	Yes	No	No	No
P4	Yes	No	No	Yes
P5	Yes	Yes	Yes	No
C1-C5	Yes	Yes	Yes	No

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4.2. User experience in BCI control

The user experience was examined with quantitative measures of emotional arousal detected by EDA sensors which monitor body temperature in Celsius, and movement using a 3-axis accelerometer. Spikes in EDA signals were synchronized with events in the video logs during the training and control sessions. Although regular patterns of emotional arousal were not found across participants, spikes in emotional arousal were found to be linked with frustration levels in difficult training levels and with failure in controlling the typing program to type the word in the experimental session. A sample of the EDA readings (microsiemens) is depicted in Fig. 5.

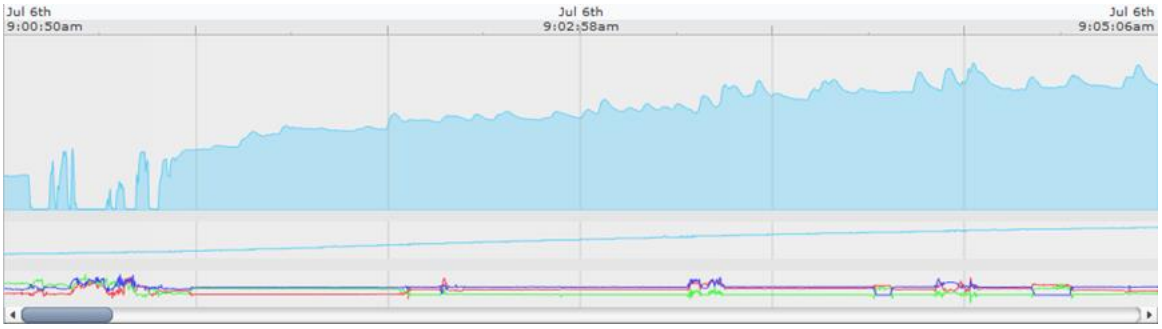

Fig. 5 Emotional Arousal Sensor Readings (EDA, Temperature, Accelerometer)

4.3. Usability measures of subjective satisfaction

The SUS survey (Appendix A) was used to measure the subjective satisfaction in the first exposure to interactive technologies. Results ranged from 27.5 to 60 in the control group and from 62.5 to 87.5 in the patients' group. Overall, participants with neurological conditions reported a higher perceived usability than controls (M=73 and SD=9.91 for patients; M=46.50 and SD=12.94 for controls). Another survey of subjective satisfaction (Appendix B) was used to examine the participants' perceived usability of the BCI device in controlling a typing application, controlling a virtual 'Push' button in a video application. The product evaluation survey completed by the study participants consisted of 12 items with the following choices of responses: 1 = strongly disagree, 2 = somewhat disagree, 3 = neither agree nor disagree, 4 = somewhat agree, 5 = strongly agree.

Table 4 shows the variations between the perceived usability of the BCI system between controls (Cs) and the patients (Ps) on questions #1-5; patients perceived the BCI device as easier to use, more helpful as an assistive technology, and were more comfortable in using the headset than controls. Table 5 lists the self-reported subjective ratings for perceived safety and aesthetics' scales. Interestingly, the perceived ease of use, safety, and aesthetics were higher in the patient population but the perceived negative image of using the BCI headset was stronger in the non-disabled group (scale #8). Patients involved in the study indicated that they are aware of the degenerative condition and the image reflected in wearing such headsets is not perceived as a concern as long as the benefit gained from such device is sought with continued control and easier communication. The final segment of the survey examined the perceived usefulness of the BCI system. The patient group exhibited more positive views regarding the BCI device when compared to the controls apart from the ease of use. However, it was noted that patients indicated that this scale applies to their current state of health and is perceived to change as their level of control deteriorates. Accessibility of the device as indicated in question #12 was a key factor in the enthusiasm exhibited by participants in this study as shown in the significant differences between the patient and control groups on the final scale.

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Table 4 Perceived Usability of Operating the BCI System

#	1	2	3	4
Survey Question	I could easily complete the task with the device	The device helped me to complete the task	It was easy to understand how to operate the device	The device was comfortable to use
M for Cs	1.80	1.60	4.60	3.40
SD for Cs	0.45	0.55	0.55	0.55
M for Ps	3.20	4.40	4.00	4.40
SD for Ps	0.84	0.55	1.22	0.89

Table 5 Perceived Safety, Aesthetical Quality, Reflective Image of BCI Headsets

#	5	6	7	8
Survey Question	Using the device was easy	Using the device felt safe	Aesthetically, I like the overall look of the device	As a "disability product, this device would draw unwanted attention.
M for Cs	2.60	3.60	4.00	3.00
SD for Cs	0.89	0.89	0.00	0.71
M for Ps	3.60	4.60	4.60	2.60
SD for Ps	1.14	0.55	0.55	1.14

Table 6 Perceived Requirements Matching of the BCI system

#	9	10	11	12
Survey Question	I think the idea behind how the device is meant to operate provides a good solution to problems I encounter in everyday life	It was easier to complete the tasks with the device than it was when using my existing equipment	Compared to other products to complete the tasks, the actual functionality of this product is better.	I would be happy to use this device if it were made available to me.
M for Cs	2.25	2.20	1.80	2.80
SD for Cs	1.50	1.30	0.84	0.45
M for Ps	3.60	1.60	2.80	4.60
SD for Ps	1.67	0.55	0.84	0.55

4.4. Performance measure – Controlling Video-player button

In this section, we describe the performance measures on controlling the video-player button. Sessions ranged in duration between 65 minutes to 98 minutes. All participants were able to train on the 'Push' command with accuracy ranging between 80-99%. All participants were able to press a virtual button on a video-player application. The button was the maximize-screen button on the video player. Participants were requested to repeat the action 3 times to ensure that the control was not initiated inadvertently by imaging a similar movement and the video log was checked to confirm that all actions were in sync with the 'Push' button in the Emotiv Cognitive Suite. The action was set with one rule in the EmoKey application. The trigger condition for the action was detecting the imagery pattern of 'Push' for duration of more than 0.2s.

4.5. Performance measure – Typing Accuracy

None of the participants were able to complete the task of typing the five-letter word “hello”. Participants in the control group exhibited more control in navigating the horizontal keypad but were not able to effectively use it to complete the typing task. Sample words that were typed at the end of the session were 'hhhe' and 'heee l' where the participants attempted to fix the words using the backspace button and retyping the letter several times. Participants in the patients' group exhibited lower

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accuracy in training in general, and the right-left navigation in particular when compared to controls. It was observed that training became increasingly complex for both groups as participants advanced from single to double commands and accuracy levels remained at low levels despite allocating the same amount of time for training the system to recognize imagery movements in the right and left directions. An example is the patient's session depicted in Fig. 6 in which accuracy for 'Push' was 97%, 'Left' was 0% and 'Right' was 7%. This patient's performance on the typing task resulted in controlling the horizontal keypad's movement in the right direction with difficulty; however, this participant was not able to reach the letters for completing the word in the task. Given the small number of patients and their conditions it is possible that the lower accuracy for the ‘Left’ and ‘Right’ buttons is not an inherent feature of the device but rather due to capabilities and limitations of the individual patients.

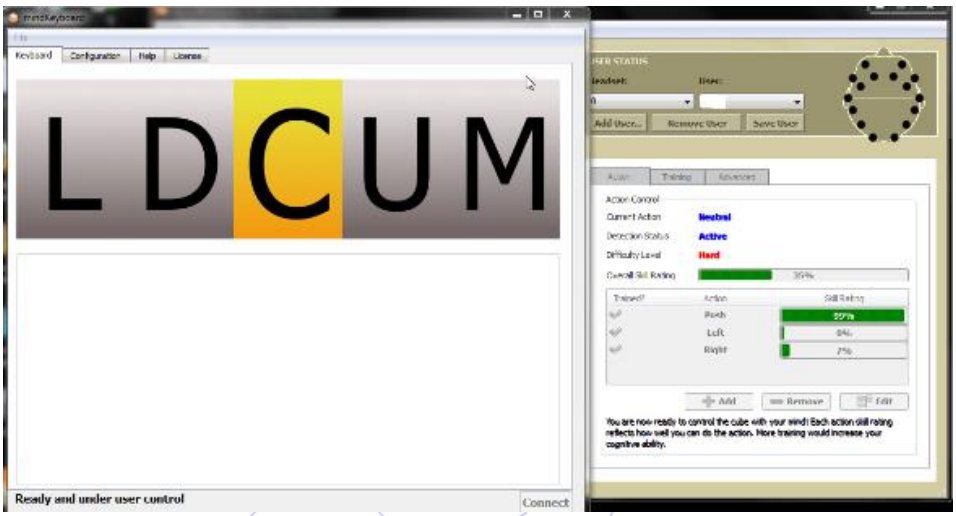

Fig. 6 Example of a participant's training accuracy levels in the typing task

5. Results and Discussion Conclusions and Future Considerations

From the results and discussion we can conclude that the proposed BCI system was acceptable by all the neurological patients who participated in the study and they perceived it safe to use. One of the limitations of our study was the sample size and this was due to the difficulty to find real patients who would voluntarily take part in the experiments. Patients participated in our study were self-selected and enthusiastic with high motivation and interest in technology. The patient group (M=73; SD=9.91) generally perceived the BCI device quite positively compared to the control group (M=46.50; SD=12.94). In terms of tasks performance, all participants in both groups were able to complete the first task successfully. However, none of them were able to complete the typing task. Participants in the control group exhibited more control in navigating the horizontal keypad but were not able to effectively use it to complete the typing task. Participants from the patients group exhibited lower accuracy in training in general, and the right-left navigation in particular when compared to controls. It was observed all participants in the patient group were able to achieve high accuracy levels in the first phase of the training (i.e. the single command).

It has been reported that consumer-grade BCI systems currently face challenges in producing clear EEG signals for control [26, 27]. In such systems, EEG signals can be easily contaminated by various noise sources such as power line interferences and the presence of unwanted physiological signals etc.[28]; this is particularly an issue if there is contamination (e.g. hair, sweat) at the skin-electrodes-scalp interface. A drop in signal quality can lead to a deterioration in the application’s performance and this is likely to have been a contributing factor for the lower performance in the spelling task. It has been reported that currently available consumer-grade BCI systems are not suitable for accuracy-critical applications, instead only being appropriate for applications such as computer games or home appliances [26].

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To improve the accuracy of the BCI system we evaluated, in future we would like to follow the directions recently introduced by researchers by incorporating: (1) hybrid signals [29] and (2) adaptive feedback training [30]. First, hybrid signals composed of two high level parameters such as brain signals (EEG) and other features like facial expressions or eye movements and in such systems accuracy of the task can be improved by adopting complementary classification [31]. Secondly studies have shown that [32] by using user adaptation during training, higher accuracy can be achieved in reduced training time. Long-term training can make users tired and affect user's mental states and eventually degrade the accuracy of a task. It was observed in our study that training became increasingly complex for both patients and control groups as participants advanced from single to double (and triple) commands and accuracy remained low. In future we hope to improve the training by incorporating an adaptive scheme. Nevertheless, our current study reported in this paper showed the general acceptance of the consumer-grade BCI device amongst neurological patients. With the suggested improvement, we hope to achieve higher accuracy in future. Our research demonstrated that when carefully designed the proposed off-the-shelf consumer grade BCI system can be acceptable to the patients. We propose future studies to utilise patient-reported outcome measures (PROM) to ascertain usability of BCI devices.

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APPENDIX A – SUS SURVEY [33]

System Usability Scale

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	Strongly disagree				Strongly agree
1. I think that I would like to use this system frequently	1	2	3	4	5
2. I found the system unnecessarily complex	1	2	3	4	5
3. I thought the system was easy to use	1	2	3	4	5
4. I think that I would need the support of a technical person to be able to use this system	1	2	3	4	5
5. I found the various functions in this system were well integrated	1	2	3	4	5
6. I thought there was too much inconsistency in this system	1	2	3	4	5
7. I would imagine that most people would learn to use this system very quickly	1	2	3	4	5
8. I found the system very cumbersome to use	1	2	3	4	5
9. I felt very confident using the system	1	2	3	4	5
10. I needed to learn a lot of things before I could get going with this system	1	2	3	4	5

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APPENDIX B – USABILITY QUESTIONNAIRE

The product evaluation survey completed by the study participants consisted of 12 items with the following choices of responses: 1 = strongly disagree, 2 = somewhat disagree, 3 = neither agree nor disagree, 4 = somewhat agree, 5 = strongly agree.

The items were as follows:

Item	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
I could easily complete the task with the device					
The device helped me to complete the tasks					
It was easy to understand how to operate the device					
The device was comfortable to use					
Using the device was easy					
Using the device felt safe					
Aesthetically, I like the overall look of the device					
As a “disability” product, this device would draw unwanted attention					
I think the idea behind how the device is meant to operate provides a good solution to problems I encounter in everyday life					
It was easier to complete the tasks with the device than it was when using my existing equipment.					
Compared to other products to complete the tasks, the actual functionality of this product is better					
I would be happy to use this device if it were made available to me					

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