In Pursuit of an Easy to Use Brain Computer Interface for Domestic Use in a Population with Brain Injury

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***Abstract*:** This paper presents original research investigating a sensor based, ambient assisted smart home platform, within the framework of a brain computer interface (BackHome). This multimodal system integrates home-based sensors, mobile monitoring, with communication tools, web browsing, smart home control and cognitive rehabilitation. The target population are people living at home with acquired brain injury. This research engaged with the target population and those without brain injury, who provided a control for system testing. Aligned with our ethical governance a strong user centric ethos was foundational to participant engagement. Participant experience included three individual sessions to complete a pre-set protocol with supervision. Evaluation methodology included observations, time logging, completion of protocol and usability questionnaires. Results confirmed the average accuracy score for the people without brain injury was 82.6% (±4.7), performing best with the cognitive rehabilitation. Target end users recorded an average accuracy score of 76% (±11.5) with the speller logging the highest accuracy score. Additional outcomes included the need to refine the aesthetic appearance, as well as improving the reliability and responsiveness of the BCI. The findings outline the importance of engaging with end users to design and develop marketable BCI products for use in a domestic environment.

Keywords: *Brain computer Interfaces; User Centred Design; P300 BCI; Acquired Brain Injury*

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I. Introduction

Brain-Computer Interfaces (BCI) are systems that are operated and controlled by electroencephalographic (EEG) brain signals. Non-invasive electrodes collect the EEG signals that are elicited by the user and send the information to the BCI so that it can be translated into a command [1]. The user is required to respond to a stimulus in real time to evoke the required EEG and while wearing a cap with electrodes on it. This enables a user to control the computer and the applications available upon that platform without any muscle activity. This technology has wide spanning functionality within society from the gaming industry [2] to an assistive technology solution for individuals with limited motor function [3]. Extensive research over the last twenty years has demonstrated that a number of different paradigms are available to effectively control BCI such as steady-state visual evoked potential (SSVEP), event-related desynchronization/ synchronization (ERD/ ERS) [4,5]; and P300 event-related potentials (ERP) [6-8]. The current focus of this paper is on BCI controlled by P300 ERP, which is one of the most commonly used BCI paradigms [9]. The ambition is to develop a BCI home based system which will underpin ambient assisted living within the smart home not only enabling independence but supporting remote healthcare.

Recent media coverage of BCI presents this technology as life changing, however it is not yet an 'off the shelf' solution [10,11]. The present challenge for BCI is to develop systems and services that are easy to use, reliable and accessible to people who could benefit from this as an assistive technology and easy for their caregivers to set up. It is evident that BCI can now control a number of applications [12-15] however little evidence of this is present beyond the laboratory [16]. Additionally, this research has primarily centred on healthy users undertaken by technical experts. The difference between the testing outcomes of these two very different populations is evidenced from comparison testing outcomes between healthy and end user groups within the literature [17-20]. The main focus of this paper is to address the challenges of moving this technology towards a real life assisted technology solution for domestic home use for people with acquired brain injury (ABI).

Kübler and her colleagues [21] describe a 'translational gap' in bringing BCI to end users in their home

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environment. This gap is said to have appeared because research has not engaged with end users and so technical experts produce systems they think end users might like as appose to what end users want, need and could use on a day-to-day basis. In order to move BCI towards home use and 'non expert' set up it is essential to engage in User Centred Design (UCD) [21]. The term UCD describes an iterative design methodology to identify the effectiveness, efficiency and satisfaction with technology where by end users are at the centre of this process. This framework has been set out in a bid to develop and standardize a method of evaluating the usability of BCI with target end users [22-25]. The effectiveness of the system is a way of finding out how accurately the user can control and select their desired symbol on the BCI. The efficiency looks at the time and effort the user needs to invest in order to engage with the BCI. Finally, satisfaction is a measure of how the user perceives the BCI and their overall acceptability with all aspects of the technology. Through this three-pronged approach incorporating psychometric tests, qualitative methods and descriptive data a holistic evaluation of such system can endeavour to bridge such a gap between end users and developers in creating a BCI for everyday use.

BCI offer the unique opportunity for people with complex disabilities to access services and applications that support inclusion, participation, enable independence and increase access to healthcare. In particular, BCI could offer a solution to people who may have no other form of communication or access to environmental or computer control. Research has focused primarily on providing people with Amyotrophic Lateral Sclerosis (ALS) an assistive technology solution [26]. Limited research has focused on people with ABI evaluating BCI [17,27,28]. This population has additional cognitive challenges along side the physical limitations they may experience as a result of their injury. Locked in syndrome (LIS) where a person has no or very limited remaining muscle function can be a residual impact of a severe ABI [29]. More recently research has also indicated that populations such as Motor Neurons/ ALS [30], Multiple Sclerosis [31], and Muscular Dystrophy [32] can also experience cognitive decline as a result of their degenerative conditions. This emphasises the importance of including people with cognitive impairments in the development and design of BCI as physical and cognitive impairments are not mutually exclusive. Thus, BCI systems have the potential to support different population in various ways such as on a more long-term basis for independence as well as through the trajectory of rehabilitation.

The overall aim of this research is to develop and evaluate a platform operated by BCI that combines devices and applications like smart home control, social networking, online and offline entertainment applications, ambient intelligent systems, and eHealth through rehabilitation as well as telemonitoring and home support [33-35]. This ambitious project has identified user requirements and system usability within this population by adopting a user-centred approach [25]. Each stage of end-user evaluation and feedback will inform the technical developers throughout the lifecycle of the project. The first iteration of testing indicated that users with ABI could use BCI however greater control was necessary, the system needs to be more reliability, and the set up process must be simpler [17]. The unique aspect of this study was that the evaluation was undertaken in a rehabilitation centre by non-experts thus beginning the evolution of moving BCI out of the laboratory, which is the ultimate aim for the final phase of testing. The current paper will focus on the user centred evaluation of the second iteration of a BCI platform with applications for communication, rehabilitation, smart home control and web browsing. The evaluation was undertaken once again by the same non- experts and in the same rehabilitation setting. New advancements in the second iteration of the prototype included the various applications and the use of famous faces as the P300 stimulus to improve the effectiveness [36,37].

II. Experimental Section

2.1. The BCI Operating System

The BCI system used a P300 based paradigm that was placed next to the user interface. The user interface was placed approximately a meter in front of the participant to enable control of applications (Figure 1). The EEG was acquired using an electrode cap with 8 active Ag/AgCl electrodes (g.Ladybird, g.tec Austria), at electrode Fz, Cz, P3,P4, PO7, POz, PO8, Oz. Channels were referenced to the right earlobe and a ground electrode was placed at FPz and the signals were amplified by a g.USBamp (g.tec Austria).

Figure 1. The BCI Operating System

2.2. Participants

Ten people were recruited to evaluate the prototype inline with a robust ethical framework approved by the University of Ulster. Each participant had evaluated a previous iteration of the prototype [17]. First, five

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participants (4 female, M= 36.6 years, ± 9.3) in the control group were recruited for the evaluation that did not have an ABI. Once the first phase of testing was complete, five target end users (1 female, M= 37 years, ± 8.7) who are living with ABI (Post ABI M= 9.8 yrs, ±3.7) were recruited. Each participant was medically stable, was post rehabilitation, had no history of epilepsy and had received a diagnosis of moderate to severe brain injury. The degree of cognitive and physical impairment varied although individuals had the cognitive ability to understand the study, the ability to give consent and to learn to interact with the BCI.

2.3 Study Design

The testing phase for the prototype required each participant to complete an extensive 40-step protocol on three occasions each. Participants were invited to evaluate the prototype in a rehabilitation centre in Northern Ireland and this setting was not controlled for any of the environmental noise that was present e.g. phones ringing, doors, people talking. The system was set up by non-experts that only had experience of setting up the previous iteration of the system. Participants sat approximately one meter away from the user interface consisting of two displays. The application display was centred in front of the participants and the BCI stimulation display was to the right of the first one, see Figure. 1. At the beginning of each session it was necessary to create a unique classifier for the user. This was created during the training sessions when the user was required to select five letters from the 6 X 6 matrix. A selection could be made when the participant attends to their target symbol and mentally count the amount of times it flashed as the rows and columns flashed at random with pictures of famous faces [36,37]. Once the classifier was created users were then asked to complete the protocol on the system.

The researcher guided the participants through the process, which included spelling the word 'BRAINPOWER', completing two cognitive rehabilitation tasks [35], tweeting '#BCI #BACKHOME' on a special web browser [9] and smart home control that involved moving a camera application in three different directions, see Figure 2. Participants with ABI were also invited to complete two additional 15-step tasks on one occasion each. The first was to operate a multimedia player called XBMC (http://www.xbmc.org) and the second task was to paint a picture using an application called Brain Painting [24,38].

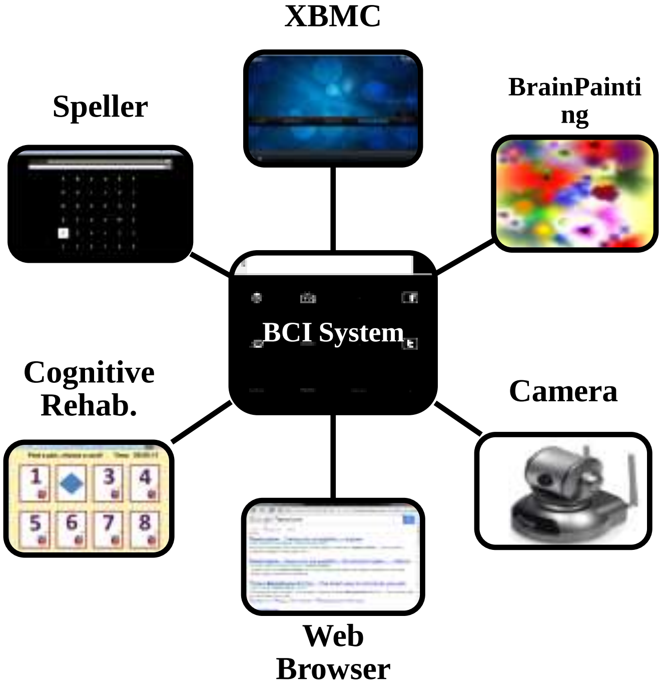

Figure 2. The tasks completed on the BCI system.

The UCD framework sets out to evaluate the usability of the system in terms of effectiveness, efficiency and satisfaction [25]. The effectiveness of the prototype was determined by calculating the percentage of correct selections made during the protocol with a threshold set out at <70% [3,26]. The BCI efficiency is calculated by the Information Transfer Rate (ITR) [39] and completing the NASA-TLX (NASA-Task Load Index: [40]) after the final session to assess workload. Finally, satisfaction was rated on the VAS (visual analogue scale) questionnaire to rate overall satisfaction between 0 and 10 after each testing session. After each final evaluation session participants completed the extended QUEST 2.0 (Quebec User Evaluation of Satisfaction with Assistive Technology: [41]) and a customized usability questionnaire.

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2.4 Data Analysis

The data was analyzed using Matlab (MathWorks, Natick, USA). The signals of the electrode position Cz were chosen to compare the two groups. Only epochs of the training with well-known target and non-target stimuli were used for analysis. Signals were filtered with a 0.5-15Hz band-pass. The epoch length was 1000ms. A baseline correction was performed with 200ms pre-stimulus data.

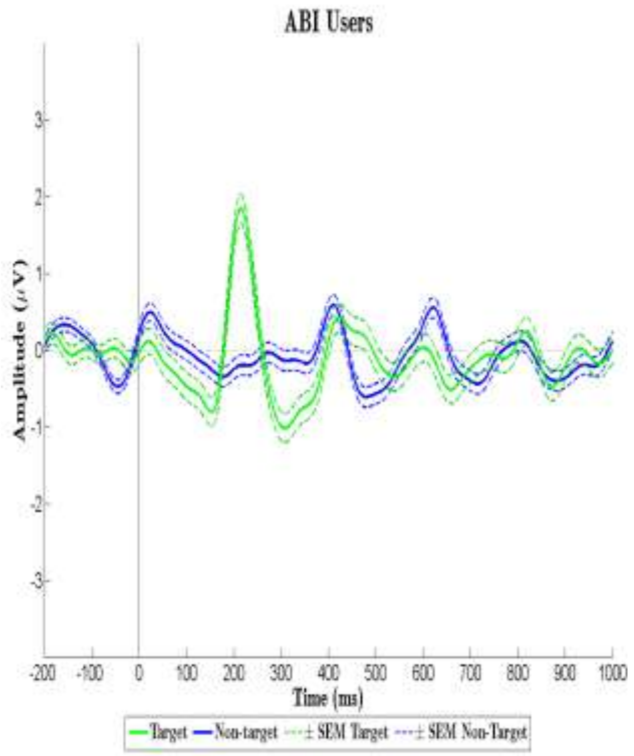
The control and end user signals were checked for statistical significant differences by means of Mann-Whitney U tests. The Bonferroni corrected significance level alpha was set at 0.05/sample length(n=256) = 0.000195. A phase difference correction was applied to compare only the amplitude differences and not the differences originated by time shifts. This correction was performed by detecting the maximum value of the P300 of both groups and shifting the signal of the ABI group so that the peaks appear at the same time.

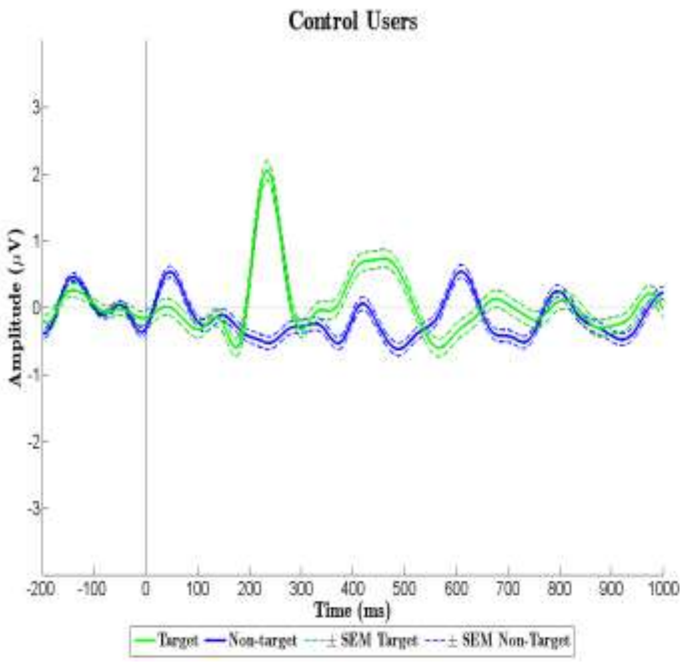
III. Results

3.1 EEG Analysis

The plots of the averaged target and non-target signals are shown in Figure 3. The error of the means of the signals is indicated with dashed lines. The mean peak P300 amplitude of the control group was 2.05(±0.14) µV and 1.85(±0.18) µV for the ABI users. The mean latency of the P300 peak was 234.4 ms for the control and 214.4 ms for the ABI users. This early occurrence of the P300 peak is most likely originated in the technical implementation of the BCI system: The event triggers might be set too early. However, the time-shift between the mean ABI and the control group P300 peak was 20 ms. On average the P300 peak occurred earlier at the ABI users.

A comparison of the target signals of both groups is shown in Figure 4. Significant differences are marked within this figure with red lines. The control group had significant higher amplitudes than the end users at some time points; see Figure 4 close up area.





a b

Figure 3. Comparison of the EEG Signals of the (**a**) ABI and (**b**) Control Group

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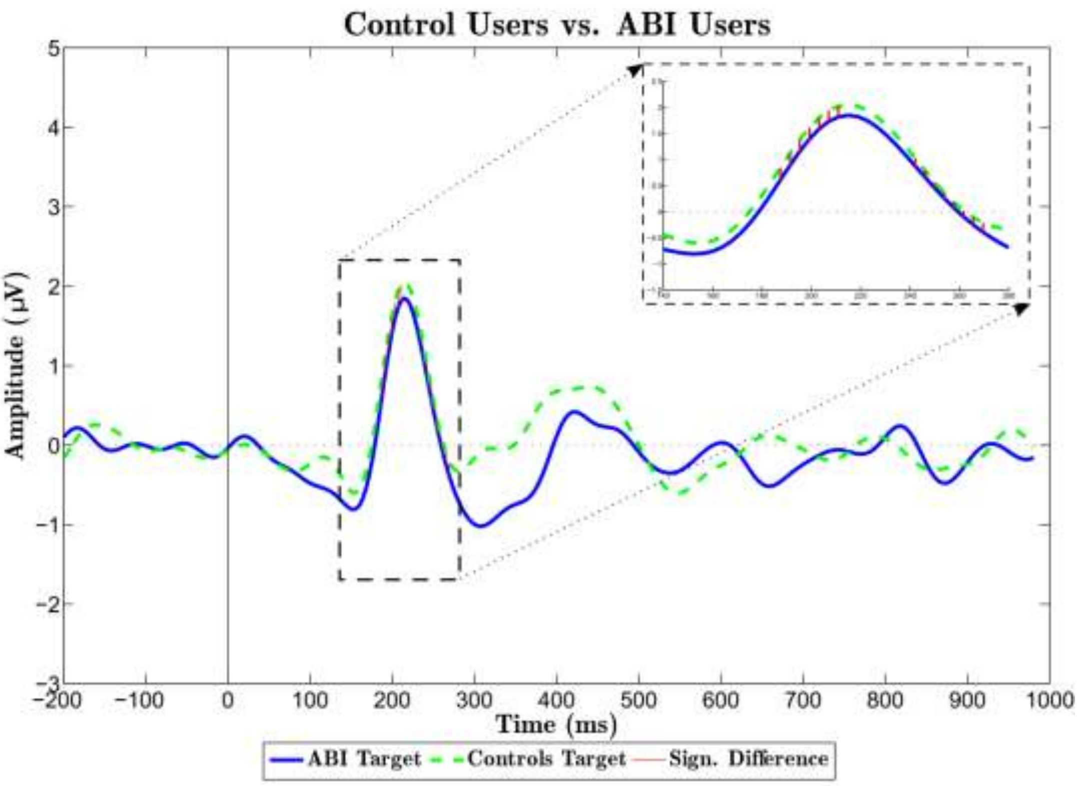

Figure 4. Time-shift corrected comparison of the EEG target signals of both groups. Significant differences between the target signals are marked with red vertical lines. A close-up of the P300 area is shown in the upper right corner.

3.2 Effectiveness

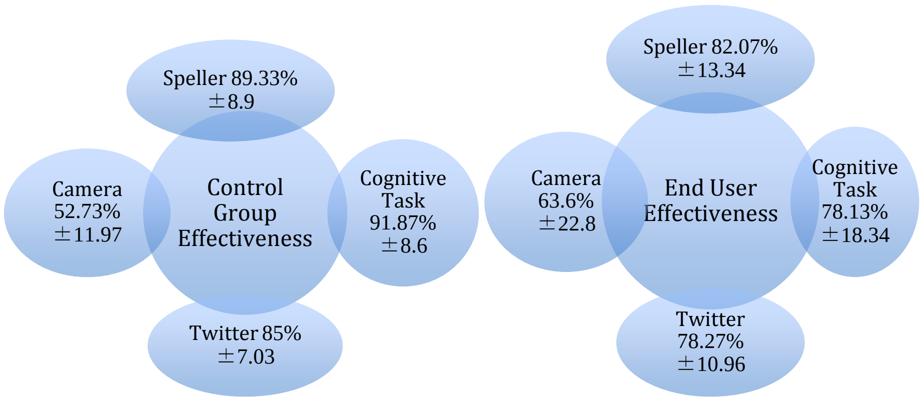

Figure 5. Overall effectiveness scores for control group and end users

The control group recorded an overall average accuracy of 82.6% (±4.7) following completion of the full protocol on three occasions. The cognitive rehabilitation tasks were the most responsive for the control group with each game scoring high accuracies (>90%) and an overall cognitive rehabilitation accuracy score of 91.87% (±8.6). End users completed the protocol with an overall average accuracy score of 76% (±11.5). The highest overall accuracy for the end user group was achieved with the Speller (82.07% ±13.34). The overall effectiveness scores for each application are set out in Figure 4.

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Table 1. End user average accuracy and information transfer rate (ITR) scores

ID	Speller		CR* Task		Twitter		Camera		VAS
	accuracy	ITR	accuracy	ITR	accuracy	ITR	accuracy	ITR	
EU1	86%	9.55	91%	14.92	81%	8.91	82%	4.46	7.7
EU2	92%	12.23	88%	11.98	87%	9.62	85%	5.36	9.3
EU3	77%	5.54	66%	7.34	72%	6.21	61%	1.87	7.2
EU4	80%	8.18	85%	12.71	85%	9.67	50%	0.30	7.2
EU5	75%	4.09	61%	5.4	66%	4.76	40%	0.37	6.9
Avg.	**82.07%**	**7.92**	**78.13%**	**10.47**	**78.27%**	**7.83**	**63.6%**	**2.47**	**7.66**
Std.	**13.34**	**3.22**	**18.34**	**3.96**	**10.96**	**2.23**	**22.8**	**2.34**	**0.96**

* Cognitive rehabilitation

The camera task reported the lowest accuracy score for both groups with the control group reported a score of 52.73% (±11.97) and the end users achieved an average of 63.6% (±22.8). The difference in the camera task accuracy scores between groups could be attributed to a system stability issue. Within the control group evaluation the system crashed when the users were trying to select the 'smart home' icon from the bottom of the opening matrix (control group= 50% / end users= 71%) in the majority of sessions, whilst this was no longer an issue during the end user testing because of stopping and starting the system between tasks. Additionally, end users used the XBMC and BrainPainting application on one occasion each achieving overall accuracy scores of 79% and 66.6%, Table 2.

Table 2. Single use end user average accuracy and information transfer rate scores

ID	XMBC		BrainPainting	
	accuracy	ITR	accuracy	ITR
EU1	94%	13.17	45%	2.19
EU2	94%	15.50	88%	9.42
EU3	79%	8.64	79%	6.19
EU4	68%	5.44	56%	2.68
EU5	60%	3.50	65%	3.42
Avg.	**79.0%**	**9.25**	**66.6%**	**4.78**
Std.	**15.3%**	**5.06**	**17.3%**	**3.02**

3.3 Efficiency

Information transfer rate is reported for end users in Table 1 and Table 2. The cognitive tasks reported higher ITR than the other application. This may be as a result of needing additional time to attend to the other screen and decide on the answer/ choice they want to select.

Table 3. NASA–TLX scores for the end users and the control group

ID	Overall Score	Mental	Physical	Temporal	Perform	Effort	Frustration
EU 1	**55.3**	77	3	47	10	86	11
EU 2	**3.4**	4	3	4	6	1	3
EU 3	**39.7**	74	18	0	25	74	9
EU 4	**43.5**	69	1	49	26	29	19
EU 5	**65.2**	81	0	10	50	89	86
CG Average*	***57.1***	*67.4*	*20.0*	*58.2*	*23.2*	*66.6*	*63.0*

** control group*

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The subjective workload using the NASA-TLX was reported in Table 3 as moderate to high workload (57.1 ±10.9) for the control group and moderate workload for end users (41.42 ± 23.5). With the exception of one end user, mental workload was reported as considerably high. Interestingly, frustration generally was low for end users.

3.4 Satisfaction

The average scores for the QUEST and ADDED Items scores are outlined in Table 4. The average QUEST score for the control group was 4.35 (±.5) and the QUEST Added Items average was 4.24 (± .5). The average QUEST score for end users was 3.86 (±.6) and the QUEST Added Items average was 3.58 (± 1.1). In particular end users scored Speed the lowest in the ADDED Items. The QUEST items rated as most important were: Ease of Use (n=6); Effectiveness (n=5); Speed (n=5); Reliability (n=5); Comfort (n= 4).

Table 4. Extended QUEST 2.0 scores for the end users and the control group

Participants	**Dimensions**	**Weight**	**Adjustment**	**Safe and secure**	**Comfort**	**Easy**	**Effective**	**Professional services**	**QUEST TOTAL SCORE**
Control Group	4	4.6	4.2	5	4.5	4	3.8	4.8	4.35
End Users	3.4	4.4	3.45	4.8	3.9	3.4	3.8	5	3.87

	Reliability	**Speed**	**Learnability**	**Aesthetic Design**	**ADDED ITEMS SCORE**
Control Group	4.3	4.6	4.8	4.1	4.2
End Users	3.8	2.8	4	3.45	3.58

(Key: 5= very satisfied; 4= satisfied; 3= more or less satisfied; 2=not very satisfied; 1= not satisfied at all (Demers, Weiss-Lambrou & Ska, 2002)

Overall both participant groups reported a degree of satisfaction with the system. The end users overall device satisfaction reported on the VAS was 7.64 (±1.78) and ranged from 6.9 to 9.3 individually on average over the three sessions. The control group indicated on the VAS (VAS=6.57±1.2) that they were not as satisfied as end users with the overall device on day-to-day basis. End users rated their satisfaction higher with the applications that responded the quickest and most accurately.

The Usability Questionnaire provided an opportunity to gather rich feedback from both evaluation groups. The control group reported feeling competent controlling the system and enjoyed aspects of the system such the Speller, the Cognitive tasks and seeing changes happening within the environment. Constructive feedback from this group included difficultly '*familiarising and navigating through the system'*, '*words and symbols are sometimes to close together to select'* and '*needing the 'carers' support to un-do 'wrong' selections, restart the system when it crashes and to over ride the system'* to bring the application window to the front of the screen. Additionally, interacting with the system was reported as tiring *'which meant it took more effort'*.

Continuity of participant engagement in this research has been strong. All of the end users were engaged in the evaluation of the first BackHome prototype and they were satisfied with improvements made from the previous iterative of the system including the P300 stimulus changing from flashing light to the famous faces *"The flashing faces have completed changed it"*. The progress was viewed positively overall and end users enjoyed interacting with the system. Concerns were raised about the systems slow response, that it can be a "*bit erratic*" or in other words unreliable, and not all end users liked the flashing as it could be sore on their eyes. End users also said *"it was not easy to learn how to interact with the system"*; and *"I think the system needs to be a lot more user friendly and more aesthetic"*. The end users felt that the system still had some improvements to do before it was ready for home use *"Speed it up; make it easier to use; more reliable; and more like real life/ everyday technology"* because *"If I had this system at home now it would just be frustrating"*.

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IV. Discussion

The results presented in this paper are from the evaluation of the second iteration of a P300 BCI prototype with a control group and end users with Acquired Brain Injury. All participants were satisfied with the overall improvements, applications and performance of the system since the evaluation of the first iteration of the prototype however an increase in the response rate and system reliability is still necessary. The significant improvements indicated in the effectiveness of the system for both the control group and end user group could be as a result of the famous faces stimulus [36,37]. The level of BCI literacy is set at above 70% [26] and this was achieved with each of the applications with the exception of the camera task. The overall reduction in control of the camera could have been attributed to the smaller P300 matrix [42] used for this smart home control and as a result of this poor outcome the camera has been removed from the future prototype.

Participants reported that the applications they enjoyed were the ones that responded the best for them through the BCI. All users reported that they liked the direct feedback from the system and this motivated the user whether it was creating a painting; selecting a video or moving the camera. The cognitive rehabilitation games were very complex tasks for a number of reasons for example it was necessary for the user to split their attention between two screens (i.e., the P 300 matrix and the application screen, see Figure 1). Also, different types of attention and memory were necessary to complete the tasks such as dividing attention between choosing an answer on the application screen and making a selection on the P300 matrix added to the significant challenge of remembering the images on the cards in order to complete the card-matching task. Difficulties such as moving their head between the two screens, trying to remember what each screen was for, and the delay attending to the P 300 matrix to make a selection made it more likely for the system to respond to the user with a false positive or suppressed selection because of the additional noise in the signals. Recommendations for the cognitive rehabilitation application include slowing down this task in some way to give end users time to decide on their answer such as incorporating a pause button. Also it would be important to have a resume button to enable users to continue their session if the page has moved on or if they feel like they need a break.

Additional findings highlighted that on the web browser application [9] the tags were not always clearly visible or in the right place. It is incredibly difficult due to the dynamic nature of the browser to ensure the tags are always in the correct location on the page however a bold black colour will be used in the future to maximise visibility. Within the XBMC application, on some occasions when the user was attending to the application screen the system would make a selection of its own. It is important to eliminate the system making selections on its own when the user is attending to the application screen. For example, if the user is watching a video through the BCI it is crucial the BCI does not make selections at random that would interfere with this. Work is currently underway to explore ways the BCI can identify when the user is not attending to the matrix to avoid unintended selections [43].

Brain Painting was another application that received a mixture of reviews. Participants found the matrix too complex to become familiar with which within the time frame of the evaluation could have lead to differences of opinion. This application is an example of needing good instructions for end users to use the entire system effectively and in order for people to benefit from all it has to offer.

Cognitive skills such as attention, working memory, and motivation are required to operate a BCI however the exact requirements are still not clear [44,45]. The results indicated that end users reported an overall lower accuracy score, experienced fatigue and there was difficulty focusing on and dividing attention between two screens. It is possible this is due to the participant's residual cognitive impairment as a result of ABI such as difficultly concentrating for periods of time as well as decreased stamina, memory and attention. The impact a cognitive impairment has on the EEG and the cognitive abilities necessary to successfully control BCI are still not evident [46]. Future work is needed to explore how to make BCI's more accessible to people with different cognitive abilities to ensure the target population for BCI can really benefit from them.

Moving the system towards home use and commercialisation a fundamental requirement is to reduce the complexity of the system and make it more reliable. A key finding from the evaluation was the number of crashes and the systems instability. In order for the set up to fit into the everyday routine the BCI needs to be an easy one-click set up. The feedback about the BCI in terms of aesthetic appearance, reliability and responsiveness found in this evaluation is not new [22,24,27]. However, this does underscore the utmost importance of these features and the need for designers and developers to take these requests seriously. Researchers have highlighted the merit of BCI development but only with the focus firmly on the personhood of end users [21,47]. In order to provide a real assistive technology solution that is cost effective for healthcare systems such issues need to be resolved to reduce device abandonment [48,49].

These finding are important to move towards a realisation of BCI as a commercially available assistive technology for home use and to offer a real life solution to enhance individuals' functional ability, quality of life and independence. The lessons learned from the present research have been disseminated to the developers so that the final platform will bring BCI closer to the ultimate goal of a commercial available system for home use. This included enhancing the aesthetic design of the electrode cap; enabling independent use of the system once the cap has been mounted and the training is complete; the applications and BCI matrix should be on one screen; and the ability to personalise the system to the unique needs of each user**.**

V. Conclusions

BCI with comprehensive sensors and home support systems are complex systems. Whilst we are moving toward intuitive systems for the non-expert, currently the complexity of start up and navigation requires support. The research aims to develop novel BCI systems to enhance the user's independence, increase access to services and ultimately enrich quality of life. It is the integration and uptake of the home based sensors, remote cognitive rehabilitation and the visualisation of services to target end users that will ensure the success, or not, of such systems. Our findings are encouraging and considered a positive contribution to our knowledge, showing promising results for the functionality and usability of the system at home by people with ABI.

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VII. Conflicts of Interest

The authors declare no conflict of interest.

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