BRAIN-COMPUTER INTERFACE VIRTUAL KEYBOARD FOR ACCESSIBILITY

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ABSTRACT

This paper describes our experiences in building a virtual keyboard implemented using a Brain-Computer Interface (BCI) that interacts with the eMotiv EPOC Neural Headset. The contribution of the work is an alternative input device for those who have a motor disability and are challenged by traditional input devices. The advantages of a virtual keyboard based on BCI are summarized and we describe its design and implementation. We also present the results of a preliminary study that has suggested several improvements for enhancing the effectiveness of the virtual keyboard.

KEY WORDS

Brain-Computer Interface; BCI; Virtual Keyboard; Accessibility; Accommodating People with Disabilities; User Interface Development; Emotiv; End-User Development

1. Introduction

General computing skills continue to be an important workforce need, and the inability to use such a common instrument as the physical keyboard alienates certain individuals from a significant portion of the workforce, and society in general. In order to provide an accessibility option for those who are unable to use a physical keyboard (e.g., those with a motor disability), we have created a Brain-Computer Interface (BCI) Virtual Keyboard. We believe a large majority of the population that is unable to use a keyboard or mouse will be able to use a BCI in a meaningful way. This belief is supported by other studies in the area of accessibility, such as Neuper et al. [5].

We utilized the eMotiv EPOC neural headset (hereafter referred to as the eMotiv headset) [1] as our physical input device for several reasons. The eMotiv headset is a consumer-ready and relatively inexpensive option for end-users. Use of consumer-ready systems has been suggested to provide a practically portable solution for recording EEG signals [2]. In addition, if our virtual keyboard proves to be successful, Emotiv provides an application store for developers using the eMotiv headset that would enable us to easily distribute our software. The eMotiv headset detects sensorimotor signals, which are neurological signals related to motor control. This approach differs from many other implementations. For example, P300-based systems rely on a signal from the brain that is generated as a response to outside stimuli [4]. Systems that rely on outside stimuli force the selection rate to be determined by the stimuli, as opposed to the user. The eMotiv headset does not rely on any outside stimuli, which we believe will give users a greater sense of control.

In the remainder of this paper, we present a novel system designed with the goal of producing a viable alternative input device for those unable to use a physical keyboard. We will first identify a number of challenges that must be overcome for our system to be a useful keyboard alternative, and then we will outline how we addressed those challenges. We will then present a preliminary study that evaluates the current implementation of our system. The study compares our results to those obtained from several other similar BCI systems. Finally, we will discuss lessons learned from both the user study and the design.

2. Design of a BCI Virtual Keyboard

This section outlines some of the challenges encountered and the design approaches that we considered while building our BCI virtual keyboard.

2.1. Challenges in using a BCI Virtual Keyboard

When considering the intended user base of the system (i.e., those with a motor disability), we identified the following challenges that guided our design:

1. Not all users will be capable of producing each input signal with the same consistency;
2. Not all users will be capable of producing the full range of input signals;
3. The design should be reusable with different languages;
4. User familiarity, or lack thereof, with keyboard layouts could affect user experience;
5. The large number of inputs available on a modern keyboard could be overwhelming if presented to the user all at once;

6. The device we are using has a limited number of available inputs that is greatly exceeded by the number of inputs available with a traditional keyboard.

In addition to the listed challenges and design objectives, we considered the effect of requiring users to train with the eMotiv headset. A new user will need to spend an initial period of training time to configure the eMotiv headset reliably and accurately. This training time may be a burden to some users upon first use. However, we believe our target user base will have the motivation to endure a period of training. Although we would like to study the effect of varying training times in the future, we currently are not certain about the optimal amount of training that will be required from users. Therefore, to mediate the impact of this unknown factor, a user is only required to produce a subset of the full range of input signals the eMotiv headset is capable of processing. In our most recent interactions with experimental users, we observed that a 10 minute training time was sufficient. We plan to investigate this issue further in future works.

2.2. Details of the Design and Implementation

This project was developed in Java using Eclipse. Java was chosen because of our past experience and the relative ease of designing a graphical user interface in Java. The eMotiv API is provided as a native C++ DLL. However, Emotiv provides a wrapper that utilizes the Java Native Access library to enable Java developers to utilize the eMotiv API. Additionally, the project uses the Java Robot class to send keyboard input from the virtual keyboard. The Robot class allows programmatic control of the mouse and keyboard (e.g., directing the mouse to a specific location of the screen or programmatically generating keyboard button events).

The overall architecture of the design focuses on an implementation of the Model-View-Controller design pattern. In this implementation, the model is the Virtual Keyboard, the view is the Graphical Display, and the controller handles the mapping of headset inputs to functions we designed in the model. We believe this architecture allows for flexibility in our implementation. This flexibility can be realized by altering the controller to allow for different devices to utilize the same model and display. Additionally, the display could be tailored to various user expectations dependent on platform-specific or societal conventions.

During the initial design phase, we identified a number of challenges that were used to guide our design. We overcame several of these challenges through user customization. First, in order to address Challenge 1 (i.e., that not all users will be capable of producing each signal with the same consistency), we allowed the headset inputs to be mapped to functions based on an XML configuration file. The input mapping allows a user to choose the most appropriate inputs for his or her ability (e.g., left- or right-wink). To address Challenges 2 and 6, our system is designed to only require at least two distinct input signals. Each available input signal maps to one of the following actions that are ordered by an initial assessment of usefulness (most useful to least useful):

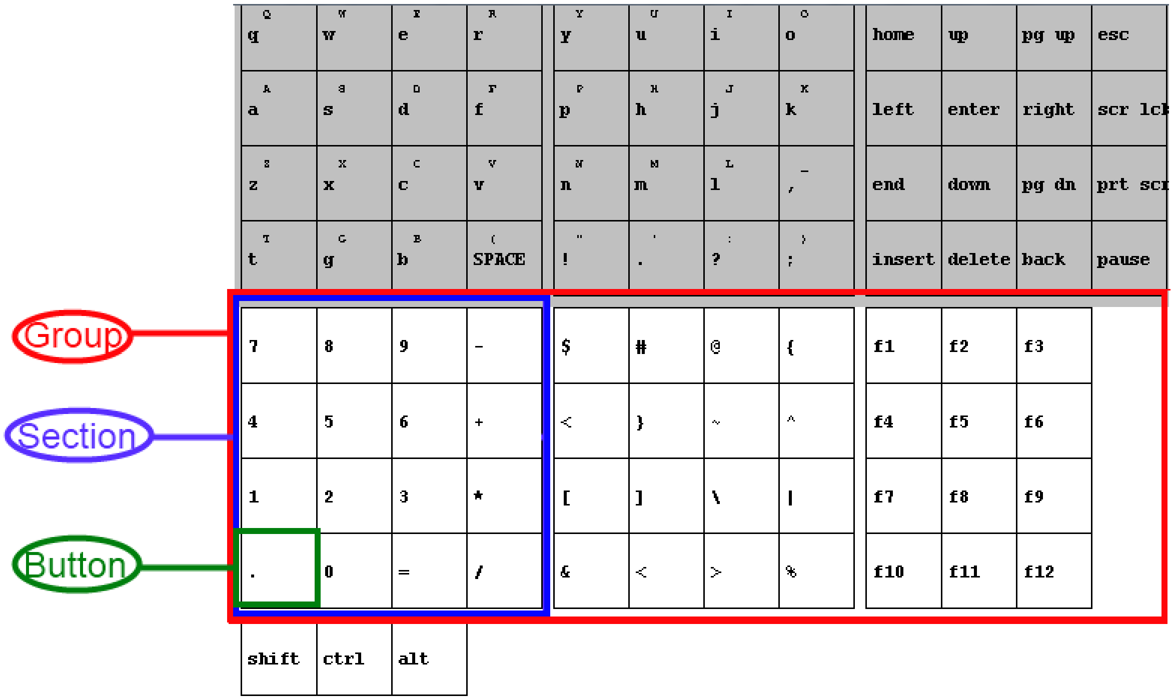

Figure 1. Annotated Screen Shot of the BCI Virtual Keyboard

1. Select
2. Move Right
3. Move Out
4. Move Down
5. Move Left
6. Move Up

To realize this limited number of inputs, we created a model of the keyboard where the user navigates through the keys to make a selection. Because of Challenge 5, we needed to minimize the average number of movements required to navigate to each key. We accomplished this by utilizing a drill-down approach in which the user starts at a high-level and selects a set of keys and then navigates within this reduced set, selecting increasingly smaller sets until the current set contains only a single key. At this point, the user selects the desired key and the system simulates the user pressing that key. In addition, each movement utilizes a wrapping implementation to allow the ability to reach any key. Also, in order to address Challenges 3 and 4, we allow the keyboard layout to be mapped from an XML file. This allows the keyboard to be tailored to the layout most comfortable to the user and to utilize the appropriate keys for the language(s) of the user. A screenshot of the current graphical interface of the system is shown in Figure 1, where the three levels of the drill-down approach are indicated: group, section, and key. In this architecture, a group contains sections and a section contains keys. The user begins at the group level, selects a group, then selects a section from within that group, and finally selects a particular key.

The eMotiv headset provides several recognition suites: the Expressiv and Cognitiv suites. The Expressiv suite detects neural signals related to facial feature movements (e.g., a blink). The Cognitiv suite allows the user to train the system to recognize custom neural states. The Expressiv suite provides enough available input signals to satisfy the needs of our virtual keyboard. However, we recognized that not all users are capable of utilizing the full suite. The Cognitiv suite provides the freedom to define inputs that are tailored to an individual. Unfortunately, as more custom inputs are added, the difficulty for the user to reproduce a specific signal increases significantly, as stated in the eMotiv SDK documentation [1]. Therefore, we allow the user to utilize a combination of inputs from both suites in order to ensure that the capability of the full system is available to all users.

3. Empirical Evaluation of the Keyboard

In this section, we present the design and results of an empirical user study that was used to evaluate the current implementation of our system.

3.1. User Study Details and Experimental Context

In order to evaluate the effectiveness of our system to assist a user in entering text without a physical keyboard, we performed a user study with seven participants. The user tests were set up as follows:

1. We utilized the eMotiv EPOC Control Panel to familiarize each participant with the facial feature recognition system (Expressiv).
2. We configured a user profile for each participant, including the training and sensitivity adjustments, the input mappings, and the keyboard layout.
3. We allowed each participant approximately 10 minutes to become familiar with the keyboard layout and navigation scheme.
4. We tasked each participant with typing a selection of text using the virtual keyboard utilizing only the Expressiv suite. Each participant had 5 minutes to complete this task.
5. We utilized the eMotiv EPOC Control Panel to train each participant to perform one input from the mental state recognition system (Cognitiv). Each subject was given approximately 10 minutes to complete this training task.
6. We updated each user profile based on the feedback from steps 4 and 5.
7. We allowed participants to familiarize themselves with utilizing the Cognitiv input in the context of the virtual keyboard.
8. We tasked each participant with typing a selection of text using the virtual keyboard utilizing both the Expressiv and Cognitiv suites. Each participant had 5 minutes to complete this task.
9. We asked each participant to complete a brief survey composed of the following questions that were measured on a 5-point scale:
    a. How would you rate the responsiveness of the keyboard without Cognitiv input?
    b. How would you rate the responsiveness of the keyboard with Cognitiv input?
    c. How would you rate the accuracy of the keyboard without Cognitiv input?
    d. How would you rate the accuracy of the keyboard with Cognitiv input?
    e. In a scenario involving *daily* use, assuming a standard keyboard is not available, how comfortable would you be with using this device?
    f. In a scenario involving *occasional* use, assuming a standard keyboard is not an option, how comfortable would you be with using this device?
    g. The device met your expectations
    h. Overall Satisfaction

User	Average Inputs per Selection	Average seconds / selection	Error Rate (%)
user1	75.11	84.50	100.00
user2	30.97	27.20	90.00
user3	37.36	27.43	85.71
user5	67.84	16.50	100.00
user6	42.37	34.50	83.33
user7	37.76	46.20	0.00
AVG.	48.57	39.39	76.51
user4	312.46	332.00	100.00

Table 1. Results with Cognitiv Input
(user 4 excluded due to inability to use system)

User	Avgerage Inputs per Selection	Average seconds / selection	Error Rate (%)
user1	15.99	6.16	57.89
user2	43.91	24.43	28.57
user3	18.30	13.13	6.25
user4	22.73	9.29	71.43
user5	50.29	26.50	66.67
user6	32.51	20.45	18.18
user7	16.64	10.89	22.22
AVG.	28.62	15.83	38.75

Table 2. Results without Cognitiv Input

3.2. Results of our User Evaluation

As shown in Table 1 and Table 2, every measured criterion was improved significantly when using the system *without* Cognitiv input (as compared to when using it with Cognitiv input). In particular, the average time it took the participants to make a selection when not using Cognitiv input was 15.8 seconds. On average, it took the same participants 39 seconds to make each input when using Cognitiv input. Additionally, the average error rate when participants were not using Cognitiv input was 38.7%, which increased to 76.5% when participants performed the same task while using Cognitiv input. One participant was excluded from the analysis of the Cognitiv input because their average selection time suggested that they were unable to control the system properly to provide meaningful input.

Participants rated the responsiveness when they were not using Cognitiv as 3.7. When Cognitiv input was added, the responsiveness rating dropped to 2.7. Participants rated their comfort using the system in an occasional use scenario with an average of 2.3. In a daily use scenario, the average comfort rating dropped to 1.7. The majority of users felt that the device met their expectations, with all but one user rating this criterion a 3 or better. However, the average overall satisfaction was a 2.7, indicating the participants were slightly unsatisfied with the system. Details of the results of the user survey can be found in Table 3.

4. Related Works

There are several BCI applications described in the literature. We found similar systems that provide context and comparison with our own virtual keyboard. These previous results are summarized in Table 4 along with relevant system details.

After reviewing similar works, we found that the studies with the highest number of input selections possible had between 25 and 40 available selections. Our system possesses 128 distinct inputs before considering key combinations. However, we believe this will not be a significant hindrance from achieving similar results. The study performed by Sellers and Donchin demonstrated that the technique they utilized (P300-based speller) required extending the time per selection to an unreasonable rate in order to improve the accuracy to an acceptable level [6]. Thompson et al. presented an evaluation of a plug-and-play BCI interface which included an evaluation of three P300-based spelling interfaces [7]. The three interfaces evaluated were BCI2000, DynaWrite, and Compass. They found that the BCI2000 environment resulted in a 13% mean error rate but had an 11% standard deviation. DynaWrite had a 13%

User/Question	a	b	c	d	e	f	g	h
1	3	2	2	3	2	4	4	4
2	4	4	3	1	1	2	3	3
3	3	1	3	1	2	2	3	2
4	4	3	4	3	1	1	1	2
5	4	1	3	1	2	2	3	2
6	4	5	3	1	2	3	3	3
Average	3.67	2.67	3.00	1.67	1.67	2.33	2.83	2.67

Table 3. Results from User Survey

Reference	System Type	Number of Available Selections	Error Rate (%)	Selection Rate (seconds per selection)
Sellers and Donchin [6]	P300	36	25	22.4
Sellers and Donchin [6]	P300	36	8	106
Yue et al. [3]	Sensorimotor	40	15	NA
Neuper et al. [5]	Sensorimotor	26	15-30	~60
Thompson, et al. [7]	P300	36	11	3.5
Thompson, et al. [7]	P300	36	13	3.5
Thompson, et al. [7]	P300	36	13	3.5

Table 4. Related Works

mean error rate, but a 9% standard deviation, meaning that it was equal to BCI2000 in a worst-case scenario. Compass again had a 13% mean error rate but only a 5% standard deviation. The accuracy reported by Thompson et al. was obtained with a selection interval of 3.5s.

The technique used by Yue et al. demonstrated a comparable accuracy rate using a sensorimotor rhythms-based speller [3]. In addition, Neuper et al. presented a study with accuracy rates similar to those proved by Yue et al., also using a sensorimotor rhythm-based speller. The study conducted by Neuper et al. is particularly noteworthy, because the participants were patients suffering from neurological diseases affecting various functional components of the nervous system [5]. This study showed that users with damage to their nervous system were able to utilize a BCI that recognized sensorimotor signals at a comparable level to those without nervous system damage. Our goal is to provide an accessibility option to individuals unable to use a physical keyboard. From our target group, we expect a significant portion of users will have nervous system damage.

While our error rate is higher than the studies mentioned previously, our selection rate without using Cognitiv input is lower than three of the techniques used in the related studies. However, our implementation must be improved to achieve a lower error rate and selection rate in order to realize our goal of providing a viable accessibility option for users unable to use a physical keyboard. We suggest a goal of 10 seconds per selection and an error rate of no more than 15%.

5. Discussion of Lessons Learned

In this section, we discuss lessons learned regarding both the results of the user study as well as the design of the virtual keyboard.

5.1. Lessons Learned Regarding the User Study

We believe the limited amount of time allotted for training the participants was a significant hindrance to the participants' ability to accurately and quickly make selections. This belief is strongly supported by the immediate feedback from users during the testing and on the follow-up survey. Providing additional training time has the potential to increase both the accuracy and responsiveness, along with the user's overall satisfaction. Though this increase in training time may seem detrimental to the eventual adoption of our system or a similar implementation, we believe the target user-base will have the motivation to endure the training times, which are also limited to the first use of the keyboard.

Another significant factor was the lack of direction given to the participants during the training process. The participants were introduced to the device and the virtual keyboard through basic descriptions of functionality. In order to judge the intuitiveness of our system, the participants were not given a significant amount of guidance regarding how to utilize the system effectively. They also were not given any specific training tasks. We believe this led to most participants failing to gain a complete understanding of the system. The Cognitiv input particularly was ineffective due to the training not reflecting actual usage. The Cognitiv training focused on using the eMotiv EPOC Control Panel rather than using the virtual keyboard. The significant difference is that the participants were not required to utilize Cognitiv and Expressiv inputs concurrently during training. We believe a structured training process would improve both accuracy and responsiveness significantly. Furthermore, a structured training process would provide participants with a more thorough understanding of the system, which should increase the participants' comfort in using our virtual keyboard.

5.2. Lessons Learned Regarding the System Design

Several potential improvements to the design were uncovered. The simplest of these was altering the display to convey to the users that the modifier keys utilized a sticky key implementation (i.e., when a modifier key is pressed, the modifier would remain active until the modifier key was pressed again). This could be achieved by highlighting the modifier keys while they are active. A more complex improvement uncovered was revealed by user frustration with the movement feature; specifically, the implementation where any movement key can be used to access any key on the keyboard if it is the only movement key available. The current implementation causes a movement key to produce a wrapping effect (i.e., when the current key is at the end of a row or column, the movement key moves the current key to the beginning of the next row or column). The wrapping effect was found to be disorienting for users when they bypassed the key they wished to select. The users generally responded to this situation by backing out of a section and restarting the selection process. This response led most users to increase the number of movements required to make the next selection and increased user frustration.

Other potential improvements were suggested directly by users. The suggested improvements include:

- Adding support for macro keys to streamline the selection of common key sequences.
- Changing the Shift key to not utilize the sticky key implementation due to the high number of situations that called for the Shift key to be activated and then immediately deactivated (e.g., when capitalizing letters).
- Some users suggested the addition of an input that deactivates and reactivates the system to prevent users from making unintended selections during periods where the user is not actively utilizing the system.

6. Threats to Validity

In this section, we present the identified threats to the validity of our study.

6.1. Internal Validity

Users were required to first test the system with only the Expressiv suite active, followed immediately by testing the system using both the Expressiv and Cognitiv suites. This repeated testing could cause a fatigue effect that may have contributed to the increased selection and error rates. We accepted this threat because each participant was only available for a brief time. Alternatively, the users could have gained experience from the first test that would have carried over to the second test, therefore decreasing selection and error rates. With the limited number of subjects, the study asked all participants to use the same ordering of tasks. The group size would be too small to determine significance if the subjects had been separated into different orderings.

6.2. Construct Validity

The participants in our study were not from within the target audience (i.e., our participants are able to use a traditional keyboard, but participated in our study by using only the virtual keyboard). We believe this is an acceptable threat. Comparing our results to those of Neuper et al. [5] demonstrates our results are similar to those of the target audience. Furthermore, given the timeframe and emergent sensitivity of the device, it was infeasible to involve users from the target demographic.

7. Conclusion and Future Work

We presented a novel system with the goal of producing a viable alternative input device for those unable to use a physical keyboard. Our system is implemented using a BCI device; in particular, the eMotiv headset. We began by identifying a number of challenges that needed to be overcome for our system to be a viable keyboard alternative, and outlined how our design overcame these challenges. We then presented a preliminary study that evaluated the current implementation of our system. The study was followed by a user survey that gauged the users' satisfaction. The results of our preliminary study were very promising, but demonstrated a need for improvement in the current implementation. We then presented several studies of similar BCI systems and compared our results to those found in the related studies. We then discussed our lessons learned. Finally, we discussed the threats to the validity of our study.

We believe our virtual keyboard, or a similar implementation, can achieve our stated goal of an accessibility option for users incapable of using a physical keyboard. Our current plans are to implement the improvements outlined in the lessons learned section and to perform a more thorough study that incorporates the lessons learned. We expect the enhancements to the system and an improved training procedure will increase the selection rate and accuracy significantly.

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