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Construct and Evaluate a Phone Dialing System Leveraging SSVEP Brain-Computer Interface

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Abstract

This study presents a SSVEP based BCI system, designed for dialing a phone number through EEG signals. Our SSVEP system leverages a tablet-based stimulator and OpenBCI Cyton board, employing Canonical Correlation Analysis for EEG signal classification. Tested on 7 participants, the system demonstrated a high accuracy rate of 98.1% in identifying the observed keys. The use of a tablet-based SSVEP stimulator was found to reduce visual fatigue compared to traditional LED stimulators. Despite its initial success, further validation with a larger cohort and in varied real-world conditions is required. This work signifies a promising advancement in utilizing BCIs in practical applications.

Keywords: BCI, EEG, SSVEP

I. Introduction

Brain-computer interfaces (BCIs) have emerged as a promising technology that holds the potential to significantly impact a range of domains from healthcare to entertainment [Wolpaw et al.(2002)Wolpaw, Birbaumer, McFarland, Pfurtscheller, and Vau BCIs allow direct communication between the brain and an external device, effectively bypassing traditional conduits of communication such as speech and movement [Kübler et al.(2005)Kübler, Nijboer, Mellinger, Vaughan, Pawelzik, Schalk, McFarl Recent advances in BCI research have led to breakthroughs in several areas such as neuroprosthetics, neurorehabilitation, and neuromarketing [Rao(2013)]. However, the practical implementation of BCI technology poses several challenges, particularly related to the reliability and usability of the system in everyday life situations.

One critical area of application for BCIs is to assist individuals with severe physical disabilities, specifically those with compromised mobility and speech capabilities. The ability to communicate and seek help, especially in critical situations, is a fundamental human necessity. For such individuals, the persistent nature of brainwave activity, which remains active as long as an individual is alive, presents a unique opportunity to harness these signals for communication purposes using a BCI system. This potential is exemplified by the development of BCIs based on steady-state visually evoked potentials (SSVEP), known to elicit the most stable and quickest event-related potentials (ERPs), and are thus ideal for real-time applications [Middendorf et al.(2000)Middendorf, McMillan, Calhoun, and Jones].

In this context, we present a novel SSVEP-based BCI system designed to dial a phone number using brainwave signals. Our system utilizes a visual interface comprising a 3x4 number pad, where each key block is associated with a specific flickering at a unique frequency. When a user focuses their gaze on a particular key, the corresponding EEG signal, which includes the frequency of the selected key block, is captured, processed, and classified. The classified signal is then transformed into the corresponding key press, transmitted to a smartphone via Bluetooth, and automatically dialed after a set number of digits have been input. Utilizing a canonical correlation analysis classifier, our system achieves a classification accuracy of 98.1%, demonstrating substantial potential for practical application in real-world settings.

The remainder of this paper is structured as follows: Section II details the methodologies employed in our research, Section III describes our experimental setup and discusses the results, and Section IV provides a comprehensive discussion and conclusion of our study.

II. METHOD

a. Steady-State Visually Evoked Potentials

Steady-state visually evoked potentials (SSVEPs) are oscillatory responses that can be elicited in the visual cortex by repetitive visual stimulation at a fixed frequency, typically ranging from 3.5 Hz to 75 Hz (Norcia et al., 2015). As a reliable and non-invasive technique, SSVEPs have been extensively used in research and application of brain-computer interfaces due to their high signal-to-noise ratio, less subject training, and considerable information transfer rate [Vialatte et al.(2010)Vialatte, Maurice, Dauwels, and Cichocki].

The optimal placement of electrodes for SSVEP recording is typically determined by the nature of the visual stimuli and the goals of the experiment. Most studies report the maximal SSVEP responses in the occipital region, specifically at Oz, O1, and O2 electrode locations, according to the international 10-20 EEG system [Pastor et al.(2003)Pastor, Artieda, Arbizu, Valencia, and Masdeu]. This is attributed to the anatomical proximity of these locations to the primary visual cortex which is most directly activated by visual stimuli.

In our study, we selected six electrode positions: PO3, POz, PO4, O1, Oz, and O2 for SSVEP recording. The choice of these locations is motivated by multiple considerations. Primarily, the chosen sites cover a broad area across the parieto-occipital and occipital regions of the scalp, allowing for a comprehensive capture of visually evoked brain activities. Specifically, the PO3, POz, and PO4 electrode positions extend the coverage to the parieto-occipital region, which is known to play a significant role in visual perception, making it a valuable area for SSVEP recordings [Keil et al.(2012)Keil, Müller, Ihssen, and Weisz]. The incorporation of these additional electrode positions not only enhances the sensitivity of the BCI system in detecting SSVEP responses but also potentially allows for the extraction of more differentiated signal features that can improve the performance of subsequent classification stages. Fig.1. represents the strategic placement of electrodes, as guided by the principles of the 10-20 system. Fig.2. represents the graphical interface of the SSVEP visual stimulator we designed and implemented.

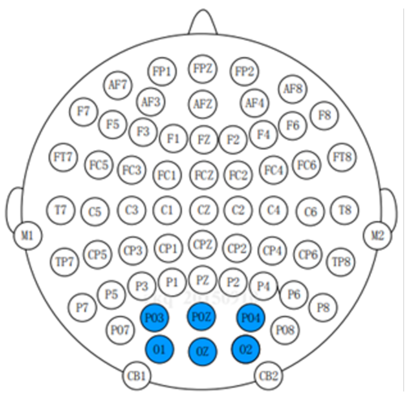

Figure 1. The placement of electrodes.

Figure 2. The graphical interface of the designed SSVEP visual stimulator.

b. Canonical Correlation Analysis

Canonical Correlation Analysis (CCA) is a statistical method that seeks to identify and measure the associations between two sets of variables [Hotelling(1992)]. This multivariate analysis technique extracts canonical variates—linear combinations of the original variables— from both variable sets that have maximal correlation with each other. As a result, CCA has been widely used in numerous fields, such as ecology, economics, psychology, and recently, it has gained considerable attention in signal processing and machine learning research [Hardoon et al.(2004)Hardoon, Szedmak, and Shawe-Taylor].

In the context of BCI, CCA is utilized to maximize the correlation between the measured EEG signals and the reference signals, which are typically derived from the characteristics of the stimuli. In fact, CCA-based SSVEP detection has proven to be one of the most effective methods, achieving high accuracy and robustness even in noisy environments [Bin et al.(2009)Bin, Gao, Yan, Hong, and Gao]. This method has demonstrated a high degree of effectiveness due to its capacity to simultaneously consider multiple harmonics of the stimulus frequencies, increasing the distinguishability of the responses.

In this study, we employed CCA in our BCI system for the analysis of SSVEP signals. The primary advantage of using CCA is its ability to process multi-channel EEG data, enabling the extraction of more comprehensive and reliable features. The adoption of CCA in our work also aids in the mitigation of artifacts and noise due to its inherent capability of maximizing the correlation with the reference signals, which consequently boosts the performance of our system. Moreover, the applicability of CCA does not rely on any presumptions about the statistical distribution of the data, making it a suitable choice for EEG signal analysis [Hardoon et al.(2004)Hardoon, Szedmak, and Shawe-Taylor].

c. The Developed SSVEP-Based BCI System

The BCI system constructed in this study is based on the SSVEP. The architecture of the system encompasses an electroencephalogram (EEG) instrument, SSVEP stimulator, signal classifier, and a signal receiver. For the EEG recording, we employed the OpenBCI Cyton board, an open-source hardware that offers eight channels. Of the available channels, we used six and positioned the corresponding electrodes over the occipital lobe of the participant's brain, where the primary visual cortex is located. This arrangement allows for real-time recording of EEG signals at a sampling frequency of 250 Hz.

Our SSVEP stimulator was designed as a numeric keypad that can run on various tablet platforms. Each key of the stimulator corresponds to a pre-set frequency, which can also be user-defined. The stimulator serves as a visual cue, eliciting SSVEP responses from the participants while they focus on the flashing keys.

Subsequent to the EEG recording and visual stimulation, the recorded signals were processed on PC using CCA. This algorithm provides real-time analysis and classification of incoming signals [Bin et al.(2009)Bin, Gao, Yan, Hong, and Gao]. The output of the classifier was then transmitted to the signal receiver, a smartphone application, which transformed the recognized signals into phone dialing commands. In this system, all signals were transferred via Bluetooth, ensuring a wireless, easy-to-implement setup. Fig.3. presents the flowchart of the entire system, detailing its components and their interplay.

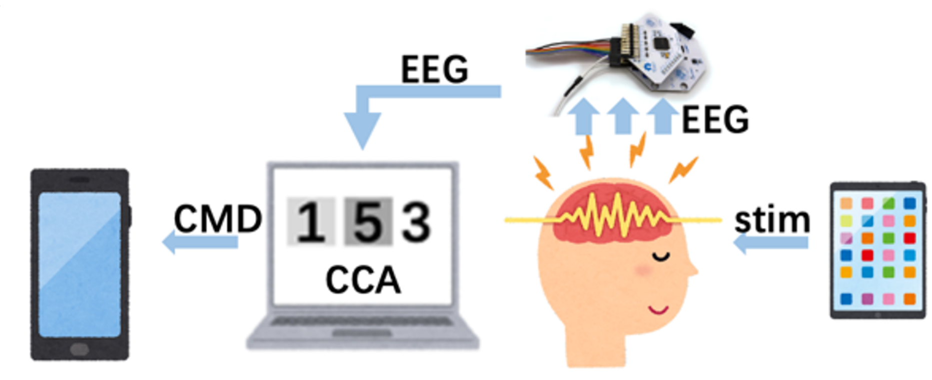

Figure 3. The flowchart of the entire system

III. EXPERIMENT AND RESULT

Our experimental procedure was designed to test the functionality and accuracy of the developed SSVEP-based BCI system. The SSVEP stimulator, designed as a digital keypad, contained keys each associated with a pre-set flickering frequency. Seven participants were involved in the experiment, all of whom were provided with proper instructions regarding the experiment's procedures and their roles. Participants were required to wear the OpenBCI EEG equipemt, with electrodes placed at positions PO3, POz, PO4, O1, Oz, O2, as per the international 10-20 system. The reference and ground electrodes were positioned on the earlobes. Table 1 shows the frequency and period settings of each stimulus block.

Experiments were conducted in a quiet, dimly lit room to minimize distractions and enhance the visual stimuli's effectiveness. Participants were asked to gaze at the SSVEP stimulator, specifically focusing on a single key for 3 seconds, followed by a 1-second interval before shifting focus to the next key. Each participant was given the liberty to choose which key to focus on, with the only condition being that the same key was not to be repeated in different experimental batches. The detailed procedure of the experiment is as follows. Step 1: The participant is asked to sit quietly in a relatively dim, quiet room. The experimenter fits the participant with an electrode cap. Step 2: With the

Table 1: The frequency and period settings of each stimulus block.

Number	Frequency (Hz)	Period (ms)
1	14.93	33.5
2	12.35	40.5
3	14.08	35.5
4	17.54	28.5
5	20.41	24.5
6	18.52	27
7	15.87	31.5
8	13.16	38
9	16.67	30
0	19.23	26
#	11.49	43.5
*	10.53	47.6

electrode positions (PO3, POz, PO4, O1, Oz, O2) confirmed, the participant's hair at these positions is moved aside to expose the scalp underneath the corresponding positions of the electrode cap. Step 3: A sufficient amount of electrode gel is applied to the electrodes. The electrodes are then inserted into the corresponding positions in the electrode cap and tightened to ensure close contact with the scalp. Step 4: The participant is asked to sequentially gaze at three keys at random, trying to avoid blinking during the continuous period. After the round of auditory prompts, there is a brief break. The program uses the CCA algorithm to calculate the nearest frequency from the collected brainwave signals, which then corresponds to the respective stimulus block, and the result is output. After the next auditory prompt, the second round begins. This is repeated until the end of the third round. Step 5: After the completion of all three rounds, the classification results from each round are obtained. These results are transmitted to a mobile phone via Bluetooth and the number is dialed out, realizing the function of making a call using brainwaves.

This cycle of focusing on three keys was repeated 20 times under identical experimental conditions for each participant, amounting to 60 key focus times per participant. As a result, across all seven participants, a total of 140 experimental batches were conducted, equating to 420 instances of key focus. Fig.4. shows the participant conducting the experiment. Fig.5. displays the OpenBCI Cyton board we used in the experiment.

Figure 4. The participant conducting the experiment.

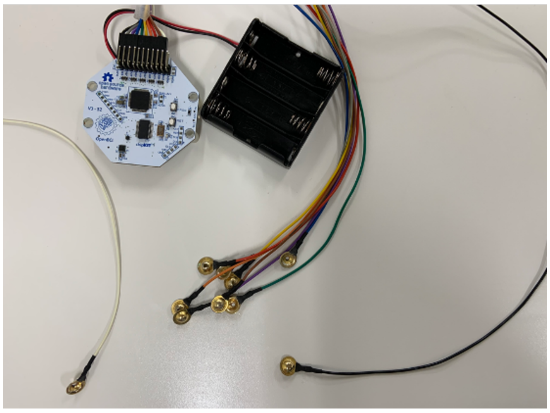

Figure 5. The OpenBCI Cyton board.

Result

The effectiveness of the SSVEP-based BCI system was evaluated by quantifying its performance in identifying the correct key based on the recorded EEG signals. Out of the total 420 key focus instances, the system successfully identified the correct key 412 times. This resulted in an impressive overall accuracy rate of 98.1%, demonstrating the system's high efficiency and accuracy. When compared to traditional LED-based SSVEP stimulators, our tablet-based SSVEP stimulator exhibited an advantage in terms of user comfort. Participants reported less visual fatigue during the experiments. This is attributed to the relatively low visual stress imposed by the tablet-based system, making it a promising option for continuous or long-term use in practical applications. These results indicate that our BCI system offers high accuracy and user comfort, highlighting its potential in various applications.

IV. CONCLUSION

The results from our experiments provide strong evidence of the potential and applicability of our SSVEP-based BCI system. The high accuracy rate of 98.1% represents a substantial achievement, particularly when considering the real-world implementation of the system. The accuracy level is indeed a critical parameter, as it directly relates to the system's reliability, a factor that will largely dictate user confidence and adoption rate in the long run.

Importantly, our system was not only accurate but also comfortable for users, a factor that should not be overlooked. As compared to traditional LED-based SSVEP stimulators, participants reported experiencing less visual fatigue during experiments using our tablet-based SSVEP stimulator. The visual strain during the interaction with a BCI system can be a significant barrier to its practical implementation. With this system, we have attempted to tackle this concern and managed to obtain positive feedback.

However, while our results are promising, it is important to recognize that this study was based on a relatively small sample size of seven participants. Future work may focus on increasing the sample size to validate the system's performance with a more diverse group of users. Further, the efficiency of our system should be tested with users in various real-world situations, and with different levels of cognitive and physical abilities.

It is also worth noting that although the participants had the liberty to choose which key to focus on, we maintained a strict condition that the same key was not to be repeated in different experimental batches. Although this was done to prevent bias in the data, it might not reflect a realistic scenario where a user may need to focus on the same key repetitively. Hence, future studies could focus on testing the system under more diverse conditions, including repeated focus on the same keys.

Lastly, while the current application of the system is dialing a phone number using brain signals, its potential applications are certainly not limited to this. Future research could explore other potential applications of this technology, such as controlling various digital devices, providing new communication channels for patients with locked-in syndrome, or even gaming.

In conclusion, our SSVEP-based BCI system has demonstrated promising potential. However, it is only through further research, testing, and development that we can fully realize the capabilities of this system, eventually unlocking a new frontier in human-computer interaction.

Acknowledgments

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Conflicts of Interest

The author has no conflict of interest about anything in this article.

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