A Novel Hybrid BCI Web Browser Based on SSVEP and Eye-Tracking

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***Abstract*—In this study, we developed and tested assistive technology for neuro-rehabilitation consisting of a novel hybrid web browser following "true web access" principles. We combined Steady-State Visual Evoked Potentials (SSVEP) derived from electroencephalography (EEG) together with gaze-point data from an eye-tracker to provide a natural method for people with severe motor impairment to access the internet without using a computer mouse. This system was tested by three healthy subjects. All subjects completed the online experiment successfully. The results showed an average overall accuracy of 88.5 ± 1.72%, whereas the copy-spelling accuracy of 100% was achieved by every subject. The average overall ITR value was 32.2 ± 1.14 bits/min. Thanks to the joining of eye-tracking technology, our system outperformed other BCI web browsers in command detection time and information transfer rate. And the user interface is much more friendly while the control panel and webpages are highly fused together.**

Keywords—brain-computer interface, electroencephalography, steady-state visual evoked potential, eye-tracking, web browser, rehabilitation

I. Introduction

Neurological disorders such as traumatic brain injury, brainstem stroke, amyotrophic lateral sclerosis (ALS), and Guillain-Barré syndrome can lead to severe or total motor paralysis often referred to as locked-in syndrome, a condition in which the patient is aware but cannot move or communicate verbally except for certain eye movements and blinking in many cases. Brain-computer interfaces (BCI) can enable direct communication between the human brain and a computer, and allow those patients to regain the ability to communicate with the outside world using external devices [1].

Steady-State Visual Evoked Potential (SSVEP) provides an important means for building BCIs. It refers to a synchronized brain wave in the occipital region generated in response to visual stimulation of frequency ranging from 1 to 90 Hz [2]. SSVEP-based BCIs are fast, reliable and require little to no training. However the frequencies that can be used for visual stimulation are limited, since harmonic frequencies cannot be used for different stimuli. Also, because the stimuli are delivered by a computer monitor, the range of available frequencies is usually limited by the refresh rate [3]. A narrower frequency interval, however, renders frequency identification more challenging. Moreover, the amplitude of SSVEP evoked by a commonly used liquid crystal display (LCD) monitor is weaker than that evoked by a light-emitting diode (LED) due to the different working principles [4]. These limitations all affect the performance of practical SSVEP-based BCI system.

Eye-tracking is widely used as an assistive technology (AT) that puts the user in volitional control of an external device using the eyes in a natural manner. An eye-tracker is a device for measuring instantaneous eye position that makes it possible for users to interact with computers or other devices using their eye-gaze. A problem in using eye-gaze for target selection arises since the basic function of the eyes – namely to acquire and perceive visual information – cannot be clearly distinguished from gaze interactions intended to control the device, and the former may be wrongly recognized as a control command. Sometimes referred to as the "Midas touch" problem [5], this issue can be circumvented if eye-tracking data is used for gaze position estimation but not for final target selection. This suggests that combining eye-tracking technology and BCIs could be a promising approach.

With rapid integration of technology in our daily lives, the ability to use the internet plays an important role in determining one's quality of life. Helping people with paralysis to regain the ability to communicate or access information via the internet is not simple since most webpages are designed for use with the mouse and keyboard and without regard for accessibility by the paralyzed. Recent research has focused on improving patients' quality of life through development of various BCI systems such as BCI spellers and BCI web browsers. Bensch et al. [6] and Karim et al. [7] developed Descartes and Nessi which are Slow Cortical Potential (SCP)-based web browsers and use binary decision trees for selection. Both of these web browsers have a simple user interface but require a long training time and offer slow navigation speeds. As examples of P300-based web browsers, Sirvent et al. [8] used function buttons to control the mouse. Martínez-Cagigal et al. [9] indexed hyperlinks on the webpage with exclusive numbers, such that users select the target by entering the specific number. Yehia et al. [10] introduced an SSVEP-based

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Demonstration video: https://youtu.be/2MwWvsqcdcM.

web browser named WeBB, which is a faster web browser which yields an average accuracy of 86.08% but still takes about 20s to make a selection. The currently fastest web browsing system was developed by He et al. which combined electrooculography (EOG) and EEG and achieved an average accuracy of 96.42% and an average selection time of 13.11s. However, all of the above studies need an additional user interface besides the webpage on the screen to operate the system, making the system complicated to use.

The current study is an extension of our previous work on a hybrid-BCI speller [16] and is aimed at developing a web browser that can be controlled in a natural way. The system was developed following "true web access" principles as guidelines, as described by Mankoff et al. [12] and Mugler et al. [13].

II. Materials and Methods

A. Subjects and Equipments

The EEG signals were acquired at 500 Hz via Synamps2 system (Neuroscan, Inc.) with 64-channel caps. A 50 Hz notch filter were applied directly in the amplifier. The gaze data was collected by a low-cost eye-tracker (Tobii Eye Tracker 4C) at 90 Hz, and the operating distance with a range of 50 cm to 95 cm. A 24.5-inch liquid-crystal display (LCD) screen (BenQ Zowie XL2546, resolution: 1920×1080 pixels) with 240 Hz refresh rate is used in this study.

Five healthy subjects with a mean age of 24.6 (1.5) years were recruited from Zhejiang University for this study. Each subject was asked to read and sign an informed consent form approved by the Institutional Review Board of the Chinese Academy of Sciences before the experiment. The subjects had the opportunity to opt-out of the study at any time.

B. Web Browsing System

This study presents a web browsing system based on our previous study of high speed and high scalability hybrid BCI spelling system which utilizing SSVEP and eye-tracking. The system consisted of server-side and client-side. And the communication between these two parts of the system is based on the WebSocket API.

The server-side is always running in the background and invisible to users. It has to detect the dwelling of the eye gaze point and send a signal to the client to start a trial. Meanwhile, the system begins recording the EEG signals until the end of the trial (trial duration is set to 4000 ms in this study). The system processes recorded signals to identify the intrinsic SSVEP frequency, and the result will be sent to the client for performing operations. Four frequencies from 13 Hz to 16 Hz with 1 Hz interval are used in this study for SSVEP stimulation. Three additional intermediate frequencies 13.5 Hz, 14.5 Hz, and 15.5 Hz are used to improve the reliability of the system—If one of these frequencies is identified, the result will be rejected and treated as missed during the experiment.

The client-side of our web browsing system is a script directly running on the web browser Google Chrome. We have tested the ability of the browser to provide stable rendering for SSVEP by customizing Cascading Style Sheets (CSS) animation. The script is automatically injected into every loaded webpage via a Google Chrome plugin named Tampermonkey, thus each webpage owns a client respectively. The script provides the ability to communicate with the server and embeds 6 function buttons and a speller into the original webpage as Hyper-Text Markup Language (HTML) elements. The function buttons are: scroll up/down buttons, navigation backward/forward buttons, homepage button and mode switch button (Fig. 1). The mode switch button provides the ability to switch between two modes: standard mode and read mode. In read mode, hyperlinks and other interactable elements are nullified and only 6 function buttons can be activated through gaze dwelling, so that the user can read and navigate text freely and will not be annoyed by any SSVEP stimulations triggered unexpectedly.

When the trial start signal is received from the server, the client finds out and activates at most 4 nearest interactable elements around the gaze point and within the range of 200 pixels (Fig. 1). The maximum number of elements that can be activated simultaneously corresponds to the number of used SSVEP stimulation frequencies. A conspicuous border is shown around all activated elements and the flickers at the bottom center of the elements then start flickering at their own exclusive frequency. The user is required to focus on the flicker corresponding to the desired element. When the frequency identification result is received, the flickering will stop, and the client will find the corresponding element

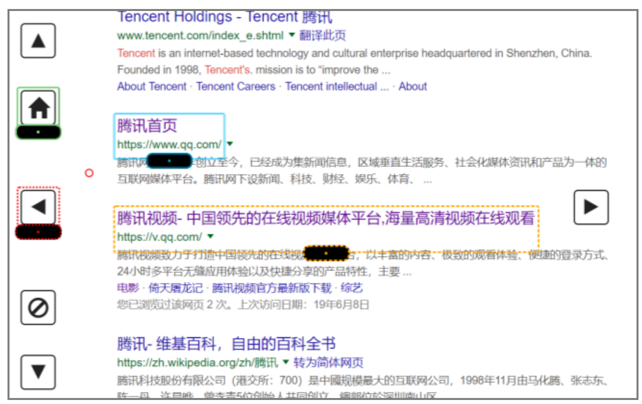

Fig. 1. GUI of our hybrid BCI web browser with 6 function buttons. The small red circle indicates the eye gaze point for clarity. Activated elements are bordered with a unique visual style.

Fig. 2. Typing the last "T" of keyword "TENCENT" in the pop-up speller dialog. The buttons are flickering to provide the visual stimulation.

according to the identified frequency. After that, an appropriate operation will be performed. For example, a mouse click action will be simulated by script if there is a hyperlink or a button, a command will be executed if there is a function button, or the in-page speller dialog will pop up if there is an edit box.

The speller dialog box (Fig. 2) is embedded in the script and becomes a part of the webpage. It is invisible by default unless the edit box is focused. At the top of the dialog, a text box shows the characters that have been already entered. A total of 71 buttons including 67 character buttons and 4 command buttons are laid out below the text box.

The web browser and the speller dialog have distinct designs. In the speller dialog case, the design of the stimulus is inherited directly from the standard SSVEP paradigm—button flickering with a size of 60×60 pixels (width × height). But in the browser, the stimulus must be designed as small as possible to avoid text covering and stimuli collisions for text readability and system usability. Additionally, our goal is to minimize the impact on target detection accuracy while reducing the stimulus dimension. Thus, the stimulus is designed as a horizontal rectangle instead of a square with the size of 50×15 pixels (not including the border) and is placed at bottom center of the target element.

C. Online Experiment Procedures

Subjects were seated in front of the screen at a distance of about 60 cm. The subject was instructed to stay as still as possible, but no chin-strap was used. Six electrodes were placed according to the 10-20 international system of electrode placement over parieto-occipital and occipital area (PO3, POz, PO4, O1, Oz, O2), the reference electrode was placed over Cz, and the ground electrode over AFz. Conductive gel was applied between electrodes and scalp to bring impedance to under 5 kΩ. The eye-tracker was calibrated for each subject via the Tobii EyeTracking (v2.16.4) software.

This experiment was designed to reproduce daily web browsing experience which include typing, clicking and navigating. Subjects were instructed to surf the internet (see YouTube video for more detail of instructions):

- Select the edit box from the homepage—Google search engine.
- Type the keyword "TENCENT" in the pop-up speller dialog, and select confirm button (8 commands in total).
- Click "Google Search" button to search.
- Open the Tencent Homepage "www.qq.com" by selecting the link at bottom of the search result page.
- Open the designated news page.
- Scrolled down to the bottom of the news page by selecting scroll down button twice.
- Use the function button to return to homepage.

Our standard experimental protocol includes 15 trials, but further trials are conducted in case of command detection errors. Thus, the total number of trials may be uncertain between sessions. It's noteworthy that the backward operation following the wrong operation is treated as correct.

Prior to the formal experiment, each subject was informed of the entire experimental procedures and a training session was conducted to ensure clarity of understanding.

D. Signal Processing

For signal processing, SSVEP features were extracted by using the filter-bank canonical correlation analysis (FBCCA) [14] for classification without performing any preprocessing steps.

According to our previous research [16], FBCCA is a robust algorithm that extends CCA by combining maximum CCA coefficients from multiple sub-bands of EEG. Thus it can be used under varying situations to offer greater stability. The models trained by most data-driven algorithms are essentially spatial filters and vulnerable to variations such as the size and position of the stimulus [15]. We proved through a simple test with different positions of SSVEP stimulus that data-driven algorithms are unstable if the position of the stimulus is uncertain.

E. Performance Evaluation

The performance of proposed BCI system is evaluated by calculating target detection accuracy and information transfer rate (ITR) [1]. Target detection accuracy is the ratio of the number of correct trials to the total number of trials in the experiment. The ITR presented in bits/min is a measure of how fast the BCI system is, calculated as:

$$ITR = (\log_2 N + P\log_2 P + (1-P)\log_2 \frac{[1-P]}{[M-1]})/T\ , \qquad (1)$$

TABLE I PERFORMANCE RESULTS OF OUR HYBRID BCI WEB BROWSER

Subjects	Browsing accuracy (%)	Copy-spelling accuracy (%)	Overall accuracy (%)	Overall ITR (bits/min)
S1	76.9	100.0	85.7	30.5
S2	81.8	100.0	89.5	34.8
S3	80.0	100.0	88.9	31.6
S4	88.9	100.0	94.1	34.8
S5	72.7	100.0	84.2	29.2
Mean (SD)	80.1 (6.0)	100.0 (0.0)	88.5 (3.8)	32.2 (2.5)

TABLE II PERFORMANCE COMPARISON WITH OTHERS, INDICATED BY RESPECTIVE MEAN (SD) VALUES

Web Browser	Accuracy (%)	Time per command (s)	Theoretical ITR (bits/min)
Present study	88.48 (3.84)	8.73 (0.30)	32.18 (2.54)
Hybrid browser [11]	96.42 (2.28)	12.82 (0.95)	25.02 (2.82)
WeBB [10]	86.07 (4.78)	20.16 (2.98)	13.55 (2.73)
P300 browser [9]	95.75 (4.48)	32.26 (11.62)	11.08 (4.13)

where N is the average number of displayed targets during the experiment (N = 58.1 in this study), P is the target detection accuracy, and T (min/command) is the average time for a command including page loading time which is calculated by dividing the duration of experiment by trial count.

III. Results

All subjects successfully completed the experiment. Trial count, accuracy, ITR and several results are shown in Table I. Subjects obtained an average accuracy of 88.5% for the web browser. The copy-spelling task performed in the pop-up speller dialog obtained an accuracy of 100% for all subjects and the average target detection accuracy for the web browsing is relatively low (only 80.1%) but still over 70%. The significant decline in accuracy ($p < 0.001$) was caused by the reduction in the size of the stimulus (60×60 pixels in pop-up speller dialog of current study but 50×15 pixels for the web browsing). This decline is somehow inevitable even if the stimulation lasted for 4 seconds long.

Table II showed the performance results of our proposed web browser and other three web browsers. The T-test and the Bonferroni correction were utilized for the tests of significance. From results, the accuracy of our system has no significant difference compared to that of WeBB ($p > 0.05$) and of the P300 browser ($p > 0.05$) but is significantly lower than the hybrid browser ($p < 0.05$). For the time cost per command, our system is significantly faster than three other systems (both $p < 0.01$). The information transfer rate is a commonly used measure of BCI performance. However, due to the high variability of web pages, ITRs in different studies cannot be directly compared. For example, the number of hyperlinks presented on a webpage can be zero or over 100 (the N is uncertain across studies). Therefore, we calculated theoretical ITRs of other three web browsers (with $N = 58.1$, the same as this study) by adopting their accuracy values and command time costs. The results showed that our system achieved a significantly higher ITR compared to the hybrid one ($p < 0.05$) and other two systems ($p < 0.01$).

IV. Discussion and Conclusion

In this study, we proposed a high-speed hybrid BCI web browsing system which provides a natural mechanism to access the internet without using a computer mouse. All subjects completed the training session within 5 minutes. It indicated that our system is easy-to-use. As some subjects reported, the stimulation time is relatively long. Due to the difference in stimulus size, the stimulus time can be set shorter directly for the speller dialog, but not for the web browsing. For higher target detection accuracy and shorter stimulation time, a better stimulus positioning algorithm can be used to ensure optimal distance among stimuli, because insufficient distance may lead to interference in SSVEP frequency identification. Also, a better frequency identification algorithm can be applied under the situations where the size of the stimulus is much smaller. As it is important to minimize fatigue caused by assistive technology, the Steady-State Motion Visual Evoked Potential (SSMVEP) or other stimulation methods, reported to be less fatiguing, may be used in future.

In conclusion, a novel hybrid BCI web browsing system has been developed that utilizes both EEG signals and eye gaze points to facilitate access to a random location on a webpage. Further we have embedded a BCI speller interface into our web browsing system to make it possible to type and perform an internet search on the webpage. Based on experimental results, our system outperformed the others in command detection time and ITR by leveraging eye-tracking technology. The system is an early prototype and many improvements can be introduced in the next iterations of development.

References

[1] Wolpaw, Jonathan R., et al. "Brain–computer interfaces for communication and control." Clinical neurophysiology 113.6 (2002): 767-791.

[2] Regan, David. "Human brain electrophysiology: evoked potentials and evoked magnetic fields in science and medicine." (1989).

[3] Volosyak, Ivan, Hubert Cecotti, and Axel Graser. "Optimal visual stimuli on LCD screens for SSVEP based Brain-Computer Interfaces." 2009 4th International IEEE/EMBS Conference on Neural Engineering. IEEE, 2009.

[4] Wu, Zhenghua, et al. "Stimulator selection in SSVEP-based BCI." Medical engineering & physics 30.8 (2008): 1079-1088.

[5] Chaudhary, Ujwal, Niels Birbaumer, and Ander Ramos-Murguialday. "Brain–computer interfaces for communication and rehabilitation." Nature Reviews Neurology 12.9 (2016): 513.

[6] Bensch, Michael, et al. "Nessi: an EEG-controlled web browser for severely paralyzed patients." Computational intelligence and neuroscience 2007 (2007).

[7] Karim, Ahmed A., et al. "Neural internet: Web surfing with brain potentials for the completely paralyzed." Neurorehabilitation and Neural Repair 20.4 (2006): 508-515.

[8] Sirvent, José L., et al. "P300-based brain-computer interface for internet browsing." Trends in practical applications of agents and multiagent systems. Springer, Berlin, Heidelberg, 2010. 615-622.

[9] Martínez-Cagigal, Víctor, et al. "An asynchronous P300-based brain-computer interface web browser for severely disabled people." IEEE Transactions on Neural Systems and Rehabilitation Engineering 25.8 (2016): 1332-1342.

[10] Yehia, Ahmed G., Seif Eldawlatly, and Mohamed Taher. "WeBB: A brain-computer interface web browser based on steady-state visual evoked potentials." 2017 12th International Conference on Computer Engineering and Systems (ICCES). IEEE, 2017.

[11] He, Shenghong, et al. "A hybrid BCI web browser based on EEG and EOG signals." 2017 39th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC). IEEE, 2017.

[12] Mankoff, Jennifer, et al. "Web accessibility for low bandwidth input." Proceedings of the fifth international ACM conference on Assistive technologies. ACM, 2002.

[13] Mugler, Emily M., et al. "Design and implementation of a P300-based brain-computer interface for controlling an internet browser." IEEE Transactions on Neural Systems and Rehabilitation Engineering 18.6 (2010): 599-609.

[14] Chen, Xiaogang, et al. "Filter bank canonical correlation analysis for implementing a high-speed SSVEP-based brain–computer interface." Journal of neural engineering 12.4 (2015): 046008.

[15] Itai, Akitoshi, and Takahumi Sakakibara. "The relationship between a location of visual stimulus and SSVEP." 2015 15th International Symposium on Communications and Information Technologies (ISCIT). IEEE, 2015.

[16] Lin, Xinyuan, Zhenyi Chen, Kedi Xu and Shaomin Zhang. "Development of a High-speed Mental Spelling System Combining Eye Tracking and SSVEP-based BCI with High Scalability," 2019 41st Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC). IEEE, 2019.