Assessing the Potential of Brain-Computer Interface Multiplayer Video Games using c-VEPs: A Pilot Study

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Abstract— **Video games have become a common and widespread form of entertainment, while non-invasive brain-computer interfaces (BCI) are emerging as potential alternative communication technologies. Combining BCIs and video games can enhance the gaming experience and make it accessible to motor-disabled individuals. Recently, code-modulated visual evoked potentials (c-VEP) have been proposed as a novel control signal able to achieve high performance with short calibration times. However, there are still no video games that use c-VEPs as a control signal. The aim of this pilot study is to develop an implementation of the 'Connect 4' multiplayer video game using a c-VEP-based BCI and test it with 10 healthy users. Participants were paired to compete in matches and carried out individual tasks. The results showed that the participants were able to control the game with an average accuracy of 94.10% and a selection time of 5.25 seconds per command, outperforming previous approaches. This suggests that the proposed video game is feasible and c-VEPs can provide smooth BCI control.**

I. INTRODUCTION

Brain-computer interface (BCI) systems are defined as communication systems that allow users to interact with the environment by monitoring and decoding brain activity, bypassing the need for muscle or nerve involvement. EEG is the most widely-used method for recording brain activity and interpreting user intent, as it is non-invasive, portable, and cost-effective [1].

The video game industry has seen significant growth in recent years, with an estimated 3.09 billion active players worldwide [2]. Despite this progress, accessibility remains a challenge for individuals with severe disabilities as the majority of games are designed to be controlled using keyboard, mouse, or joystick. In this sense, exploring the integration of BCI systems with video games holds potential for improving the quality of life and independence of motor-disabled people.

Several studies on multiplayer BCI video games have been carried out in the scientific literature [3], [4], [5], [6], but none of them have been able to achieve high performance or have been tested with a relevant number of users. Furthermore, these games only offered a single-player mode and lacked multiplayer capabilities. The latter would help to delve into how competitiveness, collaboration or motivation between players is reflected in their brain activity.

There are examples of multiplayer BCI video games adapting 'Connect 4', a classic game where two users compete to win with the goal of lining up 4 coins of the same color horizontally, vertically or diagonally. Two different versions of this game were implemented and adapted to BCI by Maby et al. [7] and Holz et al. [8], using P300 evoked potentials and sensorimotor rhythms (SMR) as control signals, respectively. While these studies demonstrated the potential of BCI multiplayer video games, their control signal choice limited their performance in terms of calibration/training time and accuracy (83.83% [7] and 62.65% [8]), hindering user experience and feasibility in real-world scenarios. Today, the limitations of previous studies can be addressed through the use of code-modulated visual evoked potentials (c-VEPs), a cutting-edge control signal that encodes commands via shifted versions of binary pseudo-random sequences. Despite its ability to offer high performance with very short calibration times (e.g., >90% with 30-60s of calibration) [9], there are still no studies that have been developed and tested a multiplayer BCI video game based on c-VEPs [9].

The objective of this pilot study is to design, develop and evaluate a BCI multiplayer video game using c-VEPs, specifically, another version of 'Connect 4' to facilitate comparison with prior research. Our video game was tested with 10 healthy participants during a single session that included individual free and guided tasks, as well as competitive multiplayer tasks.

II. SUBJECTS AND METHODOLOGY

Ten healthy users (28.8 years ± 4.28 years, 6 males, 4 females) participated in the experiments. Each participant voluntarily gave their consent to participate and was fully informed about the purpose of the study.

The BCI system consists of three main stages: (1) signal acquisition, which involves a simultaneous recording of the EEG signals from two participants; (2) signal processing, designed to decode the users' gaze direction from the EEG; and (3) the video game application, our version

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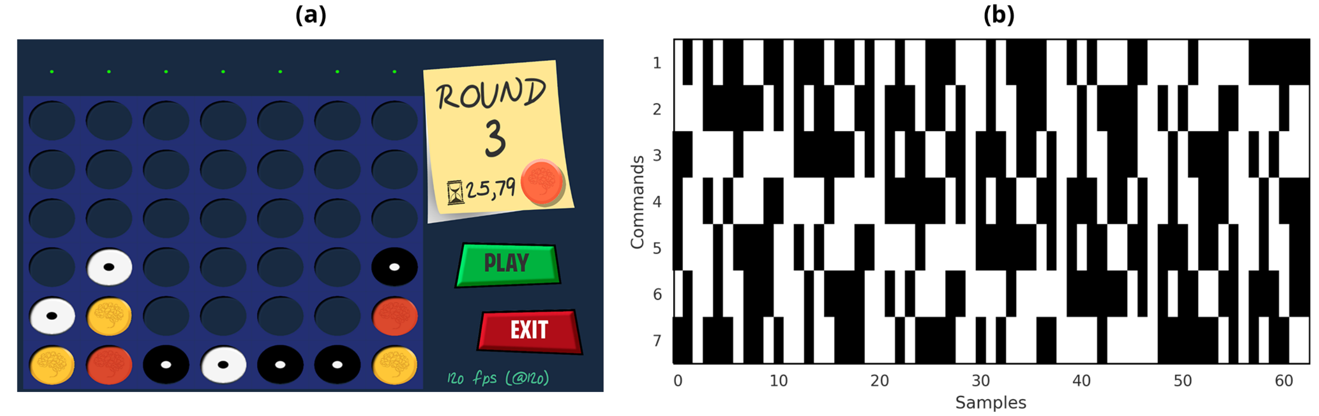

Fig. 1. (a) Snapshot of the video game graphical interface in Unity. Each column behaves as a different command, following shifted versions of the m-sequence. (b) Encoding of each column, according to lags of $\theta_i = 9i$ samples, where $i = 0, 2, \ldots, 6$.

of ‘Connect 4’ that provides real-time visual feedback to the users. These stages have been developed within the MEDUSA© ecosystem, a Python-based general-purpose framework for the development of BCI systems and neuroscience experiments (www.medusabci.com) [10]. To favor visual appearance, the application was designed in Unity, while the communication with MEDUSA© Platform is made through TCP/IP protocol.

A. *Paradigm*

The BCI has been designed using the circular shifting paradigm, which encodes each command using shifted versions of a pseudo-random sequence. The encoding was achieved using the common 63-bit binary maximum length sequence (m-sequence) generated by a linear feedback shift register (LFSR), using the polynomial $x^6 + x^5 + 1$ with an initial state of 110000 [9]. Since the stimuli is displayed at a rate of 120 Hz, a complete cycle (i.e., repetition of the m-sequence) lasts 525 ms. Although the m-sequence offers a perfect correlation, the autocorrelation of the resulting EEG response does not necessarily satisfy this condition. To facilitate decoding, it is recommended to distribute the assigned delays evenly across the 63-bit code [9].

As depicted in Figure 1, in the ‘Connect 4’ video game players take turns placing coins in 7 different columns, so in the worst-case scenario (i.e., no column has been filled up yet), we would need to encode 7 commands. To maximize the phase spacing difference between the 7 possible commands, the delays for each column were established as multiples of 9 samples.

B. *Signal acquisition*

The EEG signal was recorded using two g.Nautilus Pro devices (*g.Tec*, Guger Technologies, Austria), with a sampling rate of 250 Hz. The signals were transmitted via Bluetooth to the computer running the video game instance, a PC IntelCore i7-10700F CPU @ 2.90GHz, 32GB RAM. Eight active electrodes were placed in each scalp at positions Fz, Cz, Pz, P3, P4, PO7, PO8, and Oz, referenced to the right earlobe (A2) and grounded on AFz.

C. *Signal processing*

The initial step in the processing phase involves preprocessing the EEG signal to remove non-essential frequency ranges for c-VEP detection. This was achieved through the use of a 7th-order Butterworth infinite impulse response (IIR) bandpass filter with cutoff frequencies ranging between $1 - 30$ Hz. In terms of processing, the selected command was decoded in real-time using the standard processing method for c-VEPs based on circular shifting, as described in previous research [9]. This process was divided into two phases: calibration and testing.

In calibration, the signal is recorded when the user looks at the command encoded with the original m-sequence (i.e., without delay) for k cycles. Two versions of the EEG response were obtained after preprocessing: (1) the concatenated epochs $\boldsymbol{A} \in \mathbb{R}^{[kN_s \times N_c]}$, where N_s is the number of samples of a complete cycle and N_c is the number of channels; and (2) the epochs averaged over the k cycles $\boldsymbol{B} \in \mathbb{R}^{[N_s \times N_c]}$. To maximize the correlation between these two versions, a canonical correlation analysis (CCA) was applied. The spatial filter $\boldsymbol{\omega_b}$ that yields the maximum correlation between the concatenated epochs and the average response is then determined. The original signal is subsequently projected using this filter to obtain the main template $\boldsymbol{x}_0 = \boldsymbol{B}\boldsymbol{\omega_b}$, while the templates for the rest of the commands are obtained by shifting the original $\theta_i = 9i$ samples, where $i = 0, 2, \ldots, 6$ [9]. To remove noisy epochs, calibration epochs exhibiting a standard deviation three times greater than the average standard deviation of all of them were discarded [11].

Subsequently, in the test stage, the epochs of each trial are extracted and spatially projected with $\boldsymbol{\omega_b}$. Then, Pearson’s correlation coefficients between this projection and all templates are computed, i.e. $\boldsymbol{\rho}$. The command selected by the user will be the one corresponding to the delay whose template shows the highest correlation, i.e. $\arg\max_i(\boldsymbol{\rho})$ [9].

D. *Application*

The video game application is a version of the classic game ‘Connect 4’, where the objective is to line up four coins

TABLE I

PERFORMANCE OBTAINED FOR ALL TASKS AND USERS

User	**Guided Tasks**		**Free Tasks**		**Multiplayer Tasks**		**Tasks Mean ± STD**	
	Accuracy	ITR	Accuracy	ITR	Accuracy	ITR	Accuracy	ITR
U01	100.00%	32.08 bpm	100.00%	32.08 bpm	86.57%	29.28 bpm	95.52% ± 6.33%	31.15 bpm ± 1.32 bpm
U02	100.00%	32.08 bpm	100.00%	32.08 bpm	86.06%	29.19 bpm	95.35% ± 6.57%	31.12 bpm ± 1.36 bpm
U03	98.76%	31.73 bpm	100.00%	32.08 bpm	95.23%	30.91 bpm	98.00% ± 2.02%	31.57 bpm ± 0.49 bpm
U04	91.86%	30.23bpm	96.43%	31.18 bpm	85.94%	29.18 bpm	91.41% ± 4.29%	30.20 bpm ± 0.82 bpm
U05	96.43%	31.18 bpm	100.00%	32.08 bpm	100.00%	32.08 bpm	98.81% ± 1.68%	31.78 bpm ± 0.42 bpm
U06	86.75%	29.31 bpm	84.22%	28.89 bpm	100.00%	32.08 bpm	90.32% ± 6.92%	30.09 bpm ± 1.42 bpm
U07	88.06%	29.54 bpm	90.00%	29.88 bpm	96.29%	31.14 bpm	91.45% ± 3.51%	30.19 bpm ± 0.69 bpm
U08	88.63%	29.64 bpm	96.42%	31.17 bpm	96.66%	31.23 bpm	93.90% ± 3.73%	30.68 bpm ± 0.74 bpm
U09	100.00%	32.08 bpm	100.00%	32.08 bpm	77.81%	27.94 bpm	92.60% ± 10.46%	30.70 bpm ± 1.95 bpm
U10	98.71%	31.71 bpm	100.00%	32.08 bpm	82.14%	28.57 bpm	93.62%± 8.13%	30.79 bpm ± 1.57 bpm
Mean	**94.92%**	**30.96 bpm**	**96.71%**	**31.36 bpm**	**90.67%**	**30.16 bpm**	**94.10% ± 2.53%**	**30.83 bpm ± 0.50 bpm**
STD	5.21%	1.09 bpm	5.16%	1.07 bpm	7.49%	1.42 bpm		

ITR: information transfer rate, STD: standard deviation.

of the same color horizontally, vertically, or diagonally on a 6×7 cell board. The game is designed for two players, who compete against each other, with one controlling red coins and the other yellow coins. In addition to the multiplayer mode, our implementation can also be used in an individual player mode, where a single player controls the red and yellow coins, selecting them sequentially. To place a coin in one of the seven columns, the player focuses their gaze on the cell where they want to place the coin, while each possible position flickers following the shifted version of the sequence associated to its command. The 0 value is encoded as black, while 1 is represented as white, as depicted in Figure 1(b).

III. EXPERIMENTAL PROTOCOL

The protocol to evaluate the BCI-powered ‘Connect 4’ video game involved 10 healthy participants completing 10 tasks in a single session. The tasks performed were divided into 2 modes: (1) individual mode, consisting of guided tasks and free tasks; and (2) multiplayer mode. To verify the proper functioning of the system and increase the number of selections, the individual tasks were composed of 4 guided tasks, in which the participant was required to select commands following the order indicated by the supervisor; and 3 free tasks, in which the participant was required to win the game while following several constraints (e.g., placing coins diagonally). Finally, participants were grouped into pairs and engaged in the multiplayer mode, which involved competing against each other in 3 distinct games.

Before carrying out all the tasks, a calibration stage was performed to compute the spatial filter and templates for each user, according to the signal processing detailed in section II-C. Users were asked to focus their attention on the first cell for 10 trials of 10 cycles each, lasting 52.50 s in total. After the evaluation, an offline analysis was performed to assess the performance of our system in terms of accuracy, information transfer rate (ITR) and selection speed.

IV. RESULTS AND DISCUSSION

Table I summarizes the performance of each user in terms of accuracy and ITR for the guided, free and multiplayer tasks. As shown, the results show favorable functionality of the proposed BCI system with an average accuracy of 94.10% and an ITR of 30.83 bpm among all users and tasks. This confirms the effectiveness of the system, as a BCI system is deemed controllable when the user’s accuracy exceeds 70% [12].

In particular, the highest mean accuracy was obtained for the free tasks (96.71%); followed by the guided tasks (94.92%) and the multiplayer tasks (90.67%). Although no significant differences in accuracy were found between tasks (p-values > 0.05, Wilcoxon signed-rank test), we observed that 6 users experienced a decrease in accuracy in the multiplayer mode compared to the set of individual tasks. This decrease could be due to user fatigue or competition-related tension, as users tend to put more effort into the task when competing against another participant, which may negatively impact their results [13]. In terms of speed, all selections were made using 10 cycles, which equates to 5.25 s per command. This resulted in ITRs between 30-32 bpm, which were limited by the reduced number of commands (i.e., 7).

A. *Comparative with other studies*

Two previous studies implemented a BCI-based version of ‘Connect 4’, which allow us to make a direct comparison [7], [8]. First, it is important to discuss the sample size. Holz *et al.* [8] was conducted with only 4 users with severe motor impairments, while Maby *et al.* [7] was tested with 2 healthy control users. Our study involved 10 healthy control participants, increasing heterogeneity and strengthening the statistical power to provide more conclusive results.

Regarding achieved performances, Holz *et al.* [8] used the elicited SMRs via hand and foot motor imagery (MI) tasks, reaching an average accuracy of 62.65% with 0.53 bpm. While MI-based BCIs have potential for neurorehabilitation, their performance as a communication and control aid usually falls short of the minimum controllable threshold of 70%. On the other hand, Maby *et al.* [7] used P300 evoked potentials, reaching an average accuracy of 83.30% with

37.00 bpm. P300 potentials have been widely used in BCIs due to their high accuracy, but our c-VEP-based implementation overcame both approaches in terms of accuracy and selection speed. Our implementation achieved an average accuracy of 94.10%, which is significantly higher than those reported by Holz *et al.* [8] (p-value < 0.01, Mann-Whitney U-Test) and Maby *et al.* [7] (p-value < 0.01, Mann-Whitney U-Test).

Another parameter to compare is the calibration or training time. Holz *et al.* [8] did not require a calibration stage, but an endogenous training stage that lasted between 26.26-190 min, depending on the user; while Maby *et al.* [7] used a calibration that lasted 4.30 min, corresponding to 63 selections with 2 repetitions per trial. As shown, our implementation only requires a calibration stage that lasts 52.50 s per user. Therefore, we can conclude that our pilot study attains a significantly high accuracy with a shorter calibration time that the previous approaches.

B. Limitations and future directions

Despite the successful results of the proposed multiplayer BCI video game, there are several limitations to overcome for future research. First, it would be desirable to evaluate the proposed system with motor-disabled participants, who are the traditional target users of these BCIs. Although the quantitative analysis demonstrated the efficacy of the system, it would be advisable to carry out a qualitative analysis by means of questionnaires to take into account the users' satisfaction and improvement suggestions. In addition, a detailed analysis of the performance in function of the number of cycles could be useful to develop new early stopping algorithms aimed at increasing selection speed without compromising accuracy.

V. CONCLUSIONS

This study introduces a novel multiplayer version of 'Connect 4' using a c-VEP-based BCI for the first time. The system was evaluated with 10 healthy participants, achieving an average accuracy of 94.10% with a selection time of 5.25 s per command. A slight non-significant decrease in accuracy was observed in multiplayer tasks (90.67%) in comparison with individual free (96.71%) and guided tasks (94.92%), likely due to competitive pressure. Our system performances also overcame previous approaches in terms of accuracy, selection speed and calibration time. It is concluded that the proposed video game is feasible and robust, providing smooth BCI control.

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