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Usability of three software platforms for modifying graphical layout in visual P300-based brain-computer interface

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A R T I C L E I N F O

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A B S T R A C T

Individuals afflicted by neurodegenerative conditions such as amyotrophic lateral sclerosis may eventually reach a point where they lose the ability to communicate with the outside world through conventional muscular pathways. In these cases, brain-computer interfaces (BCIs) can be a suitable alternative, as they directly transform brain activity into external commands. A P300-based speller is a BCI for communication purposes. The most popular software platforms used to develop spellers are BCI2000 and Open-ViBE. However, these platforms can be relatively complex to set up without advanced technical knowledge. For this reason, the UMA-BCI Speller platform was recently developed, intended to facilitate the control of the system. Hence, the objective of this research was to assess and compare the user-friendliness of the three platforms put forth. A group of fifteen participants were tasked with configuring a designated speller layout using the three platforms. The findings acquired demonstrated that the UMA-BCI Speller platform exhibited the utmost level of usability, as it required the shortest time to complete the tasks and received the best feedback in the questionnaires. Overall, there was no difference between the BCI2000 and Open-ViBE platforms. In short, the UMA-BCI Speller offered the best usability and showed itself to be an easy application to use that provides many options to configure a speller graphical layout.

1. Introduction

Individuals who suffer from neurodegenerative disorders, including amyotrophic lateral sclerosis (ALS), may eventually experience profound disabilities, particularly affecting their motor system. In severe cases, these disabilities can lead to a complete loss of voluntary muscle control, encompassing eye movement and even basic functions like breathing. Consequently, individuals with such impairments are unable to communicate through conventional muscular means. Their only recourse is to rely on a brain-computer interface (BCI) system [1], which translates brain activity into commands that can be interpreted by a machine. By offering a non-muscular channel, this system enables users to interact with their environment, granting them greater independence in their daily lives.

Among BCI systems, those based on electroencephalographic (EEG) signal recording are widely used due to their non-invasive nature, good temporal resolution, and user-friendly operation. For communication purposes, three types of EEG-based BCI systems have been employed: (a) slow cortical potentials (SCPs), (b) P300 event-related potentials (ERPs), and (c) sensorimotor rhythms (SMRs) [2]. SCP- and SMR-based BCIs require extensive user training before achieving adequate control over their brain activity. Conversely, P300-based BCIs rely on the discriminative response humans naturally exhibit to infrequent target stimuli, typically visual cues, necessitating minimal training. The P300 signal, recorded from the central and parietal regions of the brain, manifests as a positive deflection in the brain wave approximately 300 ms after the presentation of the stimulus.

The main applications of P300-based BCI systems are spellers, which are intended for communication purposes [3]. The most widely applied design in this application is the row-column paradigm (RCP). The RCP, initially proposed by Farwell and Donchin [4], remains a significant reference in the field and continues to be extensively studied. In this particular BCI system, a 6x6 grid containing alphanumeric characters is presented to the user. The characters are arranged in rows and columns.

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As each row and column is randomly flashed or intensified one after the other, the user directs their attention to the specific characters within the grid that they wish to select. Following several rounds of flashing, the system identifies and presents on the screen the character that the user was supposedly focusing on during the process.

Nowadays, there are several BCI software platforms available for the configuration and control of a P300-based BCI, such as BCI2000 [5], BCILAB [6], Open-ViBE [7] and PMW [8]. However, according to Stegman et al. [9], the two most popular platforms for developing BCI systems are BCI2000 and Open-ViBE. These platforms are widely utilized and offer up-to-date software releases, comprehensive documentation, and support. Although these platforms are designed for building end-user BCI applications, implementing a P300 speller still requires technical expertise. Due to their general-purpose nature and high configurability, parameterizing them to achieve the desired speller functionality can be complex.

In response to the complexity of previous platforms and the difficulty in providing access to a target population with limited technical knowledge, the BCI research group at the University of Malaga (UMA-BCI) has recently developed a user-friendly and highly flexible BCI platform specifically tailored for P300 spellers. This platform is known as the UMA-BCI Speller [10]. The UMA-BCI Speller offers ease of use and greater adaptability, allowing users to configure any type of speller according to their specific requirements. The following is a brief summary, taken from [9] and [10], of the main features of each of these tools:

- BCI2000. The major objective of this platform was to give researchers a versatile and standard BCI experimental tool. BCI2000 has a generic framework and uses a modular program design approach. Consequently, BCI2000 can work with a variety of BCI protocol designs without requiring modifications to the main software modules. BCI2000 was written in C++, making it suitable for use on a wide range of platforms. MATLAB and Python are also supported. Online signal processing programs built in these languages enable this compatibility. It is available for Linux, Windows, and Mac OS.
- Open-ViBE. Open-ViBE allows users to construct whole scenarios using a graphical language. Therefore, no prior programming experience is necessary to construct basic BCI applications. This was a relatively new notion for BCI development at the time. This platform also comes with a full software development kit (SDK) for programmers who want to create new bespoke features. Open-ViBE was designed as a modular system that makes use of freely available portable C++ libraries.
- UMA-BCI Speller. This is an easily configurable platform oriented for patients and caregivers. Specifically, the UMA-BCI Speller acts as a wrapper of BCI2000 to build a P300-based speller application and simplifies its use. Most of BCI2000′s configurability is intentionally limited because the UMA-BCI Speller aims to control the visual layout of the speller through new multiple options outside BCI2000. Advanced users (i.e., users who already know how to manage BCI2000) could modify the specific files of BCI2000 to customize the application beyond what UMA-BCI Speller offers by default (e.g., parameters regarding the timing of the speller).

To explore variations and alternative paradigms effectively, it is crucial to have the capability to configure various elements of the speller. This includes parameters such as size, color, and type of stimuli employed, i.e., characters or images. By having a configurable speller, it becomes possible to tailor the interface to the specific needs of each patient, thereby enhancing communication facilitation. While many prior studies have primarily focused on evaluating the user control aspects of the systems (such as accuracy, information transfer rate or workload), to the best of our knowledge, there is a dearth of prior research that has offered a quantitative evaluation of their configuration. Specifically, the ease of software adaptation and preparation for user utilization has not been adequately assessed in previous works.

A suitable approach for conducting this evaluation could be based on the concept of usability (ISO 9241–11). It has been previously adopted in the evaluation of BCI proposals (e.g., Medina-Juliá et al. [11] and Sun et al. [12]) as it has the benefit of offering a broad evaluation approach that attempts to consider an overall user experience. According to ISO 9241–11, the definition of usability is: “the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use”. This definition encompasses three key measures: (i) effectiveness, which refers to the accuracy and completeness of the system in helping users accomplish their intended goals, (ii) efficiency, which relates to the resources utilized in achieving those goals, and (iii) satisfaction, which pertains to the users’ overall attitude and contentment in successfully completing a given task [13,14].

The objective of this study was to assess the usability of the three proposed BCI platforms in terms of their effectiveness, efficiency, and user satisfaction. The study specifically focused on evaluating the feasibility of these platforms to modify the speller layout, rather than the configuration of signal acquisition and processing. The reason for focusing on the speller layout is because it was considered that end-users’ priorities in real day-to-day use would be, for example, to modify the size and colors of elements to adapt them to their visual capabilities and preferences, to change these elements for others (e.g., letters, numbers or pictograms) or to change the number of these elements presented in the interface. In order to adapt the communication systems to a specific patient, signal acquisition and processing changes are less frequent than changes in layout interface. Usually, end-users of these applications—e.g., patients and their caregivers—lack the technical knowledge to manipulate other modules beyond the speller layout, so the results of the present study can also be useful to facilitate its use. Furthermore, the obtained results could aid clinicians and researchers in selecting the most suitable platform for developing communication systems utilizing P300 spellers, specifically for the target end-users, including patients with ALS. These findings would provide valuable guidance in choosing the platform that best meets the needs and requirements of this particular user group.

2. Materials and methods

2.1. Participants

The study involved 15 BCI naïve participants (named P01-P15, 9 males and 6 females) who had normal or corrected-to-normal vision. All of them were fluent in French and between 20 and 25 years old, apart from P14, who was in the 50–55 age range. According to the self-reporting questionnaire, 2 participants had minor computer experience (less than one year), 7 participants had medium experience (between 1 and 2 years) and 6 participants had major experience (more than 2 years). Written informed consent was obtained from all subjects involved in the study. The study was conducted in accordance with the Declaration of Helsinki, and approved by the Ethics Committee of the University of Malaga.

2.2. Options allowed by each platform

In order to find out which options related to the layout were allowed by each platform, a prior examination was carried out (Table 1). The different options considered affect exclusively the layout elements, such as the distribution of the keyboard elements, the keyboard background, the items presented (e.g., images or characters) or the bar where the selections would be displayed (commonly called the progress bar). We consider that, within the framework of the layout topic, the listed options are those that may be most necessary or interesting for the users of these interfaces (such as patients, caregivers, clinicians or researchers).

Thanks to this prior effort to determine which options were available

Table 1
Feasibility of modifying different parameters for speller layout across BCI2000, Open-ViBE and UMA-BCI Speller.

Option	BCI2000	Open-ViBE	UMA-BCI Speller
1) Load a specific previously configured layout	Yes	Yes	Yes
2) Change the size of the window layout	Yes	Yes	Yes
3) Change the position of the window layout	Yes	Yes	Yes
4) Change the number of columns and rows on the keyboard	Yes	Yes	Yes
5) Change the background color of the keyboard	Yes	Yes	Yes
6) Change the items in the keyboard	Yes	Yes	Yes
7) Change the color of an individual item	No	No*	Yes
8) Change the color of all items at the same time	Yes	No	Yes
9) Change the size of an individual item	Yes	Yes	No*
10) Change the size of all items at the same time	Yes	Yes	Yes
11) Change the color of an individual cell	No*	No*	Yes
12) Change the color of all cells at the same time	No	No	Yes
13) Use different colors for the cell when there is stimulation and when there is no stimulation	No*	No*	Yes
14) Change the distance between characters in the matrix	Yes	Yes	Yes
15) Use image files instead of characters in the keyboard	Yes	Yes	Yes
16) Use a different character when there is stimulation and when there is no stimulation	No	Yes	Yes
17) Use a different image when there is stimulation and when there is no stimulation	Yes	Yes	Yes
18) Change the size of the text that appears in the progress bar	Yes	Yes	Yes
19) Change the size of the progress bar	Yes	No	Yes
20) Change the space between the progress bar and the keyboard	Yes	Yes	Yes
21) Change the color of the progress bar	No	Yes	Yes

* These elements marked as "No" can be bypassed through the use of individual images that simulate the required option.

in each tool, it was possible to know which options could be fairly compared. Among the options studied, suitable tasks to be compared are those that could be executed by all three applications and would be of relevance to end-users. More specifically, of the 21 options studied, 13 could be handled by all three platforms. Among these shared options, it was necessary to decide which options would be the most recommended to study and compare. The chosen criterion was to select those options we believe could be most important to be adapted to the different needs and abilities of the target users of these interfaces. For example, a platform should be flexible enough to configure a speller with the different letters of the alphabet, manipulate the number of commands, use words or pictograms instead of letters, and adapt the size and color of visual stimuli to the needs of users in case of visual impairments (e.g., presbyopia or color blindness). Thus, the features that were thus selected for the cross-platform comparison were the following: (i) change the color of the background of the keyboard [option 5], (ii) change the size of the matrix corresponding to the keyboard [option 4], (iii) change the characters of the keyboard [option 6], (iv) change the size of the characters, individually or all of them, depending on the platform [options 9 or 10], (v) change the color of the characters, individually or all of them, depending on the platform [options 7 and 8], (vi) change the color of the cells [options 11 or 15, depending on what the platform allows], (vii) change the characters for images [option 15]. The following subsection (2.3. Procedure) will detail that these options were evaluated with a specific subtask for each of the platforms.

In order to properly understand the evaluation of these options during the control of the different BCI platforms, it is necessary to consider the following point. For example, the cell concept (i.e., the individual background of each of the interface elements) is only used by the UMA-BCI Speller platform, and is justified because the cell-shape stimulation improves performance over just character stimulation [15]. The use of this stimulation modality, as well as other options that are not allowed in some of the platforms (e.g., using characters with different colors in BCI2000 [option 7], changing the size of an individual character in UMA-BCI Speller [option 9]) or modifying the color of the cells in Open-ViBE and BCI2000 can be bypassed by using images; however, this requires such images to be previously available. This shows that some of the differences between platforms, in terms of layout, are not in what can be done, but in the ease with which it can be done.

2.3. Procedure

The experiment employed an intrasubject design, as all participants controlled the three platforms. Also, to avoid learning effects, the order of control of each platform was counterbalanced, so it was different between participants. Each participant underwent testing with the three platforms in three separate sessions conducted on the same day. There was a minimum time interval of one hour between each session. Specifically, the task in each session was to transform an initial speller into a final proposed speller through a series of subtasks.

Once the participants had declared an interest in taking part in the experiment, they were sent by e-mail the information necessary to participate, as well as the ad hoc manuals (detailed in section 2.4), so they were required to read them prior to the test. At the beginning of the first session, the experiment was explained and, after signing the informed consent, the experiment could start. The experimental setup was flexible, which means that the equipment used (e.g., computer or screen) and the location of the task execution were not the same for all participants. Nevertheless, each participant completed the three sessions using the same setup. The corresponding ad hoc manuals were available for inspection during the execution of the tasks. As previously mentioned, the experimental task for each platform consisted of transforming the graphical layout, following a sequence of steps, from an initial matrix (upper row of Fig. 1) to a final one (lower row of Fig. 1). Specifically, to reach this goal, 7 subtasks had to be completed on each of the platforms. The settings to be manipulated in each subtask were the same; however, there may have been differences in the specific commands depending on the platform. These subtasks were the following:

- Subtask 1. To change the keyboard background color to gray in BCI2000, to light blue in Open-ViBE, and to orange in UMA-BCI Speller [option 5].
- Subtask 2. To modify the matrix size to 5 × 4 in BCI2000, to 3 × 3 in Open-ViBE, and to 4 × 4 in UMA-BCI [option 4].

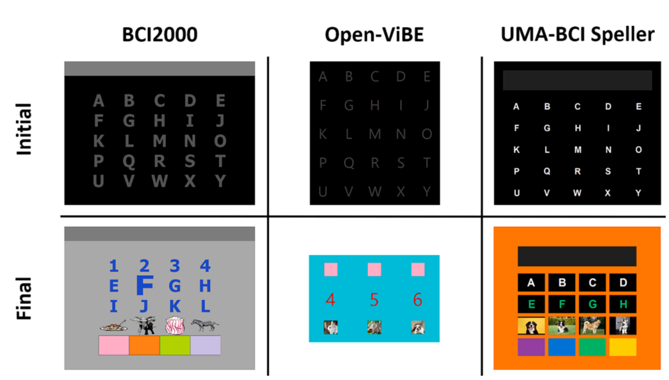


Fig. 1. Initial and final graphical layout of each software platforms: BCI2000, Open-ViBE and UMA-BCI Speller.

- Subtask 3. To change the characters in an individual row. From the first row in BCI2000 by setting "1 2 3 4", from the second row in Open-ViBE by setting "4 5 6", and from the second row in UMA-BCI Speller by setting "E F G H" [option 6].
- Subtask 4. To reshape the size of one character in BCI2000 (letter F, in row 2 and column 2) [option 9], and of all the characters in UMA-BCI Speller and Open-ViBE [option 10]. This change was made through a single action on each platform.
- Subtask 5. To change the color of all the characters in BCI2000 [option 8] to blue, of all the characters in Open-ViBE to red [option 8], and of a single row (second row, 4 characters) in UMA-BCI Speller to green [option 7]. This change was done in BCI2000 and Open-ViBE with one action; however, in UMA-BCI Speller it had to be done individually, as it asked to change only one row (with 4 characters).
- Subtask 6. To modify the background color of the cells in an individual row [option 11 and 15, depending on what the platform allows]. In BCI2000 and UMA-BCI Speller, the colors had to be changed in 4 cells (rows 5 and 4, respectively), which required one action per cell (4 actions), while in Open-ViBE the color in only 3 cells (row 1) had to be changed to a single color, which required one action less than in the cases of the previous platforms. Because the BCI2000 and Open-ViBE platforms do not have specific options concerning the cell concept, a direct manipulation of the cell color was not possible [option 11], so they employed an image intended to simulate the effect of the cell [option 15].
- Subtask 7. To change the characters in a specific row to images [option 15]. Due to the different size of the rows, in BCI2000 and UMA-BCI Speller four images were added (rows 4 and 3, respectively), while in Open-ViBE three images were added (row 3).

After the control of each platform, the users were asked to complete the corresponding questionnaires to evaluate the usability of that platform. In addition, after the last session (i.e., at the end of the monitoring of the three platforms), a questionnaire was carried out to compare the three platforms used during the experiment.

2.4. Ad hoc manuals for the BCI platforms

In this study, three BCI software platforms were compared for the modification of the layout of a visual P300-based BCI. All these platforms have the respective official manual and documentation necessary for their proper use [16–18]. However, since the participants were all inexperienced in the use of these software platforms, it was considered appropriate to facilitate their learning to perform the tasks that would be required in the experiment. To this end, three ad hoc manuals were created—one for each platform—so that the participants could learn which actions were necessary to perform the task on the different platforms and, afterwards, be able to compare them. The task consisted of modifying the graphical layout of the interface, so the manuals focused on that aim. Aspects related to, for example, signal processing, classification or presentation times were not included in these manuals. The manuals were between 850 and 1300 words each. They all included explanatory figures to visually illustrate how and where to perform each action. These manuals are attached in the original language in which they were created (French) as supplementary material.

2.5. Evaluation and statistical analysis

As stated in the introduction section, the primary aim of this study was to assess the usability of the various software platforms. The usability evaluation encompassed three dimensions: effectiveness, efficiency, and satisfaction. Effectiveness gauges the level of success in accomplishing a given task. Efficiency focuses on the resources, such as user effort and time, expended to complete the task. Satisfaction pertains to the user's subjective attitude, including their perceived comfort and acceptability when interacting with the system. Effectiveness has not been included in the assessment of the present work as it was a requirement for all participants to complete the task correctly—i.e., the same as the corresponding target layout (lower row in Fig. 1). Next, a detailed description of the dimensions of efficiency and satisfaction will be provided.

2.5.1. Efficiency

This dimension was assessed through the time required to complete each of the subtasks. These subtasks were used to compare the different execution times on each platform. There were seven variables related to these subtasks: (i) change the background color of the graphical layout [*subtask 1*], (ii) change the number of rows and columns in the matrix [*subtask 2*], (iii) change the characters for others [*subtask 3*], (iv) change the size of the characters [*subtask 4*], (v) change the color of the characters [*subtask 5*], (vi) modify the background color of the cells [*subtask 6*], and (vii) replace the characters in a given row to images [*subtask 7*]. Finally, a variable for the total time to complete the task was used [*total time*].

2.5.2. Satisfaction

This dimension was evaluated through two types of subjective questionnaires. Firstly, an individual questionnaire for each platform was used, in which users were asked to evaluate the corresponding platform they had just used. Secondly, once the participants had controlled the three platforms, they were asked to complete a questionnaire that directly compared them in order to choose the most appropriate platform according to each variable. Both questionnaires were presented to participants in French but, for the sake of clarity, the English translation will be presented in this article. These questionnaires will be detailed below.

On the one hand, the individual questionnaire consisted of 12 items ranging from 1 (completely disagree) to 5 (completely agree). The items used were extracted, or modified versions, from the Computer System Usability Questionnaire [19] or the System Usability Scale [20]. They could be grouped into three dimensions: *simplicity* (items 1–4), *speed* (items 5–8) and *information* (items 9–12). The translation of the items used in this questionnaire was as follows:

1. Overall, I am satisfied with how easy it was to use the platform.
2. I found the use of the platform easy to learn.
3. I did not notice any inconsistencies when I used it.
4. I think I wouldn't need the assistance of an expert to use this platform (without the manual).
5. I completed the tasks quickly and without going back to the manual frequently.
6. I quickly learned how to use the platform (with the manual).
7. I remember very well how to use this platform again.
8. When I made an error using this platform, it was easy and quick to correct it.
9. The help tools available on this platform (manuals, on-screen messages, etc.) were useful.
10. The information provided with this platform was easy to understand (excluding the manual).
11. The information available on the platform helps to support me in carrying out the tasks (excluding the manual).
12. The error messages presented by the platform clearly told me how to solve the problems.

On the other hand, the comparative questionnaire consisted of four items in which the user was asked to choose the platform that best suited the question according to his or her preferences. The translation of the items used was as follows:

1. Which of these platforms did you find most intuitive to use? (*most intuitive to use*)

2. Which of these platforms was the easiest to learn? (*easiest to learn*)
3. Which of these platforms did you find the most difficult to use? (*most difficult to use*)
4. Which of these platforms did you like the most? (*like the most*)

3. Results

This section will present the results of the study in reference to the efficiency and satisfaction variables. The efficiency variables will compare the time taken by each platform to accomplish the goals. The variables related to satisfaction will use subjective questionnaires where the participants indicate their opinions and preferences about the platforms.

3.1. Efficiency

The results obtained from the analysis of the variables related to the time required by the participants to execute each of the subtasks and the total time spent on each platform are presented in Fig. 2. Different Friedman tests were used to find out if there were significant differences between the scores of the platforms. If significant differences were found in any variable, multiple comparisons were made (applying the Bonferroni correction) to between which specific platforms they were found.

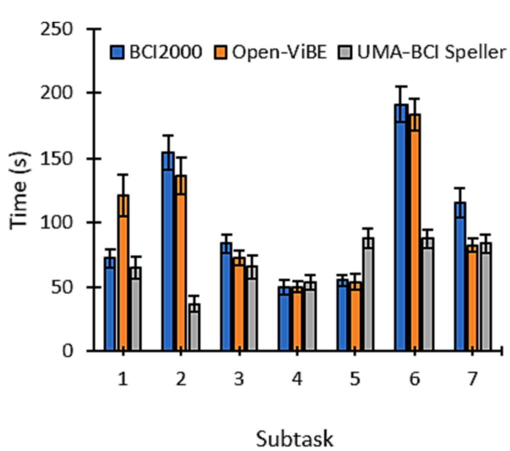
1. Subtask 1. The analysis showed significant differences in the time taken by each platform to change the graphical layout background color ($\chi 2$ (2) = 9.593; p = 0.008). Specifically, UMA-BCI Speller (64.67 ± 34.23 s) was found to require significantly less time than Open-ViBE (121.27 ± 62.59 s) (Z = 1.067; p = 0.01). The difference between BCI2000 (72.13 ± 26.96 s) and Open-ViBE (121.27 ± 62.59 s) was nearly significant in favor of BCI2000 (Z = − 0.833; p = 0.067); indeed, it would be significant without the application of the Bonferroni correction method (p = 0.022).
2. Subtask 2. In the case of the variable related to the time required to change the size of the matrix, significant differences were also found between platforms ($\chi 2$ (2) = 24.102; p < 0.001). Specifically, the UMA-BCI Speller (36.73 ± 23.51 s) required less time to perform this subtask compared to BCI2000 (154.87 ± 51.83 s) (Z = 1.7; p < 0.001) and Open-ViBE (136.2 ± 55.77 s) (Z = 1.3; p = 0.001).
3. Subtask 3. The analysis showed no significant differences in relation to the time required to change the characters to others.
4. Subtask 4. The analysis showed no significant difference in relation to the time required to change the size of the characters.
5. Subtask 5. The analysis showed significant differences between platforms in the time required to change the characters' color ($\chi 2$ (2) = 12.441; p = 0.002). Specifically, the UMA-BCI Speller (87.75 ± 28.61 s) was found to require more time to perform this subtask compared to BCI2000 (55 ± 17.44 s) (Z = 1.167; p = 0.004) and Open-ViBE (53.6 ± 24.64 s) (Z = 1.033; p = 0.014). However, it is recalled that while for the UMA-BCI Speller platform users were asked to change the color of the four characters individually (four actions), on the other platforms they changed the color of all characters, which was done with a single action.
6. Subtask 6. In the case of the variable relating to the time needed to change the color of the cells, the analysis showed significant differences between platforms ($\chi 2$ (2) = 22.8; p < 0.001). Specifically, the UMA-BCI Speller (87.27 ± 27.2 s) took less time than BCI2000 (191 ± 52.74 s) (Z = 1.6; p < 0.001) and Open-ViBE (183.4 ± 45.92 s) (Z = 1.4; p < 0.001) to complete this subtask.
7. Subtask 7. The analysis showed that the time needed to change the characters of a given row to images was different according to the platform used ($\chi 2$ (2) = 6.533; p = 0.038). However, due to the application of the Bonferroni correction method, no specific differences were found between conditions. Marginally significant differences were found between BCI2000 (115.73 ± 43.9 s) and Open-ViBE (82.4 ± 19.28 s) (Z = − 0.867; p = 0.053), in favor of Open-ViBE. If Bonferroni had not been applied, both the comparisons between BCI2000 (115.73 ± 43.9 s) versus Open-ViBE (82.4 ± 19.28 s) (Z = − 0.867; p = 0.018) and versus UMA-BCI Speller (83.6 ± 28.26 s) (Z = − 0.733; p = 0.045) would have been significant, with BCI2000 taking a longer time to complete the subtask.
8. Total time. Finally, the analysis showed significant differences between the total time spent to complete the task for each platform ($\chi 2$ (2) = 20.8; p < 0.001). Specifically, the UMA-BCI Speller (479.13 ± 124.87 s) was found to take significantly less time than BCI2000 (721.73 ± 146.09 s) (Z = 1.6; p < 0.001) and Open-ViBE (699.53 ± 156.53 s) (Z = 1.2; p = 0.003).

3.2. Satisfaction

Concerning the satisfaction dimension, the results of the individual and comparative questionnaires were analyzed. These questionnaires were intended to provide an assessment of the users' subjective experience and preferences.

3.2.1. Individual questionnaire

Three subdimensions were extracted from the individual questionnaires of each software platform: (i) *simplicity*, (ii) *speed* and (iii) *information* (Fig. 3). As in the case of the time variables related to efficiency, different Friedman tests were used to find out if there were significant differences between the scores of the platforms. If significant differences were found in any variable, multiple comparisons were made (applying the Bonferroni correction) to identify between which specific platforms they were found. The results of these analyses will be reported next.



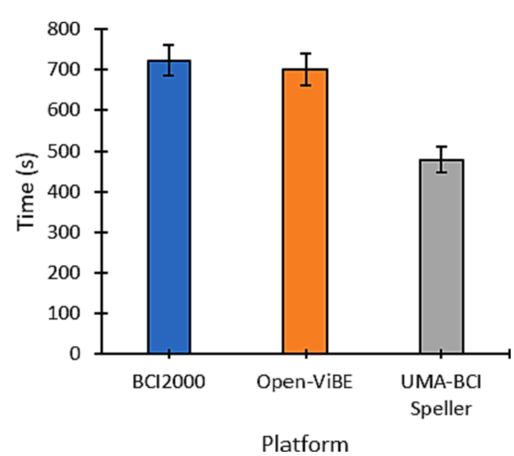


Fig. 2. Average time (±standard error) required by participants to complete each of the subtasks (left) and the entire task (right).

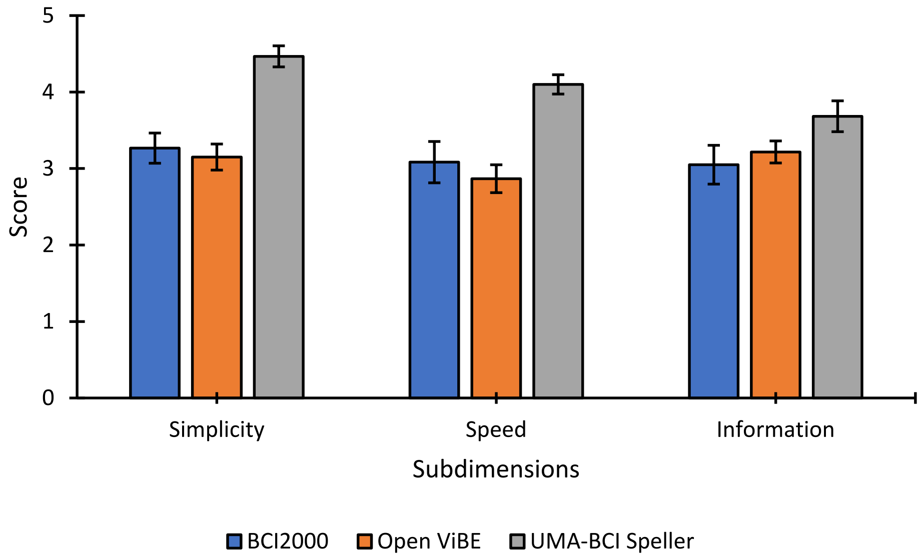


Fig. 3. Average score (±standard error) selected by participants for each software platforms in the subdimensions of the individual questionnaire. The score for each dimension of the individual questionnaire (simplicity, speed and information) was obtained by averaging the responses from four Likert-type scale items, ranging from 1 (completely disagree) to 5 (completely agree).

Firstly, it can be stated that significant differences were found between platforms in relation to the subdimension of *simplicity* ($\chi 2$ (2) = 22.351; $p < 0.001$). Specifically, differences showed that the score obtained for the UMA-BCI Speller (4.47 ± 0.53 points) was significantly higher compared to the scores of BCI2000 (3.27 ± 0.76 points) ($Z = 1.367$; $p = 0.001$) and Open-ViBE (3.15 ± 0.66 points) ($Z = 1.533$; $p < 0.001$). Secondly, the subdimension *speed* also showed significant differences between software platforms ($\chi 2$ (2) = 16.933; $p < 0.001$). Specifically, it was again shown that the UMA-BCI Speller platform (4.1 ± 0.49 points) scored better than BCI2000 (3.08 ± 1.05 points) ($Z = 1.267$; $p = 0.002$) and Open-ViBE (2.97 ± 0.71 points) ($Z = 1.333$; $p = 0.001$). Finally, like the previous subdimensions, the *information* variable showed significant differences between platforms ($\chi 2$ (2) = 8.667; $p < 0.013$). In this case, significant differences were found only between UMA-BCI Speller and Open-ViBE ($Z = 0.933$; $p = 0.032$), with a higher score for UMA-BCI Speller (3.68 ± 0.78 points) than for Open-ViBE (3.22 ± 0.56 points).

3.2.2. Comparative questionnaire

Next, one binomial test is used to explore whether the UMA-BCI Speller platform was chosen by the participants significantly above or below the chance level for each of the variables studied: (i) *easiest to learn*, (ii) *most difficult to use*, (iii) *most intuitive to use* and (iv) *like the most* (Fig. 4). We believe that focusing on the UMA-BCI Speller tool and benchmarking it in the analyses is the most appropriate approach since it has been the most recently developed and with the specific aim of improving the usability of the system. It is noted that if the UMA-BCI Speller platform had been chosen at random, it should have been selected by 1/3 of the participants (i.e., 5 out of 15 in the present article). Firstly, in relation to the variable *easiest to learn*, the UMA-BCI Speller platform was significantly selected above the chance level (14 out of 15, $Z = 4.695$; $p < 0.001$), as it was selected by 14 out of 15 participants, while only one participant chose BCI2000 and none chose Open-ViBE. Secondly, in relation to the variable *most difficult to use*, the

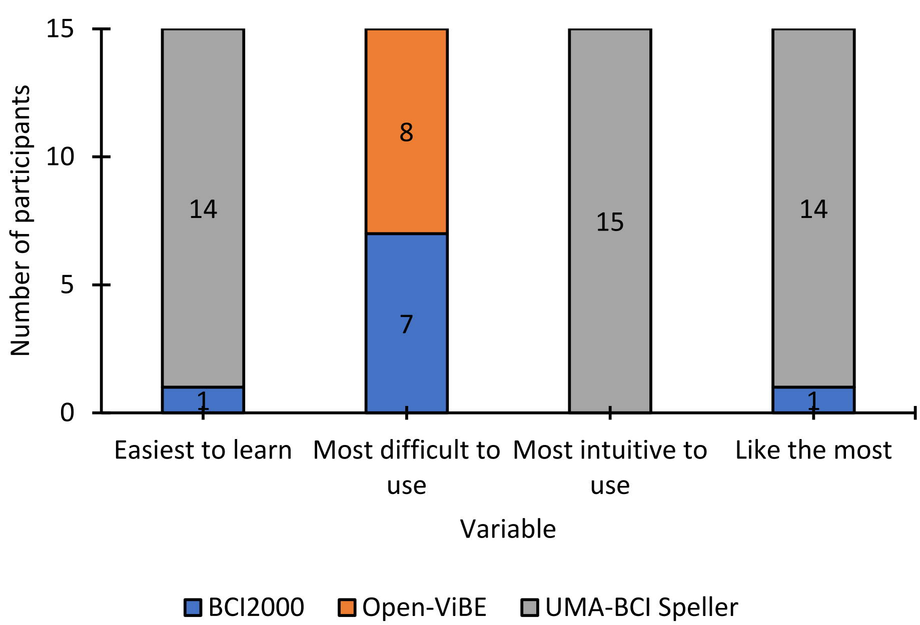


Fig. 4. Number of participants who selected each platform for the items listed in the comparative questionnaire.

UMA-BCI Speller platform was significantly selected below the chance level (0 out of 15, $Z = -2.444$; $p = 0.002$), as it was selected by none of them, while 7 chose BCI2000 and 8 chose Open-ViBE. Thirdly, in relation to the *most intuitive to use* variable, the UMA-BCI Speller platform was again significantly chosen over chance (15 out of 15, $Z = 5.244$; $p < 0.001$), as it was selected as the most intuitive by all participants. Finally, regarding the variable *like the most*, the UMA-BCI Speller platform was significantly chosen above the chance level (14 out of 15, $Z = 4.695$; $p < 0.001$), as it was selected by 14 out of 15 participants, while only one participant chose BCI2000 and, thus, none chose Open-ViBE.

4. Discussion

The overall results obtained in the present work have shown that the UMA-BCI Speller software can be denoted as the one with the best usability for novice users. This has been corroborated in both the time-related measures of efficiency and satisfaction, through either the individual or comparative questionnaires. These dimensions will be discussed in more detail below.

Firstly, in reference to the efficiency dimension, the UMA-BCI Speller tool was—compared to the other two platforms—the only one that showed significant differences in a positive direction (i.e., shorter execution times) in all subtasks, except for *subtask 5*, where it took the longest time to complete. However, as it was explained, this difference in *subtask 5* was not surprising, since the subtask required for the UMA-BCI Speller platform was not the same as the subtask required for the BCI2000 and Open-ViBE platforms. Specifically, in BCI2000 and Open-ViBE, it was required to change the color of all the characters in the matrix (on neither of these two platforms is there a specific option for individual color change), which could be done with a single action, while in UMA-BCI Speller, it was required to change four elements individually (which required four actions). In addition, it should be mentioned that for BCI2000, the color of the characters was modified through an HTML color code, so it was necessary to know the corresponding code for the desired color (e.g., # 000,000 for black, #FFFFFF for white, or #00FF00 for green). However, in Open-ViBE and UMA-BCI Speller, in addition to using the HTML code, the color could also be modified through a visual color palette. It should also be noted that the Open-ViBE platform had an advantage in some subtasks (*subtask 3*, *subtask 6* and *subtask 7*), since these subtasks asked for the modification of individual elements of a given row, and the corresponding layout had three elements per row (see the final layout for Open-ViBE in Fig. 1), instead of four as was the case in BCI2000 and UMA-BCI Speller. However, despite this advantage for Open-ViBE, the UMA-BCI Speller platform obtained a shorter execution time for *subtask 3* (to change the characters on the keyboard to other characters) and *subtask 6* (to change the color of the cells), which was even significant for *subtask 6*. In reference to the total time, the UMA-BCI Speller was the platform with the shortest *total time* required to complete all the tasks. This could indicate that the UMA-BCI Speller tool is—according to the specific tasks evaluated—the most efficient for the execution of the required assignments, at least in terms of time resources. This may be useful for daily use and easy adaptation to the needs of the BCI target population in real environments (e.g., the patient's house).

Secondly, regarding the satisfaction dimension, the results of the individual and comparative questionnaires will be discussed next. On the one hand, the scores obtained in the subdimensions of the individual questionnaire (*simplicity*, *speed* and *information*) showed that the UMA-BCI Speller platform scored significantly better than BCI2000 in the subdimensions related to *simplicity* and *speed*, and significantly better than Open-ViBE in all the three subdimensions. On the other hand, in the comparative questionnaire, the UMA-BCI Speller tool was clearly the most chosen in the positive variables (*easiest to learn*, *most intuitive to use* and *like the most*), and the least chosen in the negative (*most difficult to use*). Additionally, users were divided on *the most difficult to use* variable between BCI2000 and Open-ViBE, as they were selected by 7 and 8 users, respectively.

In summary, the results obtained in the study are in line with expectations, as the UMA-BCI Speller tool was specially designed to facilitate its use and reduce the need for technical knowledge for its control. Adapting BCI platforms to be user-friendly is one of the objectives on which the BCI community is focusing its efforts. The present work has focused on evaluating the usability of those modifications related to the speller layout that will be controlled by the user; however, other works have focused on facilitating the module related to signal processing and analysis (e.g., BioPyC [21]). In these aspects of EEG signal processing and analysis, it should be stated that the advantages of using platforms such as BCI2000 and Open-ViBE are clear. These platforms allow comprehensive control of the BCI system, through the control of other modules related to, for example, signal processing and classification. However, these aspects are not of interest to end-users as, besides not having the necessary technical knowledge to control them, the priority for them is to have an easily configurable tool that they can adapt to their needs, either to communicate with the people around them or to interact with devices or applications. In addition, there is also a trend towards the use of low-cost portable devices (see the review of [22]). This would be in line with offering patients a simple, low-cost BCI system that they can manipulate according to their knowledge and needs.

The BCI2000 and Open-ViBE platforms have been widely used by the BCI community for more than ten years [23], which proves that they are effective tools with a large community supporting them. However, the UMA-BCI Speller is a considerably newer platform—developed in 2018—that has been employed by the UMA-BCI group in several published works, in which it has demonstrated a good performance, ease of use and high adaptability (e.g., [10,24,25]). In fact, one of the group's latest works showed that the flexibility of the system even allowed it to control various messaging applications or a domotic system by sending personalized voice commands to a voice assistant (Google Assistant) [26,27]. Furthermore, the UMA-BCI Speller platform offers the advantage that, thanks to its easy configuration, researchers not directly related to the more technical aspects of BCI can easily manipulate the interface and develop experimental proposals.

Despite the clear findings of this study, there are certain limitations that need to be addressed. On one hand, it should be noted that the selected options for investigation were based on our professional criteria (informed by our experience with patients and caregivers), rather than specific studies evaluating these particular needs. Therefore, it would be beneficial to objectively assess the genuine requirements of patients and caregivers, in order to determine the options they would truly like to configure in a BCI platform. On the other hand, it is acknowledged that the evaluation conducted in this study was of short-term nature, focusing on the initial interaction between users configuring the interface and the software being employed. Hence, it would be worthwhile to explore whether this trend could be altered over a longer duration. Furthermore, it is important to consider the limitation of the studied sample in the present study. It is possible that results may differ, especially among users with extensive technical knowledge (e.g., research engineers). Nevertheless, we believe it is advisable to continue advocating for the UMA-BCI Speller tool for individuals with limited technical expertise, as other platforms like BCI2000 or OpenViBE might prove overly complex. Among the available options, UMA-BCI Speller appears to be the most suitable, although an extensive and ongoing evaluation with its target population—patients and caregivers—is still pending. Additionally, it is possible that certain researchers may perceive limitations in the UMA-BCI Speller tool regarding its parameter modification options for processing. However, it is precisely the absence of these options that allows for a user-friendly experience and maintains a clean and straightforward interface.

5. Conclusions

The present work has studied the usability of three BCI platforms—BCI2000, Open-ViBE and UMA-BCI Speller—to configure the graphical layout of a P300-based speller. Overall, UMA-BCI Speller has shown the highest level of usability: lower task completion times and enhanced subjective evaluations. Hence, this platform could be the most suitable for those cases where the user does not have extensive technical knowledge and only the graphical layout needs to be modified. Nevertheless, if changes in signal processing are desired, this can be done in the same way as in BCI2000, since UMA-BCI Speller is a BCI2000 wrapper.

The results of this study should be considered a valuable resource for choosing the optimal platform that aligns with the specific user's requirements (e.g., what they need to manipulate?) and abilities (e.g., what technical knowledge they possess?) who will be operating it. In doing so, it emphasizes the significance of not only examining the functionality of BCI applications (such as a speller or a wheelchair) but also assessing how these platforms are controlled and configured to ensure effective utilization of such applications. In addition, for future work, it would be advisable to compare the usability of each platform also for experienced BCI researchers and for the end-users of these applications, patients and caregivers. Also, in the case of end-users, it would be advisable to conduct long-term studies, where patients use the system and integrate it into their daily lives. These work proposals, together with the trend of the BCI community to offer portable and low-cost devices, would bring these systems closer to real use in the everyday and domestic scene of patients. Finally, this study encourages conducting similar comparisons among different emerging BCI platforms (e.g., Santamaría et al. [28]), and emphasizes the importance of studying both application performance and ease of configuration at the same level.

CRediT authorship contribution statement

Ricardo Ron-Angevin: Conceptualization, Methodology, Software, Writing – original draft, Visualization, Investigation, Supervision, Project administration, Funding acquisition. **Álvaro Fernández-Rodríguez:** Formal analysis, Writing – original draft, Visualization, Data curation. **Francisco Velasco-Álvarez:** Software, Data curation, Writing – review & editing. **Véronique Lespinet-Najib:** Methodology, Validation. **Jean-Marc André:** Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

[1] B. Fabio, Brain Computer Interfaces for communication and control, Frontiers in Neuroscience 4 (1900) 767–791, https://doi.org/10.3389/conf.fnins.2010.05.00007.
[2] J.N. Mak, J.R. Wolpaw, Clinical Applications of Brain—Computer Interfaces: Current State and Future Prospects, IEEE Reviews in Biomedical Engineering 2 (2009) 187–199, https://doi.org/10.1109/RBME.2009.2035356.
[3] A. Rezeika, M. Benda, P. Stawicki, F. Gembler, A. Saboor, I. Volosyak, Brain–computer interface spellers: A review, Brain Sciences 8 (4) (2018) 57.
[4] L.A. Farwell, E. Donchin, Talking off the top of your head: toward a mental prosthesis utilizing event-related brain potentials, Electroencephalography and Clinical Neurophysiology 70 (1988) 510–523, https://doi.org/10.1016/0013-4694(88)90149-6.
[5] G. Schalk, D.J. McFarland, T. Hinterberger, N. Birbaumer, J.R. Wolpaw, BCI2000: A general-purpose brain-computer interface (BCI) system, I.E.E.E. Transactions on Bio-Medical Engineering 51 (2004) 1034–1043.
[6] C.A. Kothe, S. Makeig, BCILAB: A platform for brain-computer interface development, Journal of Neural Engineering 10 (5) (2013) 056014.
[7] C. Arrouët, M. Congedo, J.E. Marvie, F. Lamarche, A. Lécuyer, B. Arnaldi, Open-ViBE: A three dimensional platform for real-time neuroscience, Journal of Neurotherapy 9 (2005) 3–25, https://doi.org/10.1300/J184v09n01_02.
[8] B. Venthur, Design and implementation of a brain-computer interface system, Intitute of Technology, Berlin, 2015.
[9] P. Stegman, C.S. Crawford, M. Andujar, A. Nijholt, J.E. Gilbert, Brain-computer interface software: A review and discussion, IEEE Trans. Human-Machine Syst. 50 (2020) 101–115, https://doi.org/10.1109/THMS.2020.2968411.
[10] F. Velasco-Álvarez, S. Sancha-Ros, E. García-Garaluz, Á. Fernández-Rodríguez, M.T.T. Medina-Juliá, R. Ron-Angevin, UMA-BCI Speller: an Easily Configurable P300 Speller Tool for End Users, Computer Methods and Programs in Biomedicine 172 (2019) 127–138, https://doi.org/10.1016/J.CMPB.2019.02.015.
[11] M.T. Medina-Juliá, A. Fernández-Rodríguez, F. Velasco-Álvarez, R. Ron-Angevin, P300-based brain-computer interface speller: Usability evaluation of three speller sizes by severely motor-disabled patients, Frontiers in Human Neuroscience 14 (2020) 1–10, https://doi.org/10.3389/fnhum.2020.583358.
[12] R. Abiri, S. Borhani, J. Kilmarx, C. Esterwood, Y. Jiang, X. Zhao, A usability study of low-cost wireless brain-computer interface for cursor control using online linear model, IEEE Trans. Human-Machine Syst. 50 (2020) 287–297, https://doi.org/10.1109/THMS.2020.2983848.
[13] J. Nielsen, in: User Experience Re-Mastered, Elsevier, 2010, pp. 3–22.
[14] J. Nielsen, R. Molich, Heuristic evaluation, Usability Ispection Methods (1994), https://doi.org/10.1089/tmj.2010.0114.
[15] Á. Fernández-Rodríguez, F. Velasco-Álvarez, M.T. Medina-Juliá, R. Ron-Angevin, Evaluation of flashing stimuli shape and colour heterogeneity using a P300 brain-computer interface speller, Neuroscience Letters 709 (2019), 134385, https://doi.org/10.1016/j.neulet.2019.134385.
[16] BCI2000 Available online: https://www.bci2000.org/ (accessed on Jul 4, 2023).
[17] OpenViBE Available online: http://openvibe.inria.fr/ (accessed on Jul 4, 2023).
[18] UMA-BCI Speller Available online: https://umabci.uma.es/index.php/en/uma-bci-speller-2/ (accessed on Jul 4, 2023).
[19] J.R. Lewis, IBM Computer Usability Satisfaction Questionnaires: Psychometric Evaluation and Instructions for Use, International Journal of Human Computer Interaction 7 (1995) 57–78, https://doi.org/10.1080/10447319509526110.
[20] J. Brooke, SUS - A quick and dirty usability scale, Usability Eval. Ind. 189 (1996) 4–7, https://doi.org/10.1002/hbm.20701.
[21] A. Appriou, L. Pillette, D. Trocellier, D. Dutartre, A. Cichocki, F. Lotte, BioPyC, an open-source python toolbox for offline electroencephalographic and physiological signals classification, Sensors 21 (17) (2021) 5740.
[22] K. Belwafi, S. Gannouni, H. Aboalsamh, Embedded brain computer interface: state-of-the-art in research, Sensors 21 (2021) 1–20, https://doi.org/10.3390/s21134293.
[23] Brunner, C.; Andreoni, G.; Bianchi, L.; Blankertz, B.; Breitwieser, C.; Kanoh, S.; Kothe, C.A.; Lécuyer, A.; Makeig, S.; Mellinger, J.; et al. BCI Software Platforms. In *Towards Practical Brain-Computer Interfaces: Bridging the Gap from Research to Real-World Applications*; Allison, B.Z., Dunne, S., Leeb, R., Del R. Millán, J., Nijholt, A., Eds.; Springer Berlin Heidelberg: Berlin, Heidelberg, 2013; pp. 303–331 ISBN 978-3-642-29746-5.
[24] R. Ron-Angevin, M.T. Medina-Juliá, Á. Fernández-Rodríguez, F. Velasco-Álvarez, J.M. Andre, V. Lespinet-Najib, L. Garcia, Performance analysis with different types of visual stimuli in a BCI-based speller under an RSVP paradigm, Frontiers in Computational Neuroscience 14 (2021), https://doi.org/10.3389/fncom.2020.587702.
[25] Á. Fernández-Rodríguez, M.T. Medina-Juliá, F. Velasco-Álvarez, R. Ron-Angevin, Different effects of using pictures as stimuli in a P300 brain-computer interface under rapid serial visual presentation or row-column paradigm, Medical & Biological Engineering & Computing 59 (2021) 869–881, https://doi.org/10.1007/s11517-021-02340-y.
[26] F. Velasco-Álvarez, Á. Fernández-Rodríguez, F.-J. Vizcaíno-Martín, A. Díaz-Estrella, R. Ron-Angevin, Brain-computer interface (BCI) control of a virtual assistant in a smartphone to manage messaging applications, Sensors 21 (11) (2021) 3716.
[27] F. Velasco-Álvarez, Á. Fernández-Rodríguez, R. Ron-Angevin, Brain-computer interface (BCI)-generated speech to control domotic devices, Neurocomputing 509 (2022) 121–136, https://doi.org/10.1016/j.neucom.2022.08.068.
[28] E. Santamaría-Vázquez, V. Martínez-Cagigal, D. Marcos-Martínez, V. Rodríguez-González, S. Pérez-Velasco, S. Moreno-Calderón, R. Hornero, MEDUSA©: A novel

Python-based software ecosystem to accelerate brain-computer interface and cognitive neuroscience research, Computer Methods and Programs in Biomedicine 230 (2023) 107357, https://doi.org/10.1016/j.cmpb.2023.107357.