# Brain-Computer Interfaces: Proposal of a Paradigm to Increase Output Commands

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**Abstract.** A BCI (Brain-Computer Interface) is based on the analysis of the brain activity recorded during certain mental activities, to control an external device. Some of these systems are based on discrimination of different mental tasks, matching the number of mental tasks to the number of control commands and providing the users with one to three commands. The main objective of this paper is to introduce the navigation paradigm proposed by the University of Málaga (UMA-BCI) which, using only two mental states, offers the user several navigation commands to be used to control a virtual wheelchair in a virtual environment (VE). In the same way, this paradigm should be used to provide different control commands to interact with videogames. In order to control the new paradigm, subjects are submitted in a progressive training based in different VEs and games. Encouraging results supported by several experiments show the usability of the paradigm.

**Keywords:** Brain-Computer Interfaces (BCI), Motor Imagery, Navigation commands, Virtual Environment (VE), Motivation, Games.

## 1 Introduction

A Brain -Computer Interface (BCI) is a system that enables a communication that is not based on muscular movements but on brain activity. One of its main uses could be in the field of medicine and especially in rehabilitation. It helps to establish a communication and control channel for people with serious motor function problems but without brain function disorder [1].

Most non-invasive BCI systems use the brain activity recorded from electrodes placed on the scalp, i.e., the electroencephalographic signals (EEG). Different features of the EEG signals can be extracted in order to encode the intent of the user. The most common EEG signal features used in current BCI systems include [2] slow cortical potentials [3], P300 potentials [4] or sensorimotor rhythms (SMRs) [5]. SMRs are based on the changes of μ (8-12 Hz) and β (18-26 Hz) rhythm amplitudes, which can be modified by voluntary thoughts through some specific mental tasks, as the motor imagery (MI) [6]. When a person performs a movement, or merely imagines it, it causes an increase or a decrease in μ and β rhythm amplitudes, which are referred to as event-related synchronization (ERS) or event-related desynchronization (ERD) [7].

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People can learn to use motor imagery to change SMR amplitudes, and this relevant characteristic is what makes SMR suitable to be used as input for a BCI.

Although for a long time BCI research has been dedicated to the medical domain, in recent years, new BCI applications are focused toward healthy users, for example BCI games [8]. Effectively, BCIs can offer a new means of playing videogames or interacting with virtual environments [9]. However, researchers can use virtual reality (VR) technologies, not only to develop games controlled by brain activity, but also to study and improve brain-computer interaction. The positive impact that the use of VR has in the subjects' performance due to motivation, realism, vivid feedback or ease of use has been reported in several studies [10], [11]. In brain-computer interface research, it is necessary to provide some type of visual feedback allowing subjects to see their progress. VR is a powerful tool with graphical possibilities to improve BCI-feedback presentation and has the capability of creating immersive and motivating environments, which are very important in guaranteeing a successful training [12].

Many BCI applications are focused on the control of a wheelchair; however, before people can use a wheelchair in a real situation, it is necessary to guarantee that they have enough control to avoid dangerous scenarios. VR is a suitable tool to provide subjects with the opportunity to train and test the application. In this way, MI-based BCIs have been used to explore VEs. Some studies that use VR describe a system in which a virtual wheelchair moves in only one direction (forward) [13, 14]. Because of this restricted movement, only one command (and therefore one mental task) is needed. Other systems let the subjects choose among more commands. In [15], a simulated robot performs two actions ('turn left then move forward' or 'turn right then move forward') in response to left or right hand MI. A more versatile application can be found in [16] with three possible commands (turn left, turn right, and move forward) selected with three MI tasks (chosen among left-hand, right-hand, foot, or tongue). These BCIs typically provide the user with one to three commands, each associated with a given task. Having a higher number of commands makes it easier to control the virtual wheelchair, since the subject has more choices to move freely (by means of an information transfer rate increase). Nevertheless, it has been reported in several studies [17, 18] that the best classification accuracy is achieved when only two classes are discriminated. In an application focused on the control of a wheelchair, a classification error (a wrong command) can cause dangerous situations, so it is crucial to guarantee a minimum error rate to keep the users safe. For this purpose, the use of a BCI system based on classification of different mental tasks to provide different commands (associating each command with a mental task) is not the best solution, increasing the probability of misclassification and requiring a very good control.

The main objective of this paper is to introduce the navigation paradigm proposed by the University of Málaga (UMA-BCI) which, using only two mental states, offers the user several navigation commands to be used to control a virtual wheelchair in a VE. In the same way, this paradigm should be used to provide different control commands to interact with videogames. In order to control the new paradigm, subjects are submitted in a progressive training based in different VEs and games.

## 2 Methods

In this section we will provide an overview on the methods usually used in the UMA-BCI.

### 2.1 Data Acquisition

The EEG is recorded from two bipolar channels with electrodes placed over the right and left hand sensorimotor area. Active electrodes are placed 2.5cm anterior and posterior to electrode positions C3 and C4 according to the 10/20 international system. The ground electrode is placed at the FPz position. Signals are amplified by a 16 channel biosignal g.BSamp (Guger Technologies) amplifier and then digitized at 128 Hz by a 12-bit resolution data acquisition NI USB-6210 (National Instruments) card. To assure low impedances between the electrodes and the scalp (desired below 5KΩ), electrolyte gel is filled into each electrode before experiments start.

### 2.2 Training Protocol

Usually, the subjects who participate in the experiments have no previous BCI experience. They all undergo a training protocol for calibration and training purposes.

This training is based on the paradigm proposed by our group (UMA-BCI) in [11], which is based in a videogame. Subjects, immersed in a VE, have to control the displacement of a car to the right or left, according to the mental task carried out, in order to avoid an obstacle. The training protocol generally consists of two sessions, the first without feedback and the second providing continuous feedback. In each session, subjects are instructed to carry out 4 experimental runs, consisting of 40 trials of 8 seconds each. The first session is used to set up classifier parameters (weight vector) for the next feedback session and the future navigation sessions. The training is carried out discriminating between two mental tasks: mental relaxation and imagined right hand movements. The feedback consists in the movement of a car to the right (hand MI) or to the left (relaxation state) depending on the classification result (Figure 1).

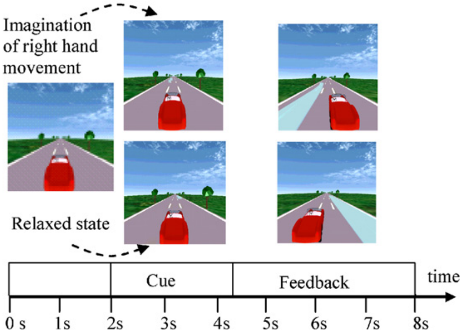

**Fig. 1.** Timing of one trial of the training with feedback

These two sessions are the same for every participant, and they allow to select those subjects who will continue with the navigation experiments, depending on the obtained results in relation with the classification error.

### 2.3 Signal Processing

For signal processing, the scheme used is that proposed by Guger et al. [19]. The feature extraction consists of estimating the average band power (*P*C3 and *P*C4) of each EEG channel in predefined, subject specific reactive frequency bands by: (i) digitally band-pass filtering the EEG using a fifth-order Butterworth filter, (ii) squaring each sample, and (iii) averaging over several consecutive past samples. A total of 64 samples are averaged, getting an estimation of the band power for an interval of 500ms. The reactive frequency band is manually selected for each subject, checking the largest difference between the power spectra of two 1s intervals (a full description about how to determine the frequency band can be found in [20]): a reference interval (0.5–1.5s) and an active interval where a mental task takes place (6–7s).

In sessions without feedback, the extracted feature parameters of the classification time points with the lowest classification error are used to set up the classifier parameters for the following session with feedback. The classification is based on the linear discriminant analysis (LDA). In the feedback sessions, the LDA classification result is converted online to the length distance $L$ that the car moves in one or the other direction. The distance $L$ is updated on the screen every four samples, that is, every 31.25 ms, to make feedback continuous to the human eye. The trial paradigm and all the algorithms used in the signal processing are implemented in MATLAB.

## 3 Navigation Paradigm

The main objective of the BCI research at the University of Málaga is to provide an asynchronous BCI system (UMA-BCI) which, by the discrimination of only two mental tasks, offers the user several output commands. These commands could be used to interact with videogames, as navigation commands to control an external device (robot, wheelchair) or be used in a VE. An asynchronous (or self-paced) system must produce outputs in response to intentional control as well as support periods of no control [21]; those are the so-called intentional control (IC) and non-control (NC) states, respectively. Both states are supported in the paradigm proposed: the system waits in a NC state in which an NC interface is shown (Figure 2a). The NC interface enables subjects to remain in the NC state (not generating any command) until they decide to change to the IC state, where the control is achieved through the IC interface (Figure 2b). The signal processing used to control both interfaces is the same as the one the described in section 2.3.

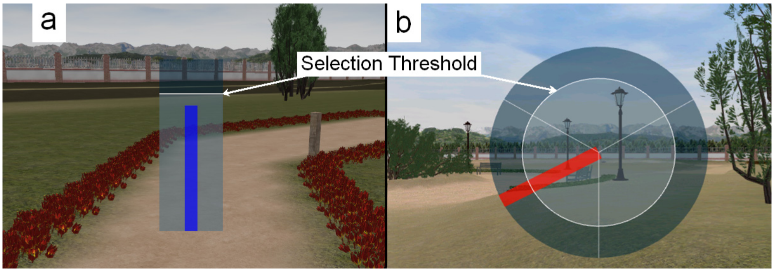

**Fig. 2.** NC interface (a) and IC interface (b)

The NC interface consists of a semi-transparent vertical blue bar placed in the centre of the screen. The bar length is computed every 62.5 ms (8 samples) as a result of the LDA classification. As preliminary study, the two mental tasks used are the same than the one used during the training phase (training protocol): right-hand MI versus relaxed state: if the classifier determines that the mental task is right-hand MI, the bar extends; otherwise (relaxation state), the bar length remains at its minimum size. In order to change from the NC to the IC state, the subject must extend the bar (carrying out the MI task) over the "selection threshold" and accumulate more than a "selection time" with the bar over this "selection threshold". If the length is temporarily (less than a "reset time") lower than the selection threshold, the accumulated selection time is not reset, but otherwise it is set to zero. All these parameters ("selection time", "selection threshold" and "reset time") are manually selected for each subject.

The IC interface to select a specific command is based on the methodology used in the design of the typewriter Hex-o-spell developed within the BBCI project [22]. This one consists of a circle divided into several parts, which correspond to the possible navigation commands. The IC interface showed in Figure 2b allows to select 3 commands: move forward, turn right and turn left. A circle divided into four parts allows to select, furthermore, the "move back" command. A bar placed in the centre of the circle is continuously rotating clockwise. The subject can extend the bar carrying out the MI task to select a command when the bar is pointing at it. The way the selection works in this interface is the same as in the NC interface, with the same selection and reset time and the same selection threshold. In the IC interface, another threshold is defined: stop threshold, which is lower than the selection threshold, and not visible to the subject. When it is exceeded, the bar stops its rotation in order to help the subject in the command selection.

Subjects receive audio cues while they interact with the system. When the state changes from IC to NC they hear the Spanish word for 'wait'; the reverse change is indicated with 'forward', since it is the first available command in the IC state. Finally, every time the bar points to a different command, they can hear the correspondent word ('forward', 'right', 'back' or 'left').

This navigation paradigm is not to be applied only in VR; it can be used in other scenarios, for example, to control a robot in an experimental situation, or a real wheelchair. In such a scenario, the need for a graphical interface to control the system may not be adequate, as it could limit the subject's field of view, for having to look at a computer screen and, at the same time, distract him from the task of controlling the device (wheelchair, robot…). If a BCI system is to be proposed that allows a subject to control a wheelchair, it should let the user watch the environment at all times.

It is for this reason that the recent work of our group is also focused on an adaptation of this system in which, after training with the graphical interface, subjects could switch gradually to an audio-cued interface. In fact, in the graphical interface proposed, the visual feedback is not necessary, as the only essential information that subjects need to receive is the cue that indicates which command is being pointed by the bar. Subjects hear an audio cue which signals them which navigation command can be selected, so they decide whether to carry out the MI task to select it, or to wait for the next command. Regarding the feedback, the actual movement of the virtual wheelchair (or of the external device) represents how subjects are performing in the control of their mental task.

## 4 Use of the System

In order to help subjects to control the proposed paradigm, a progressive training must carry out. During the first phase of the training, subjects use the paradigm combining visual and audio-cued interface together. In a second phase, only the audio cue interface is used to select the different navigation commands.

It is accepted that a more immersive environment can help keep the subject's motivation, and, as a consequence, it could lead to better results [11]. For this reason, our group works on the development of different VEs in order to help subjects to get control of the proposed paradigm (Figure 3). In order to get immersive VEs, crucial elements to take into account are realism and stereoscopic vision. Therefore, the navigation paradigm is being applied in 3D environments that faithfully reproduce real-world scenarios in their look (textures, shininess, transparency and translucency), physics (collisions, gravity and inertia) and weather conditions as rain, snow and wind. VEs can be configured to disable some of the simulation features, so ease of navigation can be adjusted to the ability and expertise of the user. Immersion is further achieved with the addition of 3D sounds, which take into account the distance, power and speed (Doppler Effect is included) of the source.

To increase the degree of immersion, the VEs are projected on a large screen. The VEs are created with OpenGL for the graphics, OpenAL for the 3D audio, and ODE for physics simulation. The C programming language is used. Interaction between MATLAB and the VE is achieved with TCP/IP communications, which allowed us to use different machines for data acquisition and processing, and environment simulation and display.

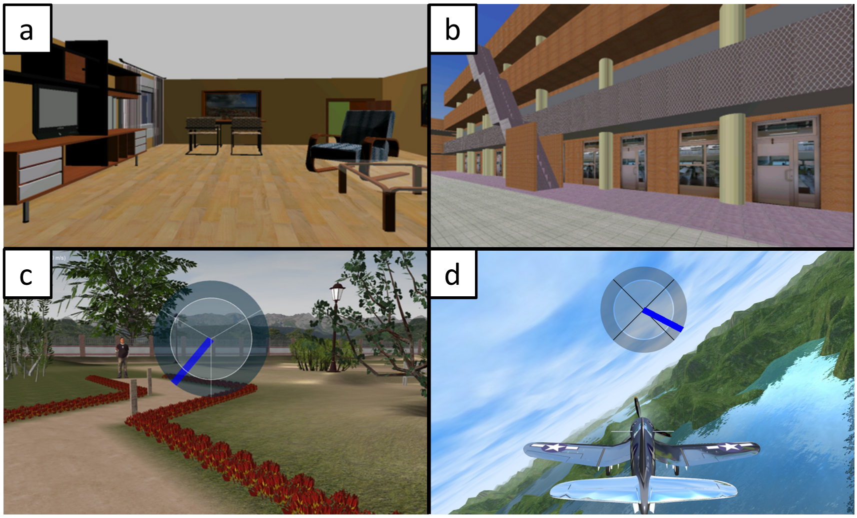

**Fig. 3.** Several VEs: a) Apartment, b) Engineering School of the University of Málaga, c) Park and corridor, d) BCI-controlled plane

By means of that versatility, users start navigating in an easy and attractive VE (Figure 3d): an environment without obstacles consisting of the control of a plane with 4 possible commands (rise, descend, turn right and left). Regarding the IC interface, the rotation speed of the feedback bar is fixed at 2.5 degrees per computation iteration (62.5 ms), so it takes 9 s to complete a turn if there is not any stop. The selection time changes among subjects, even between among sessions, in a range of 1-2 s. In fact, this VE is like a videogame but no instruction is provided. Subjects play and learn to control the plane using the graphical and the audio-cued interface.

Once they get used to the paradigm (firstly with visual and audio-cued interface, and then with only audio-cued) they progressively change to more sophisticated scenarios. These scenarios have been created in order to be recognized by the users as familiar. One of these scenarios is a virtual apartment to explore (Figure 3a). In this virtual apartment subjects can freely decide where to go, however, some obstacles must be avoided (furniture, walls,…). Another scenario is a known place, such as, the engineering school of the University of Málaga (Figure 3b), where most subjects come from. With this scenario, subjects are instructed to go to specific places, for example the bar of the school. In this second phase of the training, subjects can choose between the virtual apartment and the engineering school to navigate.

Finally, once the subjects got some control to navigate using the audio-cued interface, they participate in an experiment in which they have to follow a prefixed path to reach, as fast as they could, an avatar placed at the end of it (Figure 3 c). This path is located in a 3D virtual park. If the movement leads the subjects out of this path, the wheelchair collides with an invisible wall, so the movement finishes. During the experiments, subjects are looking at a large stereoscopic screen (2 x 1.5 m) placed at a distance of 3 m, wearing polarized glasses and earphones.

Figure 4 shows the different paths followed by a single subject in 3 different runs (the starting point is on the right side). In order to establish a criterion to compare the performance of the subject, a reference path is presented in the figure with a white line. This path is achieved with the same paradigm, but an operator uses a function generator to manually emulate the brain activity, so the bar length could be easily controlled. This path can be considered close to the optimal path that can be achieved with this paradigm. Every point where a collision happened is signalled with an arrow, and each command with a symbol in the paths. This subject collided once in run 1 and twice in run 3. Run 2 was carry out without collisions. The number of commands used is 18.3 (average between the 3 runs), that is, only 2 times the number of commands using a manual control (9).

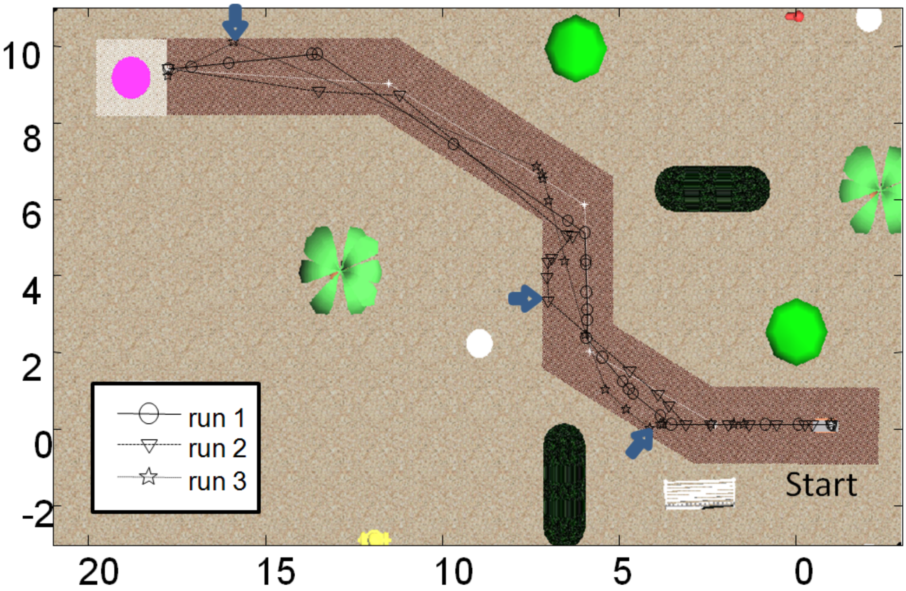

**Fig. 4.** Paths followed by a subject in a virtual park

## 5 Discussion and Conclusion

A new paradigm has been proposed to navigate through a VE using only two mental tasks, which keeps the classification accuracy at its maximum. The mapping of these mental tasks into a higher number of commands makes it possible to freely move with a friendly paradigm of interaction. This paradigm can easily be modified to let the subjects choose among a higher number of commands (for example, it could be included a fourth command to move backwards).

The subjects' motivation is a very important factor in their performance. For this reason, the use of VE with a higher degree of immersion could improve the results. Different applications of VR to BCI systems have been presented, showing how it not only helps to keep user's interest and motivation, but actually has a positive effect in the user's performance and training. Among these applications, we have focused on those oriented to the use of VR as a tool to test and train with several navigation paradigms, especially on the UMA-BCI. This last paradigm has shown its usability with encouraging results supported by several experiments. This navigation paradigm does not need to be applied only in VR, it can be used in other scenarios, for example, to control a robot in a experimental situation, or a real wheelchair.

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