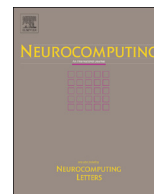




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Audio-cued motor imagery-based brain–computer interface: Navigation through virtual and real environments



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ABSTRACT

The aim of this work is to provide a navigation paradigm that could be used to control a wheelchair through a brain–computer interface (BCI). In such a case, it is desirable to control the system without a graphical interface so that it will be useful for people without gaze control. Thus, an audio-cued paradigm with several navigation commands is proposed. In order to reduce the probability of misclassification, the BCI operates with only two mental tasks: relaxed state versus imagination of right hand movements; the use of motor imagery for navigation control is not yet extended among the auditory BCIs. Two experiments are described: in the first one, users practice the switch from a graphical to an audio-cued interface with a virtual wheelchair; in the second one, they change from virtual to real environments. The obtained results support the use of the proposed interface to control a real wheelchair without the need of a screen to provide visual stimuli or feedback.

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1. Introduction

A Brain–Computer Interface (BCI) is a system that enables communication based not on muscular movements but on brain activity. This activity can be measured through electroencephalographic (EEG) signals. Several EEG signals can be detected, resulting in different types of BCIs. Sensorimotor rhythm-based BCIs (SMR-BCI) are based on the changes of μ and β rhythms. These rhythms correspond to specific features of the EEG signals characterized by their frequencies that can be modified by voluntary mental tasks. When a person performs a movement, it causes a synchronization/desynchronization in this activity (event-related synchronization/desynchronization, ERS/ERD), which involves a rhythm amplitude change. Motor control is located in the motor cortex of the brain, and different limbs control is linked to specific areas of this cortex. The outstanding property of these signals is their behaviour when someone merely imagines movements (motor imagery, MI), because this causes a change with similar features, although with notably lower amplitude [1]. This relevant characteristic is what makes SMR suitable to be used as input for a BCI.

Recently, BCI research has been targeted at the rehabilitation of motor-disabled individuals because it helps to establish a communication and control channel for them. This new channel could be used to restore motor functions (such as arm movements

through exoskeletons) or to provide them with mobility using a BCI controlled motorized wheelchair. This is the focus of this work. Before people can use it in a real situation, it is necessary to guarantee enough control to avoid dangerous scenarios. Many BCI applications based on mental task discrimination allow the user to control simulated [2] or real mobile robots [3,4]. Virtual reality (VR) is a suitable tool to provide subjects with the opportunity to train and test the application. As it is proved in [5], the use of VR techniques improves the performance. Among those BCI systems aimed at navigation, several can be found in which the subject moves in only one direction [6,7], so the user needs only one control command. Some systems offer the user more ease of use by means of more commands. In [8], 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 [9], where three possible commands (turn left, turn right, and move forward) are selected with three MI tasks (chosen from left hand, right hand, foot, and tongue). Having a higher number of commands makes it easier for the subjects to navigate through the environment, since they have more choices to move. However, some studies proved that the best classification accuracy is achieved when only two classes are discriminated [10,11]. As the systems mentioned above match the number of commands to the number of mental tasks, none of them simultaneously fulfills two basic characteristics of these kinds of systems: free mobility and optimized safety (a classification error corresponds to a wrong command, which can cause dangerous situations in the real world). In order to provide different commands without making the BCI performance worse, a new paradigm based on the discrimination of only two classes

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(one active mental task versus any other mental activity), which enabled the selection of four navigation commands, was proposed in [12]. The mapping of two states into four commands was achieved with a bar that turned in a circle and pointed to the various commands placed around it. When subjects wanted to select the command to which the bar was pointing, they carried out one MI task to extend the bar. The other mental state was the relaxed state, which made the bar keep turning. An improvement of this interface was proposed in [13], providing an asynchronous BCI (where the subject controls the timing of the interaction) which allowed subjects to navigate freely in a VE. In these previous works, a graphical interface with a feedback bar was shown to the subject; however, this could be a problem if the system is conceived to finally control a real wheelchair. For this reason, a laptop coupled to a wheelchair has occasionally been used [14,15] to provide visual feedback or stimuli (e.g. in a system based on Steady-State Visual Evoked Potentials or in a visual oddball paradigm). Nevertheless, this solution may not be adequate to control a wheelchair as it could limit the subject's field of view and, at the same time, distract him or her from the task of controlling the wheelchair by requiring him or her to look at the computer screen. Furthermore, for disabled people without gaze control a graphical interface could represent an obstacle. If a BCI system is supposed to allow a subject to control a wheelchair, it should let the user watch the environment at all times. There are works focused on auditory BCIs where the audio plays several roles: in most of them, auditory stimuli are used to elicit event-related potentials [16–21], in others cases the audio is used as feedback for the subjects, or as cue for different mental tasks that subjects must self-regulate through SCP [22], or SMR [23].

This study is a continuation of the work in [13], in which the visual paradigm is intended to be replaced by an auditory one, thus avoiding the need for the subject to look at the screen in order to execute the navigation commands. In fact, in the graphical interface proposed in [13], the visual feedback is not indispensable, as the only essential information that subjects need to receive is the cue that indicates which command the bar is pointing to, and this cue does not need to be visual.

Two experiments are described: in the first one, users practice the switch from a graphical to an audio-cued interface with a virtual wheelchair; in the second one, they change from virtual to real environments.

The first experiment presented herein establishes a comparison between the use of a graphical interface and an interface guided only by auditory cues. With new paradigm subjects hear an audio cue which signals to 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 indicates how subjects are performing in the control of their SMR.

The second experiment was conceived as a logic consequence from the results obtained from the first experiment: we concluded that this audio-cued paradigm was an adequate tool to avoid the need for a graphical interface, so the next step in our research was to use it in a real environment. We hypothesized that two levels of adaptation could be useful in the learning process: (i) first using a graphical control interface before navigating with only an audio-cued interface; (ii) changing from a virtual to a real environment. Keeping this adaptation in mind, in the second experiment subjects had to control a simulated robot in a VE and then a real mobile robot. The second experiment consisted of three sessions: in the first one, subjects controlled the system using both the graphical and the audio interface in VR; after that, they switched to an interface cued only by audio, still in VR; in the final session, they had to control a mobile robot in a real environment. To make the change from a virtual world to the

real one easier, the VE was designed to be similar to the real one (a small maze of corridors).

2. Methods

2.1. Subjects and data acquisition

As a design criterion, a conventional limit of 30% in the error rate was considered to be the maximum that could allow an efficient control of the paradigm, the same limit used in [24] for an efficient communication using a two-class BCI for spelling. In the present study, only subjects who performed under this threshold in the calibration session (see Section 2.2) continued with the navigation sessions. In the first experiment, six out of eight subjects accomplished this criterion (one man and five women, aged 21.8 ± 1.7 years). For the second experiment, an open call for subjects with previous BCI experience was done, obtaining three participants (two men and one woman, aged 24 ± 2 years).

The EEG was recorded from two bipolar channels using gold electrodes placed 2.5 cm anterior and posterior to electrode positions C3 and C4 (right and left hand sensorimotor areas, respectively) according to the 10/20 international system, as in previous experiments [13]. The ground electrode was placed at the FPz position. Signals were amplified by a 16 channel biosignal g.BSamp amplifier and then digitized at 128 Hz by a 12-bit resolution data acquisition NI USB-6210 card.

2.2. Initial training and signal processing

Before the online self-paced experiments, subjects participated in two initial training sessions for calibration purposes. This training used the paradigm proposed by our group (UMA-BCI) in [5] (based on that proposed by the Graz group [25]), in which subjects immersed in a VE had to control the displacement of a car to the right or left, depending on the mental task carried out, in order to avoid an obstacle. The training entailed discriminating between two mental tasks: mental relaxation and imagined right hand movements (right hand MI). The subjects did not receive any feedback in the first session, which was used to set up classifier parameters for the second session, in which continuous feedback was provided. In this first session, subjects were instructed to carry out four experimental runs consisting of 40 trials each. After a break of 5–10 min, the time necessary to do the offline processing, subjects participated in the second session. This feedback session consisted of four experimental runs, intended to check the effectiveness of the chosen parameters and the ability of the subject to control his or her EEG signals. In order to increase the degree of immersion, the VE was projected on a large screen (2×1.5 m) and subjects were placed at a distance of 3 m. As mentioned above, subjects from the second experiment had previous BCI experience, so they were supposed to need less training time. For this reason, the calibration sessions were slightly different: three experimental runs for the session without feedback, and only one session for the one with feedback.

Each trial was 8 s long and followed the timing shown in Fig. 1. Initially, in a scene of continuous movement, the car was being driven down the middle of three lanes. At 2 s, a puddle-like obstacle would come into view in the left or right lane at the end of the road. If it appeared in the left lane, subjects were to imagine right hand movements. If it appeared on the right, they were to remain in a relaxed state. At 4.25 s, the puddle was situated beside the car, starting the feedback period in which subjects were able to control the movement of the car to the left or right according to the classification result, in order to avoid the obstacle (session with feedback). In sessions without feedback,

the car remained in the central lane during the feedback period. At 8 s, the trial finished and then started again after a pause ranging from 0.5 s to 3 s (randomly distributed). The VE was created with VRML 2.0 and its interaction with MATLAB was achieved using the MATLAB Virtual Reality Toolbox.

The offline processing was based on the procedure detailed in [5] and consisted of estimating the average band power of each channel in predefined, subject-specific reactive (manually selected) frequency bands at 500-ms intervals. For the first session, an error time course was computed with a ten-times ten-fold cross-validation of a linear discriminant analysis (LDA). The extracted feature parameters of the classification time points with the lowest classification error were used to set up the LDA classifier parameters (weight vector) for the session with feedback. In the feedback session, the displacement 'D' of the car was computed online every 31.25 ms as a result of an LDA classification. A negative/positive value of D was translated into a left/right displacement of the car, indicating that the trial was classified as a left/right trial. The same parameters as used for the feedback session were used to calibrate the system for the online navigation experiments. The trial paradigm and all the algorithms used in the signal processing were implemented in MATLAB.

2.3. Navigation paradigm

The main objective of the BCI research at the University of Málaga is to provide an asynchronous BCI system (UMA-BCI) which, through the discrimination of only two mental states, offers the user several navigation commands to be used in a virtual or a real environment. An asynchronous (or self-paced) system must produce outputs in response to intentional control as well as support periods of no control [26]; these are the so-called intentional control (IC) and non-control (NC) states, respectively. Both states are supported in the study presented in this paper: the system waits in an NC state in which an NC interface is

shown (Fig. 2a), which 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 (Fig. 2b).

The NC interface consists of a semi-transparent vertical blue bar placed in the centre of the screen. The bar length is computed every 31.25 ms as a result of the LDA classification: if the classifier determines that the mental task is right-hand MI, the bar extends; otherwise (the other class is idle or rest state), the bar length remains at its minimum size. In order to change from the NC to the IC state, the user must accumulate more than a subject dependant 'selection time' (it ranged from 0.9 s to 1.2 s) with the bar over the '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. In Fig. 3, the timing of the selection in the IC state is shown; this timing is similar for the NC state, but in the NC the consequence of a selection is a change of state, while in the IC the consequence is a navigation action.

The IC interface is similar to the one presented in [12], comprising a circle divided into several (three or four) parts, which correspond to the possible navigation commands, with a blue bar placed in the centre of the circle that is continuously rotating clockwise (it needs 15 s to complete a turn). The subject can extend the bar when 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 (see Fig. 3 until mark 't10'). While the bar is above the selection threshold (or under it when the selection time count has not yet been reset) the bar changes its colour to red, indicating to the subject that a command selection process has started. In the IC interface, another threshold is defined (the 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 select a command. This IC interface is slightly different between the two experiments: in the first one (Fig. 2.b) three commands from which the user can choose are available (forward, right, and left), while in the second one (Fig. 5a) a fourth command was introduced (backward).

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 by '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 corresponding word: 'forward', 'right', 'left', or 'backward' (while in the first experiment subjects could choose among three navigation commands, in the second one they also had the option of choosing 'backward'). The virtual wheelchair or the robot (depending on the experiment) moves in a continuous way; it starts moving forward or turning left or right at a fixed speed and the bar (which has already stopped, since it exceeds the stop threshold) changes its colour to red. The movement is maintained as long as the bar length is above

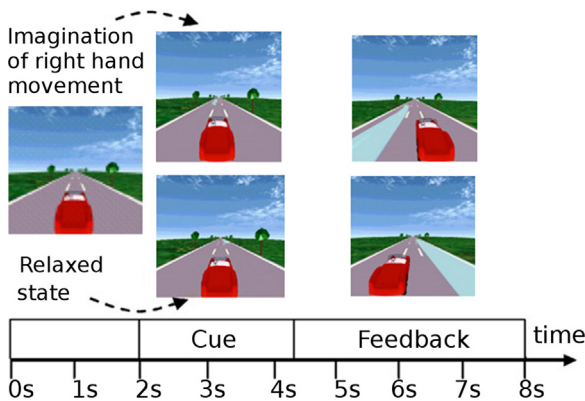


Fig. 1. Timing of one trial of the training with feedback.

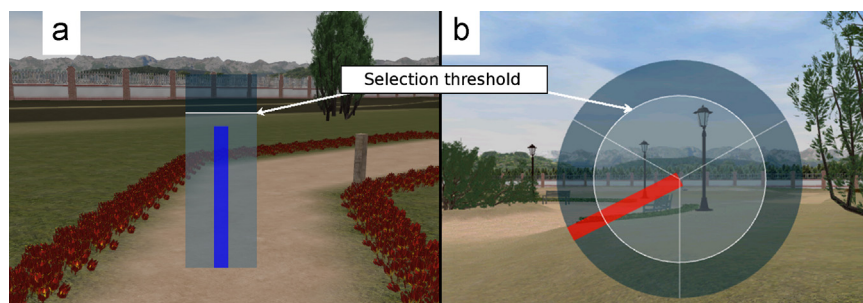


Fig. 2. NC interface (a) and IC interface (b). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

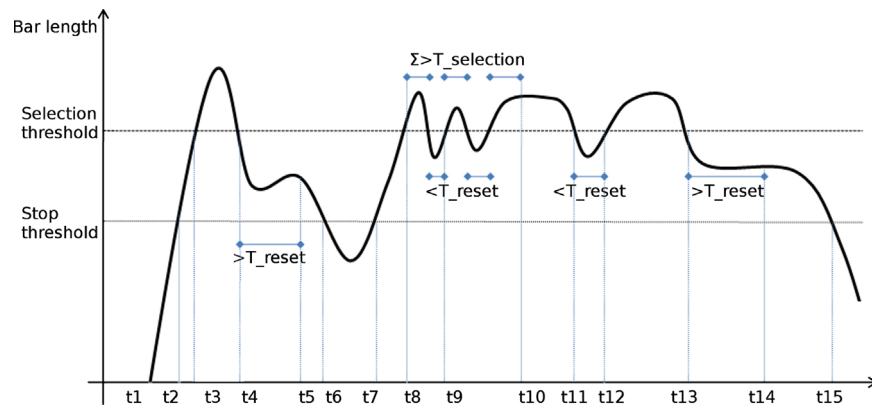


Fig. 3. Command selection example in the IC interface. Axis 'x' represents time, where some marks are indicated. Axis 'y' represents the feedback bar length at any time. The time marks indicate significant moments of the control timing. t_1 : MI starts, the bar extends while it is rotating; t_2 : the bar reaches the 'stop threshold', it stops rotating; t_3 : the bar overpasses the 'selection threshold', the 'selection time' count starts and the bar colour changes to red; t_4 : the 'reset time' count starts; t_5 : the bar has stayed under the 'selection threshold' more time than the 'reset time' ($> T_{reset}$), the 'selection time' count is reset and the bar colour changes back to blue; t_6 : the bar is under the 'stop threshold', it starts to rotate again; t_7 : the bar crosses the 'stop threshold', it stops rotating; t_8 : the bar overpasses the 'selection threshold', the 'selection time' count starts again and the bar colour changes to red; t_9 : the 'reset time' count is insufficient to reset the 'selection time' count, so this count continues; t_{10} : after three intervals, the 'selection time' count is completed, the command is selected, and the device (a virtual wheelchair, or the mobile robot) starts moving; t_{11} : the device stops temporarily; t_{12} : the 'reset time' count is insufficient to deselect the command, and the device starts to move again; $t_{13} \rightarrow t_{14}$: the 'reset time' count is completed, the command is deselected, and the bar colour changes back to blue; t_{15} : the bar length is again under the 'stop threshold', so it starts to rotate again.

the selection threshold (this means that the subject is still carrying out the MI mental task); see Fig. 3, from mark 't10'. If the bar is temporarily under this threshold (less time than the reset time has passed), the movement stops, but the system allows the subject to continue the same movement if the bar again exceeds the selection threshold. While this happens, the bar keeps its red colour to indicate this possibility to the subject. In the case that the bar remains under the selection threshold for longer than the reset time, the bar changes its colour to blue and continues rotating (if it is under the stop threshold) so that the subject can select a command again. The position of the rotating bar does not change; it restarts its rotation from the same point at which it last stopped to select a command. In this way, the subject can select the same command several times in a row, in case the reset time passes without the subject wanting to stop the movement. If subjects want to change from the IC to the NC state again, they must allow the bar to complete two turns without selecting any command.

From the results obtained with this mode of operation (continuous, with only a graphical interface [13]), it can be deduced that the paradigm could be used to train and, eventually, to control a real wheelchair. In the last sessions of both experiments, after subjects had familiarized themselves with the visual interface and the simultaneous audio cues, the graphics were removed so subjects could only see the environment (virtual or real).

2.4. Experimental procedure

In this section we will describe two experiments carried out using the same navigation paradigm. In the first one, we studied the viability of the proposed audio-cued interface to drive a virtual wheelchair. In the second one, we tested the same paradigm in an experiment which started in VR and ended by controlling, without visual cues, a real mobile robot.

2.4.1. First experiment: From a graphical to an auditory interface

This experiment consisted of three sessions (one run per session) in which participants had to follow a predetermined path to reach an avatar placed at the end of it, as fast as they could, using three navigation commands. This path was located in a 3D virtual park (see Fig. 2). The first two sessions were carried

out using both the visual and the auditory interface, and the last one only with the auditory interface. If the movement led the subject off this path, the wheelchair collided with an invisible wall (see the flowers in Fig. 2a), so the movement finished. Once they collided they needed to select a turn command, because selecting 'forward' again would lead them to a new collision, without causing any movement. After a collision happened, the bar continued its rotation from the point where it stopped, as in the case when a subject finished the selection of a command. The path consisted of five sections with a total length of 38 m. These sections were placed so that subjects had to achieve at least two turns of approximately 45° in each direction (the path is represented in Fig. 4). The dimensions of the virtual wheelchair were 1.17×0.75 m. The virtual wheelchair moved forward at a speed of 1.3 m/s and it turned at a 10 degrees/s. The point of view over the VE was an ego-perspective from an avatar sit on the virtual wheelchair. Subjects were looking at a large stereoscopic screen (2×1.5 m) placed at a distance of 3 m and they were wearing polarized glasses and earphones.

2.4.2. Second experiment: From virtual to real environments

This experiment consisted of controlling a robot (virtual and real) through a group of corridors which formed a sort of small maze. The task was to drive the robot from the start position to the goal as fast as possible, using the minimum number of navigation commands, trying to always move forward (the forward direction is indicated by an arrow on the top of the robot), and avoiding collisions. The real robot was an EPFL educational e-puck (www.e-puck.org). The e-puck is a two-wheeled, cylinder-shaped programmable robot with eight infrared sensors around its perimeter, which were configured to make the robot stop automatically when it approached an obstacle. The proposed VE (and the virtual robot) is presented in Fig. 5 (left) and was designed with the same features as the real environment (Fig. 5, right). The VE had dimensions of 70×95 cm, and the corridors were all 20 cm wide. The virtual robot is cylinder shaped with a diameter of 7.5 cm and a height of 4.7 cm. Both robots (virtual and real) were configured to stop automatically when they approached within 2 cm of an obstacle, to move at a speed of 3.9 cm/s, and to turn at 42.9 degrees/s. The point of view over the VE was similar to the one subjects had over the real one, sitting next to the maze.

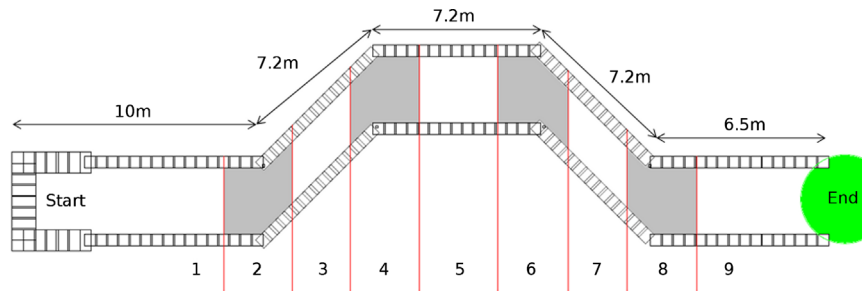


Fig. 4. Path divided into straight and curved stretches.

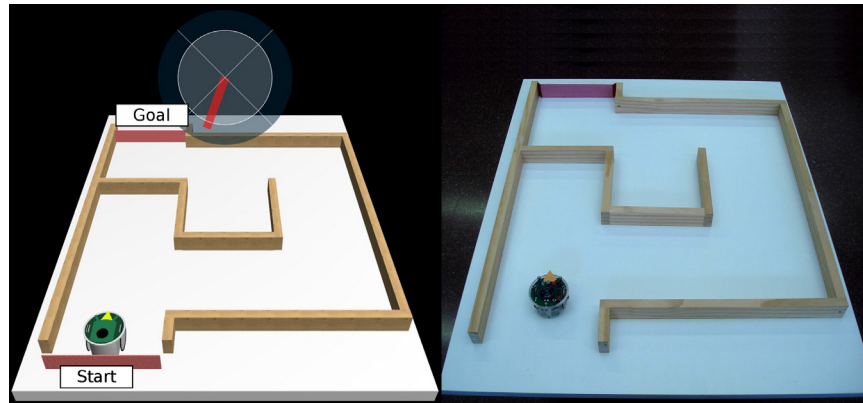


Fig. 5. Simulated mobile robot in the VE (left) and the real one. (right).

Each subject participated in three sessions, carried out on different days, with two experimental runs each. In the first session, the aim was to drive the simulated robot to the goal using the graphical and the audio-cued interfaces together. In the second session, only the audio-cued interface was used in the same VE. Finally, in the third session, the experiments consisted of controlling the real robot in a continuous way using only the audio-cued interface. In [27], a similar experiment was carried out in a discrete way to check the feasibility of changing from virtual to real environments (control through discrete commands is supposed to be easier for subjects).

To increase the degree of immersion, the VE was projected on the same large screen as was used during the initial training. The VE was written in C using OpenGL for the graphics, OpenAL for the 3D audio, and ODE for physics simulation. Interaction between MATLAB and the VE was achieved with TCP/IP communications, which allowed us to use different machines for data acquisition/processing and environment simulation/display.

3. Results

3.1. Calibration

The results in the calibration session for experiment 1 and 2 are shown in Tables 1 and 2, respectively. Column ‘MinErr (%)’ shows the minimum error rate averaged over all the trials for each subject in the calibration session without feedback; column ‘Frequency band (Hz)’ shows the chosen reactive frequency bands for each subject.

3.2. First experiment

As stated above, the six subjects firstly carried out two identical sessions, using both the visual and the auditory interface. The first one was considered an adaptation to the paradigm

Table 1
Calibration session results for experiment 1 (session without feedback).

| Subject | MinErr (%) | Frequency band (Hz) |
|--------------|------------|-------------------------|
| S_a1 | 25 | 10–14 |
| S_a3 | 17.5 | 10–13 |
| S_a4 | 28 | 8–12 |
| S_a5 | 25 | 8–13 |
| S_a7 | 25.5 | 9–12 |
| S_a8 | 23.5 | 10–13 |
| Average ± SD | 24 ± 3.5 | (11 ± 2.3)–(13.6 ± 1.5) |

Table 2
Calibration session results for experiment 2 (session without feedback).

| Subject | MinErr (%) | Frequency band (Hz) |
|--------------|-------------|-----------------------|
| S_b1 | 26.7 | 11–15 |
| S_b2 | 25.8 | 10–14 |
| S_b3 | 23 | 9–12 |
| Average ± SD | 25.17 ± 1.9 | (10 ± 1)–(12.8 ± 0.7) |

session, in which subjects should get familiarized with the environment and the navigation paradigm. For this reason, regarding the performance, we will only present here the comparison between the second and the third session; in other words, we will compare the performance of the visual and auditory interface with the only-auditory interface (Table 3).

All subjects underwent through two different conditions (case study); being the number of them too low to apply a paired-samples *t* test, a Wilcoxon test was done whose results (Table 4) shows that there are no significant differences between the two interfaces for any of the parameters ($p > 0.05$); in other words, none of the interfaces has proved to be better than the other. Despite the lack of statistical significance, the results suggest that

Table 3

Results for each subject and interface: Time needed to complete the path, number of collisions (Coll.), and number of commands of each type used (Forward, *F*; Right, *R*; Left, *L*; and Total, *T*).

| Subject | Interface | Time(s) | Coll. | <i>F</i> | <i>R</i> | <i>L</i> | Total |
|---------|-----------------|---------|-------|----------|----------|----------|-------|
| S_a1 | Visual+Auditory | 551 | 8 | 19 | 17 | 18 | 54 |
| | Auditory | 647 | 6 | 20 | 32 | 18 | 70 |
| S_a3 | Visual+Auditory | 381 | 9 | 15 | 12 | 14 | 41 |
| | Auditory | 521 | 9 | 20 | 19 | 14 | 53 |
| S_a4 | Visual+Auditory | 249 | 2 | 7 | 7 | 2 | 16 |
| | Auditory | 658 | 16 | 22 | 19 | 16 | 57 |
| S_a5 | Visual+Auditory | 749 | 19 | 26 | 25 | 22 | 73 |
| | Auditory | 486 | 13 | 18 | 13 | 15 | 46 |
| S_a7 | Visual+Auditory | 686 | 21 | 29 | 21 | 19 | 69 |
| | Auditory | 441 | 10 | 18 | 14 | 11 | 43 |
| S_a8 | Visual+Auditory | 544 | 8 | 17 | 25 | 17 | 59 |
| | Auditory | 775 | 14 | 24 | 35 | 33 | 92 |

Table 4

Results averaged over the subjects for each parameter and interface: mean (*M*), standard deviation (*SD*), Student's *T* (*T*), and statistical significance (*p*).

| Parameter | Interface | <i>M</i> (s) | <i>SD</i> (s) | <i>T</i> | <i>p</i> |
|------------|-----------------|--------------|---------------|----------|----------|
| Time | Visual+Auditory | 526.67 | 186.56 | 9 | .42 |
| | Auditory | 588 | 126.37 | | |
| Collisions | Visual+Auditory | 11.17 | 7.31 | 7.5 | .56 |
| | Auditory | 11.33 | 3.67 | | |
| Forward | Visual+Auditory | 18.83 | 7.91 | 9 | .42 |
| | Auditory | 20.33 | 2.34 | | |
| Right | Visual+Auditory | 17.83 | 7.28 | 6 | .23 |
| | Auditory | 22.00 | 9.30 | | |
| Left | Visual+Auditory | 15.33 | 7.03 | 3 | .31 |
| | Auditory | 17.83 | 7.78 | | |
| Total | Visual+Auditory | 52.00 | 20.98 | 7 | .28 |
| | Auditory | 60.17 | 18.26 | | |

Table 5

Performance for each subject and session.

| Subject | Mode | Run | Time(s) | Coll. | Forward | Right | Left | Backward | Total |
|---------|------|---------|--------------|-----------|----------|------------|------------|-----------|------------|
| S_b1 | VGS | 1 | 444.8 | 2 | 22 | 12 | 8 | 2 | 43 |
| | | 2 | 518.3 | 2 | 26 | 13 | 11 | 2 | 51 |
| | | Average | 481.5 ± 51.9 | 2 ± 0 | 24 ± 2.8 | 12.5 ± 0.7 | 9.5 ± 2.1 | 2 ± 0 | 47 ± 5.6 |
| | VS | 1 | 456 | 3 | 12 | 11 | 13 | 5 | 41 |
| | | 2 | 460 | 3 | 18 | 8 | 7 | 5 | 38 |
| | | Average | 458 ± 2.8 | 3 ± 0 | 15 ± 4.2 | 9.5 ± 2.1 | 10 ± 4.2 | 5 ± 0 | 39.5 ± 2.1 |
| | RS | 1 | 488 | 3 | 17 | 7 | 12 | 2 | 38 |
| | | 2 | 462 | 3 | 21 | 7 | 5 | 2 | 35 |
| | | Average | 475 ± 18.3 | 3 ± 0 | 19 ± 2.8 | 7 ± 0 | 8.5 ± 4.9 | 2 ± 0 | 36.5 ± 4.5 |
| S_b2 | VGS | 1 | 367 | 1 | 16 | 9 | 7 | 2 | 34 |
| | | 2 | 504 | 3 | 20 | 10 | 11 | 2 | 43 |
| | | Average | 435.5 ± 96.8 | 2 ± 1.4 | 18 ± 2.8 | 9.2 ± 0.7 | 9 ± 2.8 | 2 ± 0 | 38.5 ± 6.3 |
| | VS | 1 | 467.8 | 8 | 22 | 17 | 14 | 3 | 56 |
| | | 2 | 431 | 4 | 14 | 12 | 11 | 7 | 44 |
| | | Average | 449.4 ± 26 | 6 ± 2.8 | 18 ± 5.6 | 14.5 ± 3.5 | 12.5 ± 2.1 | 5 ± 2.8 | 50 ± 8.4 |
| | RS | 1 | 572 | 1 | 17 | 17 | 16 | 5 | 55 |
| | | 2 | 688 | 4 | 15 | 22 | 22 | 5 | 64 |
| | | Average | 630 ± 82 | 2.5 ± 2.1 | 16 ± 1.4 | 19.5 ± 3.5 | 19 ± 4.2 | 5 ± 0 | 59.5 ± 6.3 |
| S_b3 | VGS | 1 | 511 | 0 | 14 | 11 | 12 | 1 | 38 |
| | | 2 | 633 | 1 | 12 | 9 | 15 | 3 | 39 |
| | | Average | 572 ± 86.2 | 0.5 ± 0.7 | 13 ± 1.4 | 10 ± 1.4 | 13.5 ± 2.1 | 2 ± 1.4 | 38.5 ± 0.7 |
| | VS | 1 | 728 | 5 | 24 | 18 | 12 | 9 | 63 |
| | | 2 | 842 | 6 | 24 | 13 | 22 | 10 | 69 |
| | | Average | 785 ± 80.6 | 5.5 ± 0.7 | 24 ± 0 | 15.5 ± 3.5 | 17 ± 7 | 9.5 ± 0.7 | 66 ± 4.2 |
| | RS | 1 | 449 | 1 | 19 | 5 | 8 | 0 | 32 |
| | | 2 | 478 | 6 | 13 | 12 | 11 | 5 | 41 |
| | | Average | 463.5 ± 20.5 | 3.5 ± 3.5 | 16 ± 4.2 | 8.5 ± 4.9 | 9.5 ± 2.1 | 2.5 ± 3.5 | 36.5 ± 6.3 |

the use of the auditory interface does not make the performance worse, so both could be equally usable. It should be noted that this similar performance occurs even if the second paradigm does not have a graphical interface, something very important to consider when controlling a real wheelchair.

3.3. Second experiment

The nomenclature used for the tables and figures is next: VGS stands for the 'Virtual with Graphics and Sound' interface, VS for 'Virtual with only Sound' interface and RS for 'Real (environment) with Sound' interface. In Table 5, the values of different parameters obtained from each session are shown. The analyzed parameters are: the time in seconds necessary to generate the desired trajectory (Time), the number of times that the robot collided with the wall (Coll.), the number of selected commands of each type (Forward, Right, Left, and Backward) and the total number of commands used to drive the robot from the start position to the goal (Total). In Table 6 and Fig. 6 the values averaged over the subjects are shown for each run, as well as averaged for each mode (which consisted of two runs).

In order to compare the averaged results, a Student's paired samples *t*-test was performed. The results revealed that performance in time was significantly affected by execution ($t(8) = -2.616$; $p < 0.05$), whereas between runs 1 and 2 a significant rise in the mean time was observed (Mean=498.1 s vs. Mean=557.3 s). Regarding the total number of commands needed to complete the path, the averages for the first and second sessions were highly correlated ($r=0.792$ $p < .01$), which emphasizes the drop in performance (Mean=44.4 and Mean=47.1 commands, respectively). This effect can be visually checked in Fig. 6, where for most of the parameters shown the first session is better than the second (less time and fewer commands and collisions).

Table 6
Results averaged over the subjects for each run.

| Mode | Run | Time(s) | Coll. | Forward | Right | Left | Backward | Total |
|------|---------|---------------|-----------|------------|------------|------------|-----------|-------------|
| VGS | 1 | 440.9 ± 72 | 1 ± 1 | 17.3 ± 4.1 | 10.6 ± 1.5 | 9 ± 2.6 | 1.6 ± 0.5 | 38.3 ± 4.5 |
| | 2 | 551.7 ± 70.7 | 2 ± 1 | 19.3 ± 7 | 10.6 ± 2 | 12.3 ± 2.3 | 2.3 ± 0.5 | 44.3 ± 6.1 |
| | Average | 496.3 ± 78.3 | 1.5 ± 0.7 | 18.3 ± 1.4 | 10.6 ± 0 | 10.6 ± 2.3 | 1.9 ± 0.4 | 41.3 ± 4.2 |
| VS | 1 | 550.6 ± 153.7 | 5.3 ± 2.5 | 19.3 ± 6.4 | 15.3 ± 3.7 | 13 ± 1 | 5.6 ± 3 | 53.3 ± 11.2 |
| | 2 | 577.6 ± 229.3 | 4.3 ± 1.5 | 18.6 ± 5 | 11 ± 2.6 | 13.3 ± 7.7 | 7.3 ± 2.5 | 50.3 ± 16.4 |
| | Average | 564.1 ± 19 | 4.8 ± 0.7 | 18.9 ± 0.4 | 13.1 ± 3 | 13.1 ± 0.2 | 6.4 ± 1.2 | 51.8 ± 2.1 |
| RS | 1 | 503 ± 62.8 | 1.6 ± 1.1 | 17.6 ± 1.1 | 9.6 ± 6.4 | 12 ± 4 | 2.3 ± 2.5 | 41.6 ± 11.9 |
| | 2 | 542.6 ± 126.1 | 4.3 ± 1.5 | 16.3 ± 4.1 | 13.6 ± 7.6 | 12.6 ± 8.6 | 4 ± 1.7 | 46.6 ± 15.3 |
| | Average | 522.8 ± 28 | 2.9 ± 1.9 | 16.9 ± 0.9 | 11.6 ± 2.8 | 12.3 ± 0.4 | 3.1 ± 1.2 | 44.1 ± 3.5 |

As complimentary results, subjects answered a self-report questionnaire (scaled from 1 to 5, ordered from less to more) after each session regarding the usability of the paradigm (useful information to improve it) and others parameters. Among them, the most interesting for this work are: (i) 'tiredness', that showed that the three subjects were tired at the end of the session; and (ii) 'distraction', that was marked as the lowest level for every subject and session.

4. Discussion and conclusions

It should be noted that the subjects were not particularly good at controlling their SMR signals – their averaged minimum classification error percentage was 24%, which is very close to the limit of 30% (see Section 3.1, Calibration) – but they were still able to control the robot with almost no mistakes. The proposed interface greatly improves the navigation results. The explanation may be as follows: subjects do not have 'perfect' control of their SMR signals (in terms of their classification accuracy); however the subjects' intention (MI or relaxed state) determines a slow change underneath the rapid changes of the bar under or above the threshold. The way in which the selection works, with the need for a selection time above this threshold, is analogous to the effect of a low-pass filter that removes high frequency noise. In other words, a classification error in the LDA does not entail a wrong command, as it is necessary for the bar to accumulate a fixed time above the threshold for a selection to take place.

The number of participants in both experiments (six and three) is too low to obtain strong conclusions. However, the objective of this work was to test the feasibility of the navigation paradigms, and this has actually been proved with the satisfactory results of a small group of subjects.

4.1. First experiment

The training process proposed herein, associating the visual and auditory interfaces, has proven valid for a future auditory-only interaction. Anderson [28] considered the process of skill acquisition to fall into three stages of development. The first stage, called the 'cognitive stage', involves an initial encoding of the skill and entails a verbal meditation in which the learner rehearses information required for the execution of the skill. In the second stage, the 'associative stage', the subject internalizes the process, so verbal meditation no longer occurs. In the last stage, the 'autonomous stage', the learning process continues as the subject puts into practice the new skill. Here, learning consists of internalizing the graphical interface and its timing in the previous sessions in order to subsequently respond only to the auditory stimulus. We hypothesized that the use of verbal stimuli (the audio cues for each command) could enhance the learning process in the first stage

especially, but also in the second one, when the subject associates the graphical interface with the audio cues.

This statement is also supported by the results of the self-report questionnaire in which all the subjects declared they had managed to associate the auditory stimulus to the mental task which they intended to execute. They also stated that such stimuli did not become a source of distraction that could lead to a mistake.

As quoted by [23], a subject in an initial experimental situation with the visual interface associated to the auditory one shows fast acquisition of the interaction commands. However, the first time that subjects face the auditory-only interface, their performance worsens slightly (Table 4). This effect could be due to several causes: (i) 'the attention processes may be in competition during the auditory feedback' [29]; (ii) the auditory stimuli may be distracting [29], however, as stated in the previous paragraph, subjects reported it was not a distraction for them; (iii) subjects are familiarized with the graphical and auditory interface (they underwent through two sessions with both interfaces), so the first time they faced the only auditory interface it involved certain disadvantage because of the lack of knowledge about it. In the next experiment, where subjects participated in two sessions without the visual interface, the performance got lower in the first of them, but improved again in the second one, maybe due to the effect of getting familiar to it.

Subjects got different classification results in the training sessions, therefore the control over their EEG signals was different. Besides, the paradigm allows subjects to move freely, so each one chose a different command series, resulting in a specific trajectory inside the corridor with different results. Another factor observed is that typical deviations in all the variables are relatively high, which indicates that each subject has adapted himself or herself to each interface in a particular manner. On the other hand, no direct relationship is noticed between each type of interface and the execution of the path ($p > 0.05$ number of commands, collisions, and total time), which allows us to deduce that none of the interfaces is intrinsically better than the others for interacting with the system.

The objective of the research was to confirm the utility of an exclusively auditory interface, as it would make the interaction of a handicapped person in a wheelchair easier. The success in the execution of the path with no significant differences in the measures of the evaluated variables in both modes of interaction shows the effectiveness of the proposed method. We thus conclude that both types of interface are equally effective when controlling a BCI system.

4.2. Second experiment

After testing the audio-cued paradigm in a VE with acceptable success, the next step in our research was to use it in a real

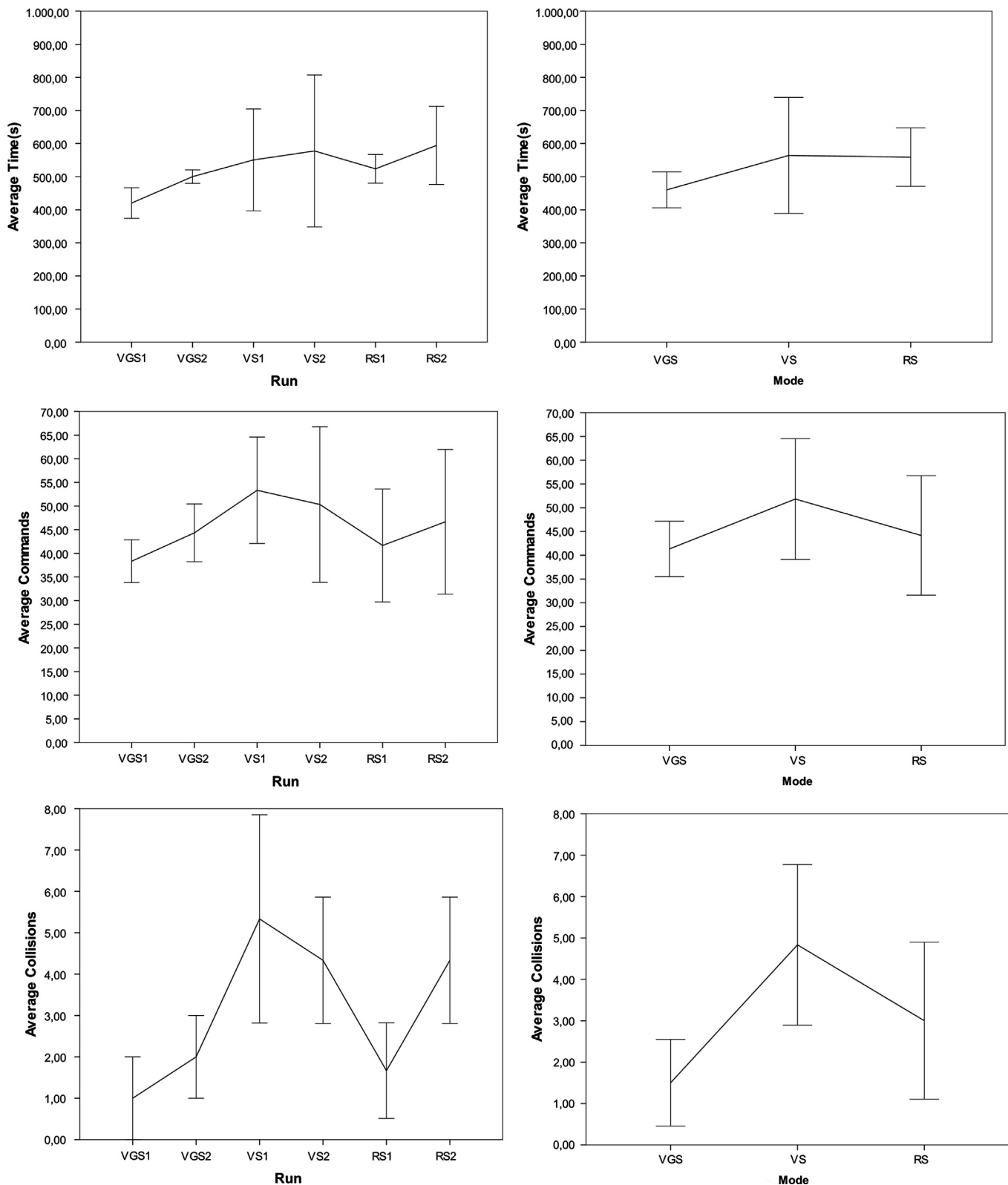


Fig. 6. Left: results averaged over the subjects for each run. Right: results averaged over the subjects and over the two runs of each mode.

environment. We hypothesized that subjects would first need a training transition from the graphical to the audio-cued paradigm (as was done for the previous experiment) in VR, so two conditions changed in the second experiment presented here: (i) subjects switched from a graphical to an audio-cued interface;

(ii) the same test was repeated in a virtual and then in a real environment.

A comparison between the first and the second session of each of the three modes (VE with graphics and sound, VE with sound only, and real robot with sound only) was done. The results

revealed that performance in time was significantly better in the first session. This reduction in performance may be explained by tiredness, as the two runs of each mode were carried out on the same day. In [30] a similar conclusion was obtained from an SMR-BCI experiment.

If we consider the average over the subjects and sessions for each mode (Table 6 and Fig. 6, right), another remarkable finding emerges: every parameter studied shows a fall in the second mode (VS) compared with the first one (VGS) and an improvement from the second to the third one (RS). The fall, as happened in the previous experiment, may be related to the auditory-only nature of the interface (the second session, VS, is the first time that subjects face the auditory-only paradigm). However, in the last session, subjects managed to improve the results compared to the second session, using the same paradigm (auditory-only) in a new (real) environment. Two factors may explain this better performance: (i) the third session was the second time that subjects used the auditory-only interface, so they experienced the effect of training in the control of the same interface due to habituation to the repeated stimulus [31]; (ii) the new environment is a real one, and the motivation of controlling a real device can be higher than in the case of a virtual one; the higher the level of motivation, the better the performance will be [30].

The proposed paradigm consists of a control interface that allows subjects to choose among several commands, but this selection is carried out by the discrimination of only two mental states. The obtained results from the two experiments support the use of the proposed paradigm to control a device (virtual or real) that can move freely in any direction. The main advantage of an audio-cued control interface is that the user does not need to gaze at a screen when he or she is controlling a real device; we tried it with a small mobile robot, but the paradigm could be used to control a real wheelchair.

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