Free Virtual Navigation Using Motor Imagery Through an Asynchronous Brain-Computer Interface

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Abstract

In this paper, an asynchronous brain-computer interface is presented that enables the control of a wheelchair in virtual environments using only one motor imagery task. The control is achieved through a graphical intentional control interface with three navigation commands (move forward, turn right, and turn left) which are displayed surrounding a circle. A bar is rotating in the center of the circle, so it points successively to the three possible commands. The user can, by motor imagery, extend this bar length to select the command at which the bar is pointing. Once a command is selected, the virtual wheelchair moves in a continuous way, so the user controls the length of the advance or the amplitude of the turns. Users can voluntarily switch from this interface to a noncontrol interface (and vice versa) when they do not want to generate any command. After performing a cue-based feedback training, three subjects carried out an experiment in which they had to navigate through the same fixed path to reach an objective. The results obtained support the viability of the system.

1 Introduction

For some people who cannot use their muscles to communicate (due to different causes), a brain-computer interface (BCI) could be an adequate solution because it enables communication that is based not on muscular movements but on brain activity that can be measured through electroencephalographic (EEG) signals. Sensorimotor rhythm-based BCIs (SMR-BCI) are based on the changes in μ and β rhythms, which can be modified by voluntary thoughts through such specific mental tasks as motor imagery (MI; Kübler & Müller, 2007). When a person performs a movement (or merely imagines it), it causes a synchronization/desynchronization in the neuron activity (event-related synchronization/desynchronization, ERS/ERD) which involves a μ rhythm amplitude change (Neuper & Pfurtscheller, 1999). This relevant characteristic is what makes SMR suitable to be used as input for a BCI.

The main aim of BCI research is to provide severely disabled people with an alternative nonmuscular communication channel. Researchers have worked to

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develop many applications that improve the quality of life of these patients, for whom BCIs represent a viable channel through which to interact with their environment. Among these applications, there are some where subjects take control of a real wheelchair in an experimental situation (Galán, Nuttin, Vanhooydonck, et al., 2008). However, in most cases subjects are instructed to drive a simulated wheelchair in a virtual environment (VE). Before people can use a wheelchair in a real situation, it is necessary to guarantee that they have enough control to avoid dangerous scenarios. Virtual reality (VR) is a suitable tool to provide subjects with the opportunity to train and test the application.

Some studies in which VR is used describe a system in which the wheelchair moves in only one direction (forward) (Leeb, Friedman, et al., 2007; Leeb, Settgast, Fellner, & Pfurtscheller, 2007). 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 Tsui and Gan (2007), 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 Scherer et al. (2008) 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). Having a higher number of commands makes it easier to control the wheelchair, since the subject has more choices to move freely (by means of an information transfer rate increase). The mentioned works connect the number of commands to the number of mental tasks. Nevertheless, it has been reported in several studies (Kronegg, Chanel, Voloshynovskiy, & Pun, 2007; Obermaier, Neuper, Guger, & Pfurtscheller, 2001) 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. In order to maintain this safety, in Ron-Angevin, Díaz-Estrella, and Velasco-Álvarez (2009) a paradigm was proposed which, using only two mental states, enabled subjects to move in a VE using four navigation commands. The mapping of two states into four commands was achieved with a bar that turned in a circle and pointed to the different commands placed around it. When subjects wanted to select the command at which the bar was pointing, they carried out one MI task to extend the bar. The other mental state was relaxed state, which made the bar keep turning. The idea is based on the speller described in Müller et al. (2008). Recently, other works have proposed systems that allow the user to select four choices using one MI (Friedrich et al., 2009; Geng & Gan, 2008), although they are not specifically applied to the control of a wheelchair.

Regarding the way in which a subject can control the system, many works aimed at navigation in VE have the limitation of being synchronous: the control is system-paced, that is, the subject can only interact with the environment at certain instants indicated by the system. Recent research tends to let the subjects decide when to control the system (Galán, Nuttin, Vanhooydonck, et al., 2008; Leeb, Friedman, et al., 2007; Leeb, Settgast, et al., 2007; Scherer et al., 2008; Tsui & Gan, 2007), which is a more natural form of interaction. These systems, called self-paced or asynchronous, distinguish between two states: (i) a noncontrol (NC) state in which subjects can be involved in any activity different from the control of the BCI (so the system should not generate any control command), and (ii) an intentional control (IC) state, in which subjects can control the system by specific mental tasks (Leeb, Friedman, et al.; Scherer). Subjects voluntarily switch the state they are in. In Velasco-Álvarez & Ron-Angevin (2009) an asynchronous system was presented as an improvement of the one proposed in Ron-Angevin et al. (2009). In that system, the selection of a command involved a discrete movement in the VE (90° turns to the left or the right, and fixed distance advances). Other works let the subjects move in a VE (or in an experimental situation) but put some intelligence into the system, which helps the users and interprets their intentions regarding, for example, the proximity of obstacles or the presence of several possible paths to follow (Escolano, Antelis, & Mínguez, 2009; Galán, Nuttin, Lew, et al., 2008; Millán, Renkens, Mouriño, & Gerstner, 2004). The mentioned systems receive high level commands from the user and move in an optimum way depending on the scenario.

The purpose of this work is to check the usefulness of an asynchronous system that lets the user move freely and in a continuous way in a VE using three low level commands (move forward, turn right, and turn left). The control is achieved with the execution of only one MI task. The new system waits in an NC state until subjects voluntarily enter the IC state. In such a state, subjects are offered a graphical interface with three navigation commands (move forward, turn right, and turn left) which they can choose by carrying out only one MI.

The present work is a continuation of the one presented in Velasco-Álvarez and Ron-Angevin (2009). In that work, the paradigm was first evaluated as if it were a synchronous system (the users were told which command they should select, and when to do it), with interesting results: a false positives (FP) rate of only 2.22% (i.e., undesired changes to the IC state), and an accuracy of 94% in the selection of the correct command. Those results showed that the paradigm could be used in a safe way, so the next step consisted of adapting it to approach a BCI that enabled the user to navigate freely in a continuous way, letting the subject precisely control each movement.

2 Methods

2.1 Subjects and Data Acquisition

Three healthy right-handed subjects participated in the study: S1 (female, age 19), S2 (male, age 25), and S3 (male, age 28). S2 and S3 had previous BCI experience.

The EEG was recorded from two bipolar channels. The active electrodes were 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. The ground electrode was placed at the FPz position. Signals were 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.

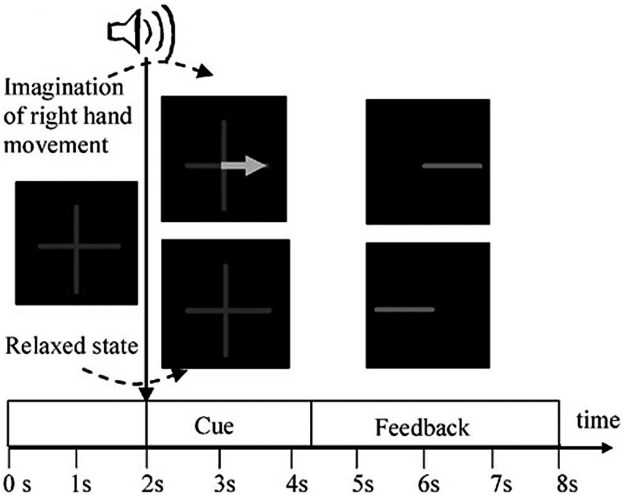

Figure 1. *Timing of one trial of the experiment with feedback. For the first 2 s there is no cue, and subjects stay relaxed. At t = 2 s, a short beep sounds and the cue indicating the mental task to be carried out is shown until t = 4.25 s. Then, until the end of the trial (t = 8 s), the feedback is presented as a horizontal bar extending to the left or the right.*

2.2 Initial Training

Although two of the subjects had experience in BCI, they all underwent two initial training sessions for calibration and training purposes. The training protocol was the same as that used in Ron-Angevin et al. (2009), which is based on that proposed by the Graz BCI in Guger et al. (2001). It consisted of two sessions, the first without and the second with feedback. The first session was used to set up classifier parameters (weight vector) for the next feedback session and the navigation sessions. During each session, subjects were instructed to carry out four experimental runs consisting of 40 trials each. The training was carried out discriminating between two mental tasks: mental relaxation and imagined right hand movements (20 of each type, randomly distributed). The duration of each trial was 8 s, and each trail started again after a pause, ranging from 0.5 to 3 s (randomly distributed). Subjects were looking at a large screen (2 × 1.5 m) placed at a distance of 3 m. The timing of the training is shown in Figure 1. F1

The trial began with the presentation of a cross in the center of the screen, indicating that subjects should stay as relaxed as possible. At 2 s, a short beep signaled the beginning of the mental task to be carried out. The appearance, for 2.25 s, of an arrow on top of the cross pointing to the right was the cue for subjects to imagine continuous movement of the right hand. Otherwise, subjects had to stay in a relaxed state. In the case of a feedback session, at 4.25 s the feedback stimulus was presented for 3.75 s. This consisted of a horizontal bar which extended online further to the right or left depending on the classification result.

2.3 Signal Processing

For signal processing, the scheme used is that proposed by Guger, Edlinger, Harkam, Niedermayer, and Pfurtscheller (2003). No online artifact detection was used. The feature extraction consisted of estimating the average band power 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 were averaged, obtaining an estimation of the band power for an interval of 500 ms. The reactive frequency band was manually selected for each subject, checking the largest difference between the power spectra of two 1 s intervals (a full description of how to determine the frequency band can be found in Pfurtscheller, 1999): a reference interval (0.5–1.5 s) and an active interval in which a mental task took place (6–7 s). The obtained values of these bands were: 9–11 Hz, 10–14 Hz, and 7–10 Hz for subjects S1, S2, and S3, respectively. The classification was based on linear discriminant analysis (LDA). Signal processing was done in MATLAB.

For each session, the error time course was computed with a 10 times 10-fold cross validation of a linear discriminant for each time point $t = 500$ ms (more detail about how to compute the error time courses can be found in Guger et al., 2001). In sessions without feedback, the extracted feature parameters of the classification time points with the lowest classification error were used to set up the LDA classifier parameters for the following session with feedback. In the feedback sessions, the LDA classification result was converted online to the length L of the feedback bar. The length L was updated on the screen every four samples, that is, each $t = 31.25$ ms, to make feedback as continuous as possible. A negative/positive value of L was translated into a left/right extension of the feedback; therefore, the trial was classified as a relaxed/right trial.

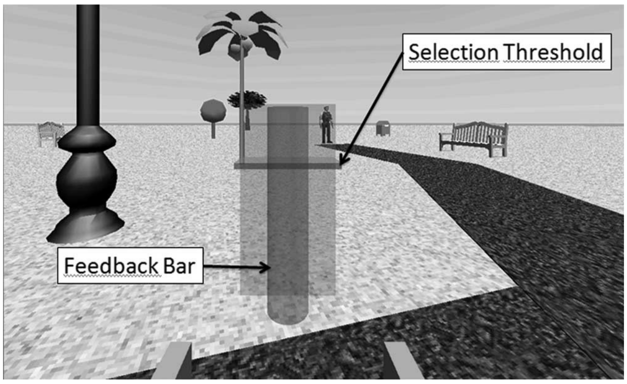

Figure 2. *NC interface. A vertical bar shows the feedback. When the subject carries out the MI task, it extends upward and reaches the selection threshold in order to change to the IC state.*

The updating of the bar length every four samples also marked the timing of the computation iterations for the later online signal processing in the navigation sessions.

2.4 Paradigm Description

The VE created to be navigated through consists of a park where subjects can move freely with a virtual wheelchair (the point of view is bound to it; Figure 2 and Figure 3) but they need to avoid several obstacles (trees, bushes, lamps, benches, and others). F2 F3

The interaction with the VE is achieved in an asynchronous way, as follows: the subject can switch from an NC state to an IC state using the same mental task used to control the virtual wheelchair. The system waits in an NC state in which an NC interface is shown. The NC interface allows the 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. Subjects can switch from the

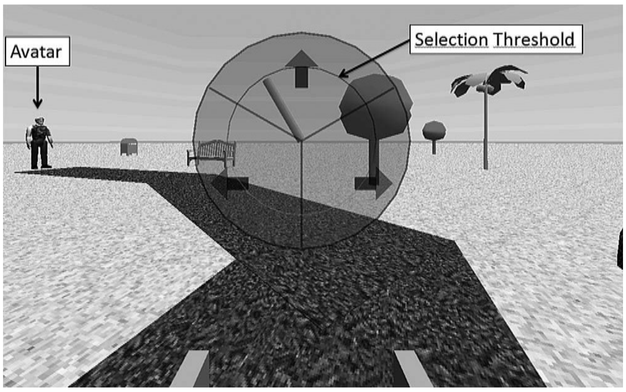

Figure 3. *IC interface. The feedback bar rotates, pointing to the three possible commands to be chosen. To select a command, the user carries out the MI task to extend the bar and reach the selection threshold. The objective of the trial is to reach the avatar placed at the end of the path.*

NC state to the IC state carrying out only one mental task. The system is calibrated with the parameters from the previous sessions, so it is able to recognize the MI task (otherwise, the system classifies the subject's mental state as the rest state). The change from the IC to the NC state is performed automatically after some defined time in which the subject has not generated any command.

The NC interface (see Figure 2) consists of a semi-transparent vertical blue bar placed in the center of the screen. The bar length is computed every 31.25 ms (four samples, as in the case of the training sessions with feedback) as a result of the LDA classification: if the classifier determines that the mental task is a right hand MI, the bar extends; otherwise (rest state) the bar length remains at its minimum size. When the length exceeds a subject dependent selection threshold for a given selection time (also chosen by each subject), the system changes to the IC state. Once the selection threshold is exceeded, the bar color changes immediately to yellow and then progressively to red as long as the length is above the selection threshold until the selection time has passed. If the length is temporarily lower than the selection threshold, the bar color does not change unless it lasts less than the selection threshold for a reset time; in this case the color turns again to blue, and the selection time is reset. The color changes represent another kind of feedback that enables subjects to know how long (approximately) they still need to succeed in their selection.

The mentioned parameters used to control the interface (selection time, reset time, selection threshold) were adjusted by an operator during the first few minutes of the first session. During this time, the operator changed the values until the subjects felt comfortable. However, none of the subjects wanted to change the values of the reset time or the selection threshold, so they kept them at the default values: 1 s and 70% of the maximum level, respectively. Regarding the selection time, the chosen values were 1.2 s, 0.8 s, and 1 s for S1, S2, and S3, respectively.

The IC interface (see Figure 3) is similar to the one presented in Velasco-Álvarez and Ron-Angevin (2009): a circle divided into three parts that correspond to the possible navigation commands (move forward, turn right, and turn left), with a bar placed in the center of the circle that 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 parameters. In the IC interface, another threshold is defined (the stop threshold), which is not visible for the user. When it is exceeded, the bar stops its rotation in order to help the subject in the command selection. This value was also adjusted in the previous period of the first session. All the subjects kept it at 60% of the maximum level. The rotation speed is fixed at 40 deg/s, so it takes 9 s to complete a turn if there is no stop.

The system presented in this paper is based on the one shown in Velasco-Álvarez and Ron-Angevin (2009). The main difference from that one is the kind of movement that the selection of a command entails. In that work, the subject moved through the VE in a discrete way (turning 90° right or left, or moving forward by a fixed distance) and once the movement had finished, the system changed again to the NC state. In the present case, the interaction is more natural, as the movement is now not discrete but continuous.

Once a command is selected, the virtual wheelchair starts moving forward at a fixed speed of 0.62 m/s or turning left or right at 11.25 deg/s (it takes 32 s to complete a turn). Similar to what happened in the command selection, the movement is maintained as long as the bar length is above the selection threshold (this means that the subject is still carrying out the MI mental task). If the bar is temporarily under this threshold (less time than the reset time), the movement stops, but the system allows the subject to continue the same movement if the bar again exceeds the selection threshold. While it happens, the bar keeps its red color to indicate this possibility to the subject. In the case that the bar remains under the selection threshold longer than the reset time, the bar changes its color to blue and continues rotating so that the subject can select a command again. The position of the rotating bar does not change; it takes its rotation up again 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. Furthermore, this fact helps in the solution of another problem. In Friedrich et al. (2009) a four-choice BCI was controlled with only one MI task in a way quite similar to the one presented here. In that study, they concluded that the error probability of each option was dependent on its position in the interface (the same conclusions were obtained in Velasco-Álvarez & Ron-Angevin, 2009). In those works, the commands were always offered in the same order. Taking the rotation up from the point at which it last stopped balances this position dependent error.

When subjects want to change to the NC state again, they must leave the bar to complete two turns without selecting any command and then the system switches to the NC state. In Figure 4, an example sequence is presented in which the user changes from the NC state to the IC state and performs a movement turning right in two steps.

To increase the degree of immersion, as in the training sessions, the VE was projected on a large screen (2 × 1.5 m) and subjects were placed at a distance of 3 m. The VE was created with VRML 2.0, and its interaction with MATLAB was achieved using the MATLAB Virtual Reality Toolbox.

2.5 Navigation Sessions

In the study presented in Velasco-Álvarez and Ron-Angevin (2009), an evaluation of the paradigm was done regarding the ability of subjects to change from one state to another and to select a series of commands. There, the reader can check the high accuracy rates obtained in both cases. The aim of this study is to show that the paradigm can be used to navigate through a VE under realistic conditions. To this end, the experiments carried out by the subjects consisted of several runs in which they had to follow a prefixed path to reach an avatar placed at the end of it as fast as they could. In order to compare their performance in this task, they were forced to stay within the limits of a 2 m wide path. If the movement led the subjects out of this path, the wheelchair collided with an invisible wall, so the movement finished. 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 was wide enough to allow the users to maneuver in an easy way, as the dimensions of the wheelchair were 70 × 40 cm. The total length of the path was 29 m, distributed in three sections of 5 m and two of 7 m length. These sections were placed so that subjects had to achieve at least two turns of approximately 45° in each direction (see Figure 5 [a, b, and c]). In principle, the experiment consisted of three runs for each subject.

After these sessions, one of the subjects (S2) participated in a longer version of the same experiment, with an extension consisting of another four 7 m long sections (total length 57 m) distributed in a way that forced the subject to carry out four turns in each direction (see Figure 5 [d]).

3 Results

In this section we present the results obtained in the navigation sessions.

Table 1 (top) shows the results of the three subjects in

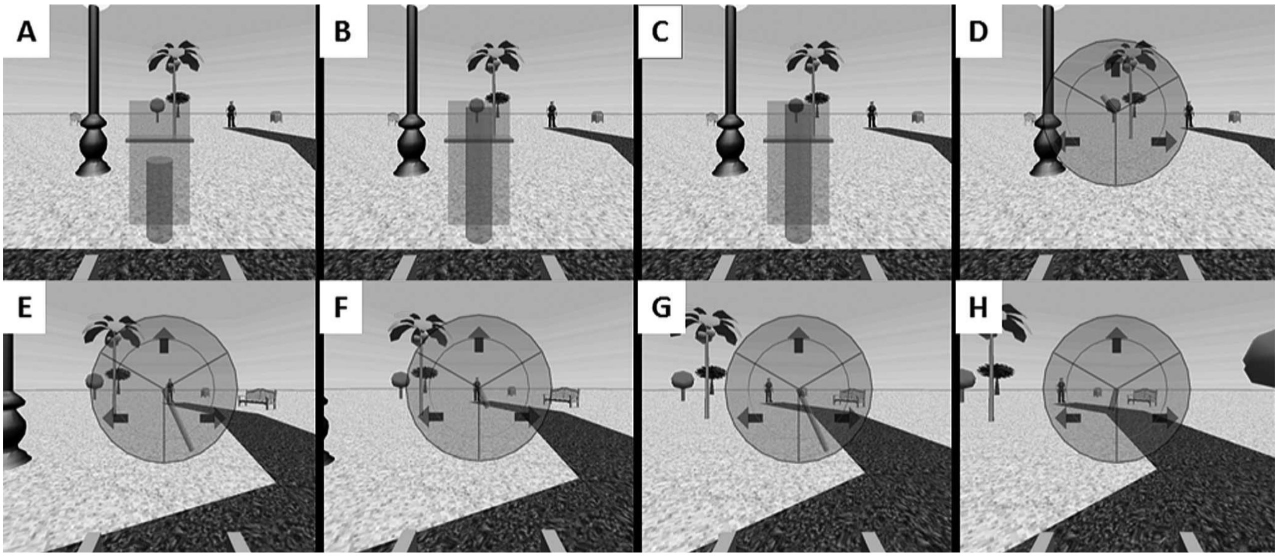

Figure 4. *Example sequence. (a) The system waits in the NC state. (b) The subject carries out the MI task, and the feedback bar reaches the selection threshold and changes its color to a brighter one (yellow). (c) The bar stays above the selection threshold, gradually darkening its color (to red). (d) The selection time passes and the system changes to the IC state. The bar starts rotating. (e) The subject has selected the command Right. The bar has stopped and, as in steps a to c, it has previously changed from a bright color to a darker one. While the bar is above the selection threshold, the wheelchair turns to the right. (f) The bar length is under the selection threshold, the movement stops, but the bar keeps its red color and does not move (if the reset time does not pass). (g) The bar is again above the selection threshold, and the wheelchair continues its movement to the right. (h) The bar length has lasted longer than the reset time under the selection threshold, the movement has finished, and the bar has turned blue again and has taken its rotation up again from the point where it stopped.*

the same scenario. Unfortunately, one of the subjects (S1) could not finish the experiment for personal reasons, so we show only two runs for this subject. In Table 1 (bottom), the results obtained for S2 in the second VE are presented. The different paths that the subjects followed can be found in Figure 5. In order to establish a criterion to compare the performance of the subjects, in both cases a reference path is presented. This path was achieved with the same paradigm, but an operator used a function generator to manually emulate the brain activity, so the bar length could be easily controlled. A similar comparison can be found in Millán et al. (2004). This path can be considered to be close to the optimal path that can be achieved with this paradigm. The reference path is shown in the figures with a white line.

Table 1 presents, for each subject and run, the time needed to reach the avatar. In the next four columns, the number of commands of each type that subjects selected is presented, as well as, within parentheses, the number of commands used by the operator in the reference path (considered as a minimum). At this point the way in which the command selection has been considered must be described. As has been described in the previous section, a command can be selected when the bar is pointing at it, and after the movement has finished, the bar continues its rotation from the same point. Thus, when a subject chooses the same command several times in a row (without the bar completing another turn), it has been considered as only one selection in the tables, so it can be compared with the reference path. In the Collisions column, the number of times that the subject collided with the border of the path is presented. The Extra turns column shows how many times the bar completed a turn without the subject selecting a command. It is worth mentioning that these extra turns only count as one extra turn, because in the case that more turns were completed without a command, it would lead to the NC state. The next column, Misses (%), is calculated as the number of extra turns divided by the total number of commands; this column gives an idea of how well subjects could keep control in the IC state. The IC changes column counts how many times the subject needed to change from the NC to the IC state (the first one is mandatory because the subjects started in the NC state). Finally, the last column shows the mean time needed to achieve these changes from one state to the other. In Table 1, the reader can find for these results the mean values calculated for each subject, as well as the total and mean values for all the runs.

In Figure 5 the reader can compare the different paths carried out by the subjects (the starting point is on the right side) with the reference path, which is shown in white. Everyplace where a collision happened is noted with an arrow. It has been mentioned before that selecting a command can lead to several movements of the same type if the reset time does not pass, or if the subject gets to choose the same command in the same turn. Although those selections appear as only one command in the tables, each step is marked with a symbol in the path (even when in a straight line), which gives a general idea of how well the subjects controlled the advance.

4 Discussion and Conclusion

Regarding the results, the mean values of the times needed to reach the objective (taking into account

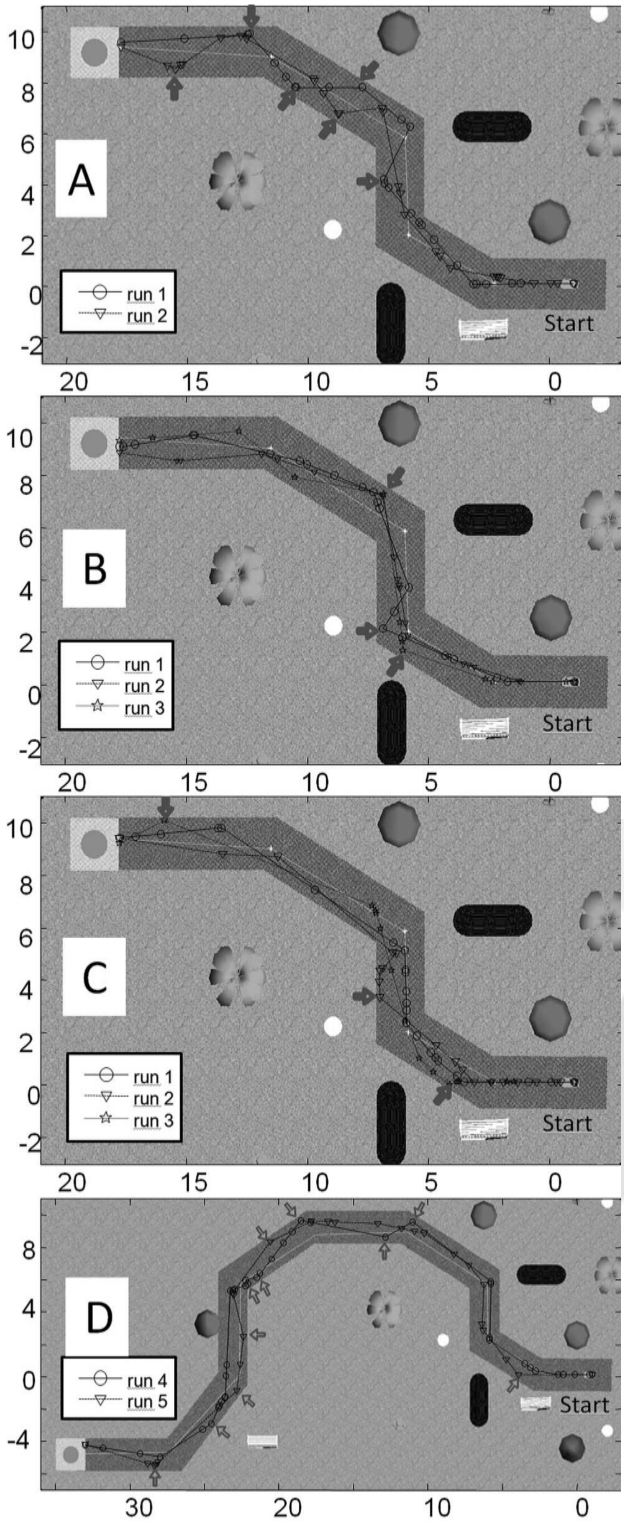

Figure 5. *Different paths followed by the subjects. They were forced to stay within the limits of the dark corridor. The white lines mark the reference path. The gray arrows point to the place where collisions happened. (a) First path for S1. (b) First path for S2. (c) First path for S3. (d) The results for the second path of S2.*

Table 1 *For Every Subject and Run (Top Part for the First Path and Bottom Part for the Second): Time Needed to Complete the Path, Time (s), Number of Commands of Each Type Used (F, R, L, and T for Forward, Right, Left, and Total, Respectively), Number of Collisions Detected (Collisions), Number of Extra Turns Taken (Extra Turns), Percentage of Extra Turns Calculated Over the Total Number of Commands, Misses (%), Number of Changes to the IC State (IC Changes), and Mean Time Employed in the Changes of State, T_{NC} (s).*

Subject	Run	Time (s)	Commands				Collisions	Extra turns	Misses (%)	IC changes	T_{NC} (s)
			F (5)	R (2)	L (2)	T (9)					
First VE, all three participants											
S1	1	656	10	10	6	26	4	4	15.4	1	10.9
	2	617	11	7	6	24	2	4	16.7	1	6.6
	Mean	636.5	10.5	8.5	6	25	3	4	16	1	8.2
S2	1	624	11	5	5	21	1	6	28.6	2	7.9
	2	589	11	6	3	20	0	8	40	1	9.1
	3	364	7	3	4	14	2	2	14.3	1	11.7
	Mean	525.7	9.7	4.7	4	18.3	1	5.3	28.9	1.3	9.1
S3	1	580	9	5	6	20	0	1	5	1	18.8
	2	667	10	9	6	25	1	3	12	1	4.5
	3	527	7	4	5	16	2	1	6.3	1	7.8
	Mean	591.3	8.7	6	5.7	20.3	1	1.7	8.4	1	10.4
All	All		76	49	41	166	12	29		9	
	Mean	578	9.5	6.1	5.1	20.8	1.5	3.6	17.3	1.1	9.5
Second VE, Participant S2 only											
S2	4	1282	23*	14**	11**	$48^{\dagger}$	6	8	16.7	4	18.4
	5	807	15*	7**	10**	$32^{\dagger}$	5	6	18.8	1	4.2
	Mean	1044.5	19	10.5	10.5	40	5.5	7	17.5	2.5	15.6

* Nine commands.

** Four commands.

† Seventeen commands.

the length of both paths) show that subjects took 19.4 s on average to advance 1 m.

Contrasting the results for the number of commands with the reference path, it is worth mentioning that subjects needed a total of 246 (166 + 80) commands, while the reference paths would have needed 106 (eight runs with nine commands and two runs with 17 commands). This means that subjects needed 2.32 times the number of commands needed when using a manual control.

The number of collisions detected must be highlighted. Out of a total of 114 advance commands, 23 would have led the subjects out of the fixed path (20%). This result is perceptibly higher than the one reported in the previous study (Velasco-Álvarez & Ron-Angevin, 2009) in relation to the error rate in the command selection (6%). The reason may be related to the instructions given to the subjects, whose objective was to reach the avatar as soon as possible. As they knew that a collision would make the movement stop, it is possible that they chose to move forward while the system allowed them. Another possible reason is the subjective perception of the distance in the VE. The wheelchair could move to within 0.25 m of the border of the path, but from the point of view of the user in the VE it was not easy to determine where this limit was.

The results related to the users' ability to control the transitions between states show that only four nondesired changes to the NC state happened (subjects were asked to complete the path as soon as possible, so every change to the NC state can be considered to be undesired) out of a total of 246 commands, giving a rate of 1.6%. Another interesting result is that the majority of the commands were chosen in the first turn of the bar; only 17%, Misses, needed one extra turn.

The last column shows the mean time needed to switch from the NC to the IC state. Here again, the results (9.5 s and 15.6 s) are higher than those obtained in the evaluation sessions in Velasco-Álvarez and Ron-Angevin (2009; 5.78 s). The reason for this behavior can be found in the fact that in this study most cases only needed one change in the IC changes column and this happened at the beginning of the trial, when subjects were still getting used to the system.

The usability of the system is supported by the numerical results, and can be intuitively comprehended by looking at the graphical representations of the paths followed by the users, which adapt reasonably well to the reference path. Although the number of subjects is not high enough to deduce strong conclusions, the preliminary results of the experiment suggest that it is possible to navigate through a VE using only one MI task, which keeps the classification accuracy at its maximum (by means of the classification of only two states: MI vs. rest). The mapping of these mental tasks into a higher number of commands makes it possible to move freely 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, a fourth command, to move backward, could be included).

Although it was not the main aim of this work, we will include next a brief discussion about the performance evolution of subjects over time. A comparison of that performance can be established in terms of the time and the total number of commands needed to reach the objective. These values are shown in Table 1 in the Time and Command columns. Only the second run of subject S3 has worse performance than a previous one. What is more, this subject improved his results in the last run compared to the other two runs.

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. Our group has recently been working on the development of VE with more powerful graphical tools, because the use of VRML 2.0 and the MATLAB Virtual Reality Toolbox has serious limitations in relation to realism (as it is the case of stereoscopic vision).

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 an experimental situation or a real wheelchair. In such a scenario, the need for a graphical interface to control the system can be a drawback for paralyzed people who cannot control the movements of their eyes. 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.

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