Asynchronous Brain-Computer Interface to Navigate in Virtual Environments Using One Motor Imagery

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Abstract. A Brain-Computer Interface (BCI) application focused on the control of a wheelchair must consider the danger which a wrong command would involve in a real situation. Virtual reality is a suitable tool to provide subjects with the opportunity to train and test the application before using it under real conditions. Recent studies aimed at such control let the subject decide the timing of the interaction, those are the so-called asynchronous BCI. One way to reduce the probability of misclassification is to achieve control with only two different mental tasks. The system presented in this paper combines the mentioned advantages in a paradigm that enables the control of a virtual wheelchair with three commands: move forward, turn left and turn right. The results obtained over three subjects support the viability of the proposed system.

Keywords: Brain-computer interface (BCI), virtual environment (VE), navigation, asynchronous, motor imagery (MI), mental tasks.

1 Introduction

A Brain-Computer Interface (BCI) is a system that enables a communication that is not based on muscular movements but during brain activity. This activity can be measured through electroencephalographic (EEG) signals. Several EEG signals can be detected, resulting in different types of BCI. Sensorimotor rhythm-based BCIs (SMR-BCI) are based on the changes of μ and β rhythms [1]. These rhythms correspond to specific features of the EEG signals characterized by their frequencies that can be modified by voluntary thoughts. When a person performs a movement, it causes a synchronization/desynchronization in this activity (event-related synchronization /desynchronization, ERS/ERD) which involves a μ rhythm amplitude change. However, the outstanding property of these signals is their behaviour when someone merely considers movement (motor imagery, MI), because this causes a similar amplitude change [2]. This relevant characteristic is what makes SMR suitable to be used as input for a BCI.

The main aim of the BCI research is to provide severely disabled people with an alternative non-muscular communication channel. Researchers have worked to develop many applications to improve the quality of life of these patients, for whom a BCI represents a viable channel to interact within their environment. Among these

applications, there are some where subjects take control of a real wheelchair in an experimental situation [3]. 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. In order to control a wheelchair, several paradigms can be used. We will mention some of the works related to this field, in the following paragraph.

Some studies describe a system in which the wheelchair moves in only one direction (move forward) [4], [5]. 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 [6], 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 [7] with three possible commands (three MI tasks): turn left, turn right and move forward. 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 bind the number of commands to the number of mental tasks. Nevertheless, it has been reported in several studies ([8], [9]) that the best classification accuracy is achieved when only two classes are discriminated. For this kind of applications, the aim of which is to control 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. 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 moments given by the system. Recent research tends to let the subjects decide when to control the system [3]-[7], which is a more natural form of interaction. These systems, called self-paced or asynchronous, distinguish between two states: (i) a non-control (NC) state in which subjects can be involved in a mental activity different to controlling the BCI, and (ii) an intentional control (IC) state, in which subjects can control the system by specific mental tasks [5], [7]. Subjects switch voluntarily the state they are in.

The purpose of this study is to present an asynchronous paradigm to improve the synchronous system proposed in [10]. The new system waits in a NC state, until subjects voluntarily enter the IC state. In such state, subjects are offered a graphical interface with three navigation commands (move forward, turn right and turn left) they can choose carrying out only one MI. After a command is selected, the system performs the appropriate action and returns to the NC state.

2   Methods

2.1   Subjects and Data Acquisition

Three subjects (male, right-handed, age 24 ± 11.4), named S1, S2 and S3 participated in the study. They had all previous BCI experience.

The EEG was recorded from two bipolar channels. The active electrodes were placed 2.5 cm anterior and posterior to electrode position C3 and C4 (right and left

hand sensorimotor area, respectively) according to the 10/20 international system. The ground electrode was placed at FPz position. Signals were amplified by a four channel Coulborn V75-08 amplifier and then digitazed at 128 Hz by a 12 bit resolution data acquisition card DAQCard-6025E (National Instruments).

2.2 Initial Training and Signal Processing

Although all subjects had experience in BCI, they underwent two initial training sessions for calibration purposes. This training was the same as the used in [10], and was based in the paradigm proposed by the Graz group (see [11] for details), in which a bar extended according to the mental task carried out (relaxed state or right hand MI). The training protocol consisted of two sessions: a first one without feedback and the other one providing continuous feedback. An offline processing of the first session (see [10] for details) made possible to determine the parameters for the feedback session. The same parameters were used to calibrate the system for the VE exploration sessions. This processing is based in the procedure detailed in [12], and consisted of estimating the average band power of each channel in predefined, subject specific reactive frequency (manually selected) bands at interval of 500 ms. In the feedback session, the length of the bar was computed on line every 31.25 ms as a result of a Linear Discriminant Analysis (LDA) classification. The trial paradigm and all the algorithms used in the signal processing were implemented in MATLAB

2.3 Virtual Environment Exploration Sessions

Paradigm Description. The VE created to navigate through consisted of a park where subjects could move freely (Figures 1 and 2) but needed to avoid several obstacles (trees, bushes, lamps, benches and others).

The system waited in a NC state in which it an NC interface was shown. The NC interface enabled subjects to remain in the NC state (not generating any command) until they decided to change to the IC state, where the control was achieved through the IC interface.

The NC interface consisted of a semi-transparent vertical blue bar placed in the centre of the screen. The bar length was computed every 62.5 ms as a result of the LDA classification: if the classifier determined that the mental task was right hand MI, the bar extended; otherwise (relaxed state), the bar length remained at its minimum size. When the length exceeded a subject dependant selection threshold (Figure 1) for a selection time (also chosen by each subject) the system changed to the IC state. Once the threshold was exceeded, the bar colour changed immediately to yellow, and then, progressively to red while the length was above the threshold, until the selection time had passed. If the length was temporarily lower than the threshold, the bar colour did not change unless it lasted less than the threshold for a reset time; in this case the colour turned again to blue, and the selection time was reset. The colour changes represented another kind of feedback that enabled subjects to know how much time (approximately) they still needed to succeed in their selection.

The IC interface was similar to the one presented in [10]: a circle divided into three parts, which corresponded to the possible navigation commands (move forward, turn right and turn left), with a bar placed in the centre of the circle that was continuously

rotating clockwise. The subject could extend the bar carrying out the MI task to select a command when the bar was pointing at it. The way the selection worked in this interface was the same as in the NC interface, with the same selection and reset time and selection threshold. In the IC interface, another threshold was defined (stop threshold). When it was exceeded, the bar stopped its rotation in order to help the subject in the command selection. The rotation speed was fixed to 2.5 degrees every computation iteration, so it lasted 9 s to complete a turn if there was not any stop.

Once a command was selected, the subject moved in the VE as a consequence in a discrete way: it turned 90º right or left, or it moved forward a fixed distance (1 m in the VE) or until it collided with an obstacle. After the movement, the system changed again to the NC state. Subjects could choose a pause time in the changes between the two states.

To increase the degree of inmersion, the VE was projected on a large screen (2 x 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.
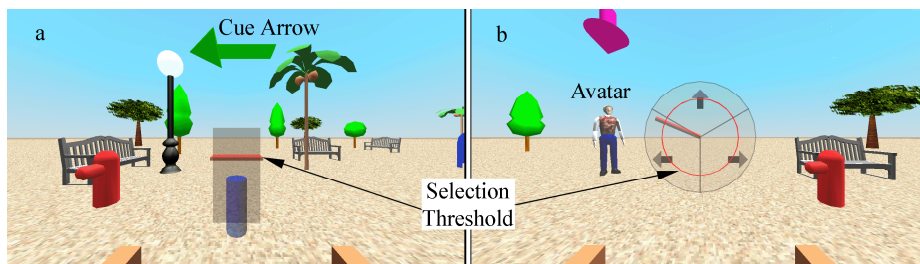

Fig. 1. NC interface (a) and IC interface (b)

Evaluation Sessions. One important issue in a BCI system is its evaluation. In an asynchronous system, in which subjects can freely select a command (whatever command, whenever they want), this evaluation is difficult to establish.

What we propose in this paper to evaluate our paradigm, is to use it firstly as a synchronous BCI, before letting subjects navigate in the VE. For this reason, after the initial training, subjects underwent an evaluation session, in which they were asked to select a series of commands after determined cues. The cue consisted of the colour change of an arrow at the top of the screen whose direction indicated which command should the subject select once he/she got the IC state (move forward, turn right or turn left). The initial colour was red, meaning that subjects should not yet change to the IC state. After a random time (2 – 5 s), the arrow colour changed to green, indicating that subjects should carry out the MI to change to the IC state.

The two main parameters measured in the NC state were true positive (TP) and false positive (FP) rates, which corresponded to an activation in the correct or incorrect moment (after the cue or before it), respectively. The nomenclature was taken from [13]. In the IC, the main measure is the performance error.

Each subject underwent a first run, which took approximately 10 minutes, so that they could become familiar with the paradigm, and the system could be calibrated. The calibration consisted of the choice of the selection, pause and reset time and the selection and stop threshold adequate to each subject. The same day they participated in two evaluation runs. In a separate day they had other three runs. Each run consisted of 21 trials (7 of each command, randomly distributed).

Free Navigation Sessions. After the system was evaluated, subjects participated in the sessions which represented the main aim of this study. They were asked to move freely through the VE to reach an objective: an avatar placed 24 m (Manhattan or grid-line distance) away from the subject's initial position. The objective of this test was to check the usefulness of the system, simulating the behaviour in a real environment. In these sessions, the only cue the system gave to the subjects was the relative position of the avatar, indicated by an arrow pointing in the direction of the objective in case it was not in the subjects' field of view. As users were not supposed to follow the same route, a command could be considered neither wrong nor correct, so the measures that were taken correspond to the number of commands and the time needed to reach the avatar.

3   Results

3.1   Evaluation Sessions

In the evaluation sessions, two points of view were taken into account. First of all, several parameters were measured for each subject, according to their performance in the NC state. In Table 1 the number of FP activations is shown for each subject and run. The parameter FP (%) was computed over 105 trials. In the two last columns, we show the mean time subjects used to change to the IC state when they did it after (Mean TP T_{NC}) and before the cue (Mean FP T_{NC}).

Table 1. Results for the NC state during the evaluation sessions

| Subject | FP | | | | | | FP (%) | Mean TP T_{NC} $\pm$ SD (s) | Mean FP T_{NC} $\pm$ SD (s) |
| | Run | | | | | All runs | | | |
	1	2	3	4	5				
S1	0	0	0	1	0	1	0.95	6.86 $\pm$ 0.97	1.69 $\pm$ 0.00
S2	1	0	0	1	0	2	1.69	7.02 $\pm$ 1.22	1.14 $\pm$ 0.89
S3	2	0	0	2	0	4	3.81	3.41 $\pm$ 0.35	2.46 $\pm$ 0.52
All	3	0	0	4	0	7	2.22	5.78 $\pm$ 0.56	1.97 $\pm$ 0.63

These times were measured from the beginning of the trial in the FP and from the system cue in the TP. These times include the selection time chosen by each subject in the calibration session: 1.3 s, 1 s and 1.2 s for S1, S2 and S3 respectively.

Secondly, subjects' performance in the IC state is shown in Table 2. These measures do not consider if the change from NC to IC was due to a TP or a FP. They represent the subjects' capability to select the commands they were asked. We show the number of errors they made in each run and for each kind of command they were asked, as well as the total number of errors. The parameter Error (%) is computed over 35 trials for each command (105 trials for all of them). The last two columns present the time that subjects needed to select a command starting: i) at the moment the bar pointed to this one (Mean block T_{IC}) and ii:) when the IC interface was shown (Mean total T_{IC}).

Table 2. Results in the IC state in the evaluation sessions

| Subject | Command | Errors | | | | | | Error (%) | Mean block $T_{IC} \pm$ SD (s) | Mean total $T_{IC} \pm$ SD (s) |
| | | Run | | | | | All runs | | | |
		1	2	3	4	5				
S1	Forward	0	0	0	0	1	1	2.86	4.46 ± 0.77	5.91 ± 1.95
	Right	0	0	0	0	0	0	0	4.69 ± 0.8	12.04 ± 2.93
	Left	1	0	0	1	1	3	8.57	4.41 ± 0.83	13.86 ± 1.38
	All	1	0	0	1	2	4	3.80	4.52 ± 0.45	10.55 ± 1.42
S2	Forward	0	0	0	0	0	0	0	3.35 ± 0.74	11.8 ± 3.92
	Right	1	0	0	1	0	2	5.71	3.2 ± 0.6	17.7 ± 7.6
	Left	2	0	1	0	1	4	11.42	4.07 ± 0.76	18.8 ± 4.48
	All	3	0	1	1	1	6	5.71	3.58 ± 0.4	15.97 ± 3.16
S3	Forward	0	0	0	0	0	0	0	3.95 ± 0.68	6.7 ± 1.62
	Right	2	0	0	1	0	3	8.57	3.18 ± 0.48	7.63 ± 1.17
	Left	2	1	0	3	0	6	17.1	3.27 ± 0.48	10.86 ± 0.76
	All	4	1	0	4	0	9	8.57	3.5 ± 0.32	8.06 ± 0.86
All	All	8	1	1	6	3	19	6.03	3.88 ± 0.23	11.56 ± 1.24

3.2 Free Navigation Sessions

The results obtained in the navigation sessions are shown in Table 3, and the different paths subjects followed in Figure 2. The table presents the number of commands of each type that subjects selected. Mean T_{NC} and Mean total T_{IC} show the mean time they needed to get the IC state and to select a command respectively. Finally the total time used to reach the avatar is presented (T_{TOT}).

Table 3. Results in the free navigation sessions

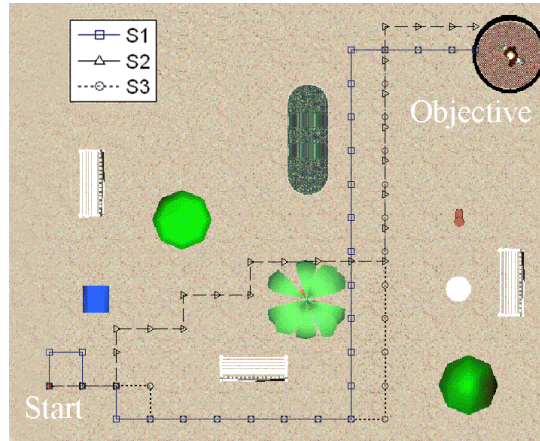| Subject	Forward	Right	Left	Total	Mean $T_{NC} \pm$ SD (s)	Mean total T_{IC} (s)	T_{TOT} (s)
S1	27	7	6	40	4.62 ± 0.86	5.96	638
S2	24	5	4	33	4.41 ± 1.23	8.98	619
S3	25	3	2	30	3.86 ± 0.83	4.74	420

Fig. 2. Paths covered by the three subjects

4   Discussion and Conclusion

Three trained subjects participated in the study. Firstly they underwent two training sessions for calibration purposes. Afterwards they were able to remarkably control a virtual wheelchair within the first two sessions using the proposed paradigm. This paradigm combines the main advantage of a system with several classes (i.e. to have different control commands to ease the way of interaction) with the high classification accuracy which provides a system with only two mental tasks. We have presented an asynchronous BCI, in the sense that it is the subject who gives the cue to the system when he/she wants to achieve control.

Although the number of subjects is not high enough to deduce strong conclusions, the results of the evaluation sessions show that with a very low FP rate (2.22%), subjects could select the commands they wanted with an error rate close to 6%.

Another important fact is that the mean time needed to get the IC state and to select a command among three (4.33 and 6.56 s respectively, averaged over the three subjects during the navigation session) is quite low to consider the paradigm as useful. In these sessions subjects showed more motivation, and maybe for this reason, they achieved an error rate lower than 1%.

There is a remarkable difference in the time that S3 needed to reach the avatar in front of S2 and S1. It can be explained because S3 chose the shortest route (in term of number of commands) and had a lower T_{NC} and T_{IC} time.

It must be mentioned that from a total of 103 commands (for all subjects), only one was considered incorrect by subjects (the first advance of S1), and only one collision occurred (the fourth advance of S2). The average selection time in these sessions was noticeably lower than in the evaluation sessions because of the higher appearance rate of the command forward, which, due to its position in the IC interface, needed less time to be selected.

The recent work of our group is aimed at extending the study to a continuous movement, instead of the discrete advances and turns presented in this paper.

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