# BCI-based Navigation in Virtual and Real Environments

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**Abstract.** A Brain-Computer Interface (BCI) is a system that enables people to control an external device with their brain activity, without the need of any muscular activity. Researchers in the BCI field aim to develop applications to improve the quality of life of severely disabled patients, for whom a BCI can be a useful channel for interaction with their environment. Some of these systems are intended to control a mobile device (e. g. a wheelchair). Virtual Reality is a powerful tool that can provide the subjects with an opportunity to train and to test different applications in a safe environment. This technical review will focus on systems aimed at navigation, both in virtual and real environments.

**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 not based on muscular movements but on brain activity. Several methods are used to detect brain activity, some of them by using electrodes implanted in the brain or cortex. However, the most frequently used methods are those in which the recording of the signals is obtained through 'non-invasive' means, i.e., the electrodes are not implanted in the brain but placed superficially on the scalp. The brain signals obtained through these methods are called Electroencephalographic (EEG) signals. Several kinds of EEG signals can be detected, resulting in different types of BCIs. Some of them analyze the brain's response to given stimuli; those are the BCIs based on 'Event Related Potentials' (ERPs) [1] and their steady-state versions, in both the visual [2] and the auditory [3] modalities. Other systems process the EEG resulting from voluntary thoughts; among those, the most used are the BCIs based on 'Sensorimotor Rhythms' (SMR). These rhythms are specific EEG signals characterised by its frequencies. The main objective of research in the BCI field is to provide disabled people with an alternative communication channel, not based on muscular activity. Due to different causes, such as Amyotrophic Lateral Sclerosis (ALS), brain paralysis or several brain damages, people can arrive in a state in which they lose their motor capability (usually the control of the eyes remains) but they retain their sensory and cognitive skills. This is the so-called ‘locked-in state’ (LIS). If all muscular control is lost, then this state is referred to as ‘complete locked-in state’ (CLIS). Current research is unable to conclude whether or not, in such a state, cognitive skills remain present [4].

Researchers in this field endeavour to develop different applications that can improve the quality of life of these patients establishing alternative communication channels. Research studies have been developed in several areas, such as those dedicated to provide amputee patients with neuroprosthesis movement [5], speller devices [6], ‘smart home’ control applications [7], EEG-controlled Web browsers [8], training [9] or systems focused on the control of a mobile device (such as a wheelchair). Among the latter, some systems allow subjects to control a real wheelchair in an experimental scenario [10], or a small robot in a real environment that simulates a house [11]. However, in most studies, the subjects participate in experiments with a simulated wheelchair in a Virtual Environment (VE). The objective of this paper is to review the BCI systems aimed at navigation, both in virtual and real environments.

## 2 BCI and Virtual Reality

Before people can use a wheelchair in a real environment, it is necessary to guarantee that they have enough control to avoid dangerous situations. Virtual Reality (VR) is a powerful tool for providing subjects with the opportunity to train with and to test an application in a safe environment. Another advantage of navigating through a VE is that every detail on the environment is under control, so the experiments can be carried out in many different situations and can provide much information on multiple aspects of subjects’ performance. On the other hand, VR is used too in order to get a highly immersive scenario that can affect to the results. Regarding the training process, Pineda [12] cites several factors that can enhance learning in a BCI: i) the subject’s active engagement, ii) frequent interaction with the environment, iii) feedback presence and iv) existence of links to real world context. VR encourages subjects to be motivated, it allows a suitable interaction, it can provide many kinds of feedback and it can reproduce real world environments. Some examples of BCIs using VR for reasons other than navigation are given in the following.

In [13], a virtual arm appears in a screen placed next to where the subject’s real arm is. The representation of movement of the virtual limb is called ‘bio-feedback’. In [14], a different kind of feedback is given; a brain is shown on a screen so that the subjects can see their own brain activity. In the same work, two VR BCI-games are presented, one using MI to make a spaceship levitate and the other using Steady-State Visual Evoked Potentials (SSVEP) to keep an avatar balanced. The training performance of a system using classic feedback and another using VR are compared in [15]; the conclusion is that VR enhances performance. The work in [12] uses SMR to make an avatar turn right or left in a video game, whilst other movements are controlled via a keyboard. The popular game World of Warcraft has been adapted to be controlled via a BCI system [16].

# 3 Navigation in Virtual Environments

Early BCI systems aimed at navigation were usually system-paced or asynchronous. In those systems, the subject moved through the VE to fixed locations (determined by the system) and then he was asked to select a new movement. The system showed some kind of signal to cue subjects when the action could take place. Most recent applications let subjects to control the timing of the interaction. These systems are called self-paced or asynchronous. One main advantage of the asynchronous systems is that the freedom to move is usually higher, as subjects do not need only to move among specific locations, but they move freely through the VE.

## 3.1 Synchronous systems

Among the synchronous systems, Friedman [17] focuses on the experience of the navigation in highly immersive environments (using a Cave Automatic Virtual Environment, CAVE). Subjects carried out two experiments using two mental tasks: they changed their point of view in a virtual bar; or they moved forward in a virtual street.

A similar experiment is presented in [18]; a navigation paradigm with two mental tasks to move through fixed paths in a virtual apartment is proposed. The right or left hand motor imagery (MI) enabled subjects to select two different commands at each junction, out of three possible commands: turn right or left and move forward.

In [19], subjects moved right or left in a virtual street with both hands MI tasks.

Another work that used SMR to navigate is [20], where subjects performed one MI task to extend a rotating bar that pointed to four possible commands in order to select them; two mental tasks are mapped this way into four navigation commands.

Bayliss in [21] randomly flashed several elements in a virtual apartment, thus evoking the P300 potential in the well-known oddball paradigm (necessarily synchronous). After the selection, an avatar moved towards the object and interacted with it.

The work in [22] used the P300 to compare three different navigation paradigms: i) by means of flashes over the objects, ii) selecting positions of a matrix superimposed to the VE, and iii) selecting 'tiles' of a virtual image (square sections of a screen).

In [23], a comparison was established between a BCI-based and a gaze-controlled navigation system, using a screen to project the VE and another one to provide subjects with a command matrix.

Chung [24] describes a SSVEP-based system that allowed subjects to generate low-level commands, but it registered the sequences of these basic commands in order to provide subject-dependant high-level commands.

Finally, Faller [25] presents another SSVEP-based system with three stimuli that subjects used to move with low-level commands in a virtual apartment or in a slalom test avoiding obstacles.

## 3.2 Asynchronous systems.

Self-paced systems are usually more versatile because the subjects control the timing of the interaction. However, they may be more difficult to control because they need to support two states: i) one in which subjects do not generate control commands over the system, Non-Control (NC) state; and ii) an Intentional Control (IC) state where they execute control over the system.

As these systems are asynchronous, they mostly use endogenous signals, because these signals let the subjects switch between the two states without the need to wait for an indication from the system. Usually, these systems rely on SMR mental tasks.

The simplest systems to control are those that use only two mental classes. This can be because they only have one active mental task classified versus 'rest', so they only move in one possible direction. Some examples are the works of Leeb [26, 27], where subjects performed feet MI in order to advance in different VE.

By using more tasks, a more versatile system can be achieved; it is the case of [28], in which the classification of left and right hand MI is used to turn an avatar in a VE, and the real movement of the feet is used to move forward.

The same simple classification (both hands MI) has been used in [29] to move through a grid of hexagons. After each turn command, the system forced an advance in the pointed direction. The change between the NC and IC states is achieved by using the parameters 'dwell time' and 'refractory time', when the brain activity must be kept above (or under) certain threshold in order to switch the state.

The work presented in [30] does not use VR techniques, but it shows the blueprint of an apartment. This experiment used three MI tasks: right or left hand MI made an avatar turn both sides, while feet MI made it advance. The switch from the NC to the IC state was achieved with the feet MI task. After that, subjects could choose a turn command. After the turn, the system changed back to the NC state and the avatar started moving in the pointed direction; this movement was kept until subjects stopped it with the feet MI task (which made the system change again to the IC state).

Three mental tasks were used by the Graz group in [31]. In the latter study, both hands and feet MI made an avatar turn and move forward in a virtual park. Subjects switched from the NC to the IC state when one of the three MI tasks was detected.

Three classes were also used in [10], which included some intelligence in the system, providing high-level commands. The executed action after the selection of a command was determined by the knowledge that the system had of the environment, so it 'modulated' the subject intention making the more appropriate movement.

One more work that classifies three MI classes is [32]; MI tasks are not directly interpreted as navigation commands but they are used to move through a decision tree in order to choose among several high level options.

The UMA-BCI group (University of Malaga) continued with the work started in [20], changing the system so it supported the NC and IC states [33]. The use of one hand MI in a NC interface made the system change from the NC to the IC state, and then, with the same MI task subjects could select among three navigation commands that were sequentially pointed by a rotating bar. The selection of a command involved a discrete movement.

On a later experiment [34], the same navigation paradigm was used to provide continuous movements: after the selection of a command the movement was kept while the MI task was above certain threshold.

Finally, a new version of the same paradigm was proposed in [35], in which the visual interface was replaced by auditory cues.

## 4 Navigation in Real Environments

Some the works involving BCIs and robots are preliminary studies preceding the use of the system in a real wheelchair, whereas others are robot-oriented applications in which the robot can complete different actions, not just move in the environment.

### 4.1 Robots

ERP potentials are often used in this kind of system, like [36], where the user watched a screen with the subjective vision of the robot in the environment. Some items were superimposed in the image, which could be selected through an oddball paradigm. These items represented the discrete possibilities of movement.

A similar paradigm, but based on SSVEP potentials is used in [37] to control a car equipped with a video camera.

Some applications let subjects control a robot to perform specific actions, not to move freely in the environment. That is the case of [38], where ERP potentials were used to control a robot that manipulated different objects.

The system in [39] maps two MI tasks into three navigation commands: subjects generated different patterns of MI tasks that corresponded to the three commands.

Three MI tasks are used in [40] to move a humanoid robot in a labyrinth.

Another study that uses MI task is [41]; four MI tasks made the robot move forward, stop, turn right and turn left with discrete movements.

In [42], the same paradigm used in [35] (first visual and then auditory) provided four commands to move a robot in a small maze of corridors with both discrete and continuous movements.

Some experiments are based on high-level commands, letting the system move with intelligence to better perform the action, depending on the specific scenario. In [43], subjects used three mental tasks to select six potential commands. The mapping from three tasks into six commands was achieved through a 'finite state machine'.

Halfway between the low and the high-level commands are the hybrid systems that can adapt their commands. An example is [44], where subjects started performing low-level actions through SSVEP. Once a series of commands had been validated, it was included as a high-level action.

### 4.2 Wheelchairs

Most part of the systems controlling a wheelchair keep the use of-high level commands with some intelligence applied to the wheelchair.

The IDIAP group continued using the paradigm mentioned before [43] to control a real wheelchair. In [45] the probabilities that a command had to be selected depended not only on subjects intention (through SMR-related tasks) but also on the position of the wheelchair regarding obstacles, enabling a 'shared' control.

Another work that uses MI, but with low-level commands is [46]. Three MI tasks moved the wheelchair forward or made it turn. However, this is a hybrid systems because it relied on the actual movement of the cheek for the stop command.

The system presented in [47] is hybrid too: both hands MI tasks were used to make the wheelchair turn, feet MI to make the advance movement slower, and the potential P300 to accelerate.

The group from the University of Zaragoza used the same paradigm described in [36] to control an intelligent wheelchair [48]: with the potential P300 subjects selected fixed positions from a tri-dimensional reconstruction of the real environment.

The P300 is used in [49] to select different objectives pre-known by the system.

The study in [50] describes a SSVEP-controlled wheelchair with four possible low-level commands.

Four commands are used too in [51], but the control is achieved with P300.

Finally, the work of [52] will be mentioned here. This system is hybrid, providing subjects with high-level commands that could be replaced by low-level commands in case the subjects wanted to assume the control in a specific situation.

## 5 Summary

Several navigation systems have been mentioned, whose characteristics will be briefly described next.

Regarding two classifications, there are endogenous and exogenous systems, as well as synchronous and asynchronous. The endogenous and asynchronous systems are those that better fit the control model of a navigation device, as subjects execute the control in a direct way (because of being endogenous) and they can do it at any moment they want (because of being asynchronous).

The mentioned systems use high-level commands (‘Go straight and turn right on the next corner’ or ‘go to the kitchen’, for example) and low-level commands (‘turn left’). The first are easier to control because subjects do not need to indicate every single movement. On the other hand, the systems based on low-level commands allow users to move with more autonomy, because they can go to any point in the environment, without the limitation of moving among pre-defined locations. Adaptive systems use low-level and high-level commands in different situations.

The more versatile systems are those that provide subjects with more navigation commands. Those cases in which subjects can only move in one direction (‘forward’) or are controlled with only two commands (‘turn left and turn right’) provide subjects with little range of action. Systems with three or more commands use to bind the number of commands with the number of mental tasks used to control them. However, as deduced from [53, 54], an increase on the number of mental tasks can reduce the classification accuracy. On the other hand, some systems use less mental tasks to control a device with a higher number of commands (through a mapping of some mental tasks into more commands at the cost of a slower control.

The research in this field is relatively recent; however, the currents works show the interest of the different groups, who keep achieving promising results.

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