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Jonathan Mercier

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Thèse



**THESE INSA Rennes**  
sous le sceau de l'Université européenne de Bretagne  
pour obtenir le titre de  
DOCTEUR DE L'INSA DE RENNES  
Spécialité : Informatique

présentée par  
**Jonathan Mercier-Ganady**

**ECOLE DOCTORALE : MATISSE**  
**LABORATOIRE : IRISA**

## Contribution to the Study of the Use of Brain-Computer Interfaces in Virtual and Augmented Reality

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# Contribution to the Study of the Use of Brain-Computer Interfaces in Virtual and Augmented Reality

Jonathan Mercier-Ganady



En partenariat avec



IRISA







*Reality didn't have to be real. Maybe if conditions were right, it just had to be what people believed...*

Terry Pratchett, Moving Pictures



# Thanks

First, I would like to thank the members of my jury for agreeing to evaluate my work and my manuscript: Pr. Bruno Arnaldi for agreeing to preside my thesis defense committee, Pr. Indira Thouvenin and Dr. Martin Hachet for being rapporteurs on my manuscript, and finally Pr. Guillaume Moreau for his examination of my work. Thank you very much for your comments and your useful remarks.

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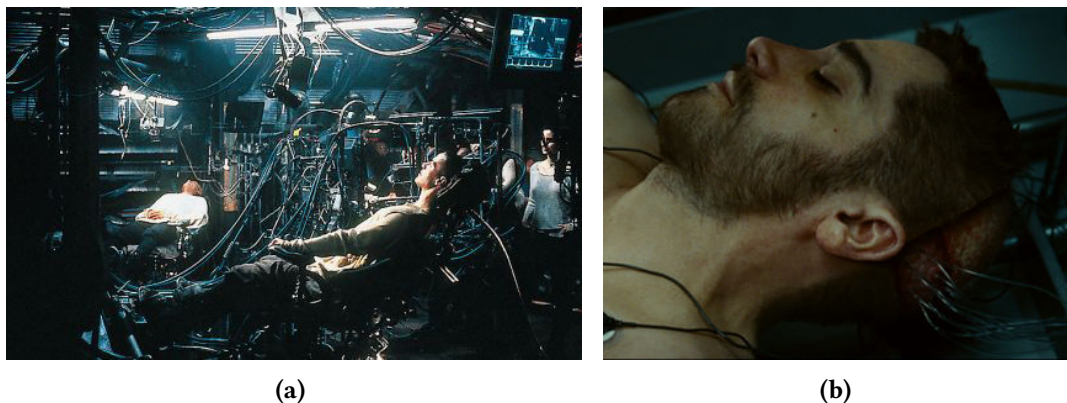
# Acronyms

AR	Augmented Reality
BCI	Brain-Computer Interface
CAVE	Cave Automatic Virtual Environment
EEG	ElectroEncephaloGraphy
HMD	Head-Mounted Display
SSVEP	Steady State Visually Evoked Potential
VR	Virtual Reality



# Introduction

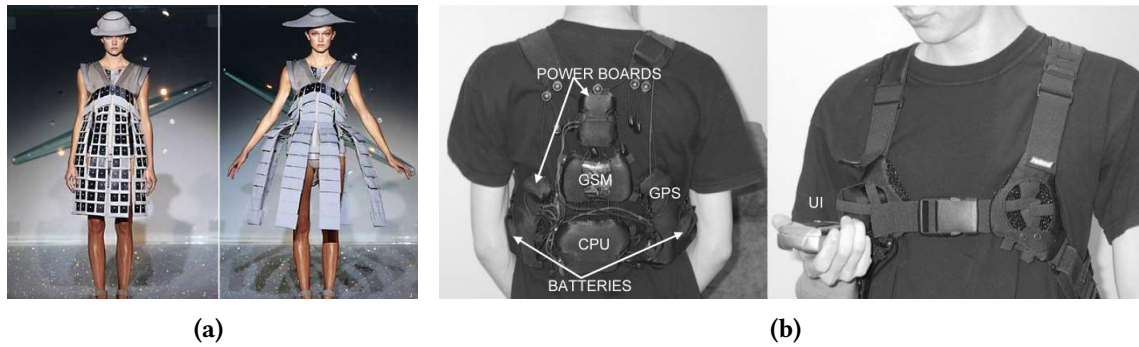
CONTROLLING a virtual world using one’s brain activity has been already and early considered by both researchers and artists. Science-fiction has provided examples of such interfaces. For instance, in the movie “The Matrix”, humans have a connection port in the back of the head that allows them to connect to and interact with a virtual world called the Matrix (see [Figure 1](#)). In “Source Code”, another movie released in 2011, a soldier is embodied into a deceased person during her last 8 minutes in order to identify a bomber. This soldier is connected to a Brain-Computer Interface (BCI) that allows him to observe and interact with an alternate reality. These fictional examples pave the way for new uses of BCIs, especially to control virtual or real worlds.



**Figure 1** – Science-fiction illustrations of a brain-computer interface used to interact with a virtual world. (a) Picture from the movie “The Matrix”. Warner Bros, 1999. (b) Picture from the movie “Source Code”. Summit Entertainment, 2011.

The work presented in this manuscript concerns the use of BCIs in both Virtual Reality (VR) and Augmented Reality (AR). This work was part of a collaborative research project called Homo Textilus. It aimed at studying the future of smart clothes which are made up with smart textiles, “able to sense stimuli from the environment, to react to them and adapt to them by integration of functionalities in the textile structure” [[Van Langenhove and Hertleer, 2004](#)]. Smart clothes are “ordinary clothing, augmented with electrical or non-electrical components and intelligent fabrics” [[Rantanen et al., 2000](#)]. They can integrate electronic components, mechanical actuators, but also sensors to measure heartbeat, temperature, etc. Smart clothes prototypes have already been produced. Some of them have been displayed on fashion shows (see [Figure 2, \(a\)](#)). A “survival smart clothing prototype” has been designed by Rantanen et al., which illustrates another use-case for smart clothes (see [Figure 2, \(b\)](#)) [[Rantanen et al., 2002](#)].

In the context of the Homo Textilus project, the objective of this thesis was to integrate a brain-computer interface to real or virtual smart clothes. Thus the final objective of this PhD was to study the combination of BCI, VR and AR systems for the design of novel generations of smart clothes.



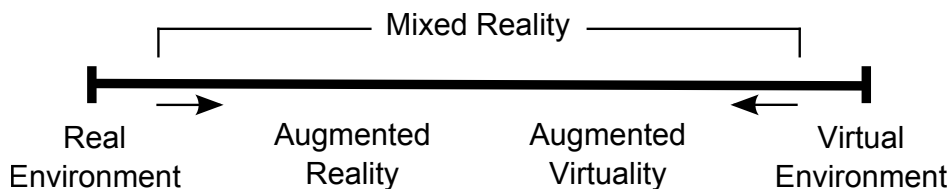
**Figure 2** – Two examples of smart clothes. (a) Smart clothes using actuators to change their shape. Design by Hussein Chalayan. Photo: Agence France Presse. (b) The supporting structure of smart clothing for the arctic environment [Rantanen et al., 2002].

**Definitions:**

**Brain-computer interface:** A brain-computer interface is defined by Wolpaw et al. as a “communication system that does not depend on the brain’s normal output pathways of peripheral nerves and muscles” [Wolpaw et al., 2000]. A BCI provides an alternate route for sending commands to computers or other devices. ElectroEncephaloGraphy (EEG), one of the most frequently used techniques within the BCI community to access to brain activity, is the “recording of electrical activity along the scalp produced by the firing of neurons within the brain” [Niedermeyer and da Silva, 2005]. Since BCIs can be used to send commands, they can be associated with VR as a novel input device [Edlinger et al., 2011].

**Virtual reality:** Earlier definitions of virtual reality were purely “technologically-based”. For instance, Greenbaum described VR as “an alternate world filled with computer-generated images that respond to human movement” [Greenbaum, 1992]. Later definitions, such as the one proposed by Steuer, define VR using either this “technological-based approach” or in terms of “presence”. Steuer defines presence as “the sense of being in an environment”, telepresence as “the experience of presence in an environment by means of a communication medium” and, finally, VR as “a real or simulated environment in which a perceiver experiences telepresence” [Steuer, 1992].

**Augmented reality:** Milgram et al. proposed the concept of “reality-virtuality continuum” (see Figure 3), and “mixed reality” [Milgram et al., 1995]. Mixed reality is defined as an environment “in which real world and virtual world objects are presented together within a single display”. Real environments and virtual environment are located on each side of this continuum. According to Milgram et al., AR is a subset of mixed reality, close to the real environment. AR can be defined as being a reality “in which 3D virtual objects are integrated into a 3D real environment in real time” [Azuma et al., 1997]. AR and VR share the presence of virtual objects with which users can interact.



**Figure 3** – The Reality-Virtuality Continuum [Milgram et al., 1995].

### Combining brain-computer interfaces with virtual reality and augmented reality

The last decade has seen an increase of interest in using brain-computer interfaces within virtual environments [Lotte et al., 2013a], and more specifically, within video-games [Lécuyer et al., 2008; Nijholt et al., 2009]. Indeed, BCIs were essentially used for medical purposes, i.e. as a communication pathway for paralyzed persons [McFarland and Wolpaw, 2011], but new use-cases for healthy users are appearing [Allison et al., 2007a].

Lotte proposed an overview of the limitations and perspectives of the use of BCIs for video-games [Lotte, 2011]. He listed a number of possible limitations when using an EEG-based BCI: notably the requirement for the user to remain static to prevent EEG noise, the low amount of commands that can be distinguished using only the BCI, and the low performance in terms of latency compared to classical input devices. Overcoming these limitations could be achieved by improving the BCI technologically, but also by adapting the interaction techniques. An interaction technique is “the fusion of input and output, consisting of all software and hardware elements, that provides a way for the user to accomplish a task” [Tucker, 2004]. One of these adaptations could be the use of a hybrid BCI.

A hybrid BCI is defined by Pfurtscheller as being “composed of two BCIs, or at least one BCI and another system” [Pfurtscheller, 2010]. One possible use of hybrid BCIs is to enhance the performance of a system by supplementing one component with another. A classical example of a sequential hybrid BCI is the “brain switch” [Pfurtscheller, 2010], where one BCI is used as a trigger for the activation (or deactivation) of another BCI.

More and more, instead of being considered as a replacement, BCIs could therefore be seen as a complement to classical interfaces [Lécuyer et al., 2008].

### Challenges

Figure 4 displays the architecture and the components of a VR/AR system using a BCI as a complement to another input device manipulated with motor activity and represented by a hand. An interaction technique receives user motor/cognitive activity data and sends commands to the virtual environment. The result can be either augmented or virtual reality, depending on whether the virtual environment is associated with the real environment or not. A visual display sends images that can be perceived by the eyes and interpreted by the brain. This figure illustrates the various combinations that can be achieved between multiple inputs (BCI or not) and VR/AR displays.

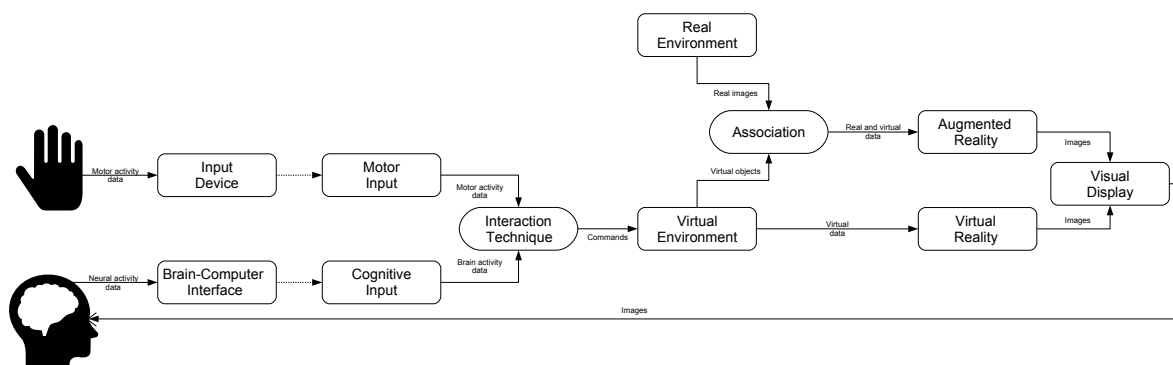


Figure 4 – General architecture of VR/AR systems integrating a BCI.

In this PhD we focus on several challenges concerning the combination of brain-computer interface and virtual/augmented reality systems:

- **Compatibility of brain-computer interfaces and virtual/augmented reality systems:** testing the compatibility between BCIs and VR/AR can be divided into three levels: hardware, software, and usage. On the hardware level, are the system components compatible with each other? What impairs the combination of two hardware components? At the software level, what software components could be developed to enable and facilitate the simultaneous use of a BCI and VR/AR? Finally, at the usage level, is it possible for people to use both a BCI and a VR/AR system at the same time?
- **Learning of BCI-based interaction in virtual environments:** can users be trained to control their brain activity while being immersed in a virtual environment? How can their brain activity be exploited to better interact in VR/AR systems? What type of novel visualization tools exploiting VR/AR technologies could be developed to achieve these goals?
- **Novel usages of brain-computer interfaces combined with virtual/augmented reality:** what novel uses can be found for systems combining BCIs and VR/AR? How can these uses be evaluated in terms of performance and usability? Could smart clothes benefit from BCI technology, possibly in combination with VR/AR systems?

### The Homo Textilus project

This PhD was funded by the administrative region of Brittany and the French National Research Agency within the Homo Textilus project (February 2012 – September 2015). The Homo Textilus project aimed at studying the sociological impact of the next generation of smart clothes. More specifically, studying how smart clothes could be accepted by users, listing the technological limitations and challenges, producing a state of the art on these clothes and, finally, designing and developing prototypes. The project involved six partners: Tomorrowland, Lutin, Lip6, Inria, GEMTEX, and RCP Design Global. The role of our laboratory (Inria) in this project was to study potential and technological challenges of the integration of BCIs with smart clothes and to design and conceive prototypes and proofs of concept.

Within this project, BCIs were seen as a novel input/sensors and were studied to provide a way to measure various cognitive attributes of the wearer, and modify the virtual environments and/or clothes attributes/actuators accordingly. VR/AR could also provide a testbed for such novel smart clothes whose production is often complicated and expensive.

### Thesis methodology

The methodology adopted in this thesis follows the 4 stages described thereafter:

1. **Feasibility study on compatibility of virtual reality and brain-computer interface systems:** we conducted an evaluation of the BCI performance when simultaneously using a BCI and another input device. A muscular task requiring a progressive amount of engagement was used. In addition, a cognitive task was also performed to control the BCI. The success rate of both tasks was measured.
2. **Learning and visualization tools for brain activity based on VR/AR:** we have proposed new tools allowing users to visualize their brain activity in real-time. These tools could make learning how to control brain activity easier. Various prototypes for real-time 3D visualization of brain activity in VR/AR have been designed and evaluated.

3. **Virtual reality testbed for smart clothes:** we have designed a VR/AR testbed to test and evaluate smart clothes applications with a minimal investment of time and resources. This system allowed users to test the wearing of smart clothes and interact with various kinds of inputs.
4. **Design of novel concepts of smart clothes based on BCIs:** we have studied the design of new concepts of smart clothes based on BCIs. We have extended our VR/AR testbed to integrate a BCI, allowing to adapt various properties of the virtual clothes. We have designed and evaluated a prototype called the “Invisibility Cloak”, allowing users to camouflage themselves in AR using a BCI.

## Contributions

**Chapter 1** is an overview of related work about brain-computer interfaces and virtual/augmented reality. The main characteristics of BCIs are first provided, followed by a description of the different types of BCIs and some examples. The chapter also provides an overview of the previous uses of BCIs in VR and AR.

**Chapter 2** proposes to study whether a brain-computer interface can be used simultaneously with another input device. To this end, a game-like prototype serves as a support for a study on the effects of muscular activity on the BCI performance. A concentration or relaxation mental task is performed in combination with a muscular task of varying intensity. Three levels of muscular activity are tested: from no motion at all to a highly demanding muscular activity. The performance of the BCI is measured in all combinations.

**Chapter 3** introduces novel tools for the visualization of brain activity in real-time based on virtual/augmented reality. A first prototype called the “Mind-Mirror” provides a way for users to visualize their own brain activity in real-time in their head as if they were looking into a mirror. A second prototype called the “Mind-Window” is a mobile and multi-user setup where tablet computers can be used to visualize the brain activity of another person in real-time. Finally, a third prototype called “Mind-Inside” is a highly immersive VR system based on a Head-Mounted Display (HMD) and enabling telepresence and immersion inside one’s brain. A user study evaluates both the objective and subjective performance of the Mind-Mirror prototype, compared to a more classical visualization. One of the most promising applications for these prototypes is neurofeedback, which is “a form of behavioural training aimed at developing skills for self-regulation of brain activity” [Heinrich et al., 2007].

**Chapter 4** targets the use of brain-computer interfaces for controlling smart clothes. Several prototypes and a user study concern this direction. A first prototype shows how users can wear and test virtual clothes and other garments thanks to AR. A second prototype enables the control and the change of appearance of these virtual clothes depending on the mental state of the BCI user. Finally, an experimental study evaluates how well participants can control an invisibility power within a virtual environment with the help of a BCI. This leads to the concept of an “Invisibility Cloak” with which participants can camouflage themselves in AR using a BCI.

Finally, **Chapter 5** concludes this work and presents some perspectives for future studies.





# Chapter 1

## Related work

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This chapter provides an overview of related work in the field of Brain-Computer Interfaces (BCIs) and their combination with other user inputs notably when related to Virtual Reality (VR) and/or Augmented Reality (AR). The first section of this chapter describes how BCIs operate: what are the main brain structures and how is the brain data acquired. The most common ElectroEncephaloGraphy (EEG) markers are then described. The second section of this chapter deals with the concept of hybrid BCIs, which represents a combination of a BCI with another input device. This section notably describes some representative examples of systems based on hybrid BCIs. The final section of this chapter surveys the combination of a BCI with VR and AR systems.

### 1.1 Brain-computer interfaces: short overview and basic principles

A brain-computer interface is a communication and control channel that “acquires brain signals, analyses them, and translates them into commands that are relayed to an output device to carry out a desired action” [Shih et al., 2012] and “does not depend in any way on the brain’s normal output pathways” [McFarland and Wolpaw, 2011]. Analysis of brain signals requires some knowledge of the inner workings of the human brain. This section provides an overview of the brain structure principles and how brain data acquisition can be performed, as well as how this data can be interpreted. This section refers to the following articles: [McFarland and Wolpaw, 2011; Shih et al., 2012] or surveys: [Allison et al., 2007b; Mason et al., 2007], and to the following book: [Niedermeyer and da Silva, 2005].

### 1.1.1 Brain structure and brain data acquisition

A human brain is divided into three parts: the brain stem, the cerebellum and the cerebrum. The cerebrum is itself divided into two hemispheres: left and right. The surface of the cerebrum is called the cortex and is divided into four zones called “lobes” (see Figure 1.1). The frontal lobe is used for cognitive functions such as speech, movements and other executive functions. The temporal lobe deals with auditory, visual and language functions. It is also used for emotional processing. The parietal lobe is used for reading/writing, language comprehension, attention and spatial awareness. Lastly, the occipital lobe is involved in visual processing [Gray, 1918].

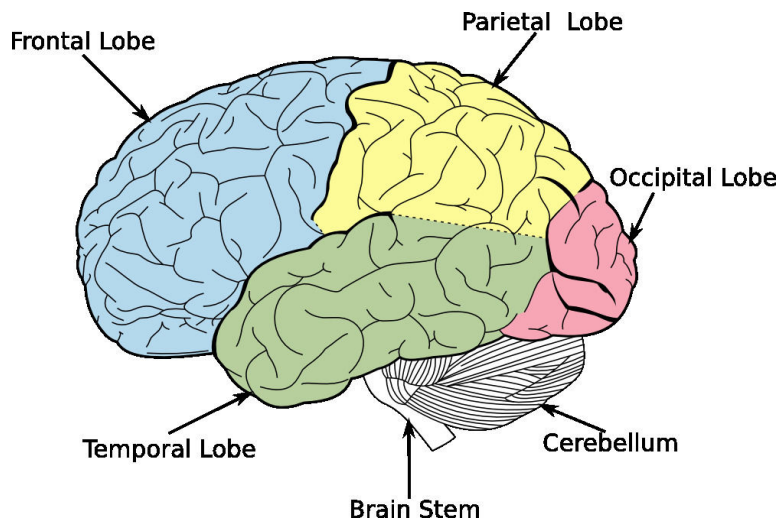


Figure 1.1 – Lateral view of the brain lobes. Derived from [Gray, 1918].

Recording brain activity can be achieved by using electrical fields, blood pressure, or magnetic fields. Gathering this information is called “acquisition”. Retrieval of brain data can be achieved with the help of invasive or non-invasive methods, depending on whether the measurement device is placed on the brain tissues themselves or on the scalp. A BCI is then called “invasive” or “non-invasive” [McFarland and Wolpaw, 2011]. Invasive systems are less prone to noise than non-invasive interfaces, but need a surgical operation to be placed on the user and have to be removed or replaced after some time due to the rejection phenomenon. While invasive BCIs mainly use electrocorticography [Leuthardt et al., 2006], non-invasive BCIs can use various methods: EEG [Niedermeyer and da Silva, 2005], near-infrared spectroscopy [Bunce et al., 2006], magnetoencephalography [Hämäläinen et al., 1993], and functional magnetic resonance imaging [Ogawa et al., 1992]. Each approach differs in cost, efficiency and mobility. Many BCI systems use EEG because of its ease of use and low cost compared to magnetoencephalography or functional magnetic resonance imaging devices. EEG uses active or passive electrodes placed on the scalp to gather data from the brain thanks to the electric potentials it emits [Niedermeyer and da Silva, 2005].

Non-invasive medical applications of BCIs most often use EEG. The BrainAmp<sup>1</sup> and the g.USBamp<sup>2</sup> are two examples of medical EEG amplifiers, that are used with proprietary EEG electrodes. In recent years, new non-medical uses of EEG-based BCIs have appeared in fields like entertainment and video-games. Novel EEG hardware were produced, with a lower cost, such as the Emotiv EPOC<sup>3</sup>. Duvinage et al. compared a medical and a non-medical EEG device in a specific application [Duvinage et al., 2012]. Comparing classification results of a medical system called “ANT” and the EPOC, they logically found out that the medical system had better results. However the EPOC

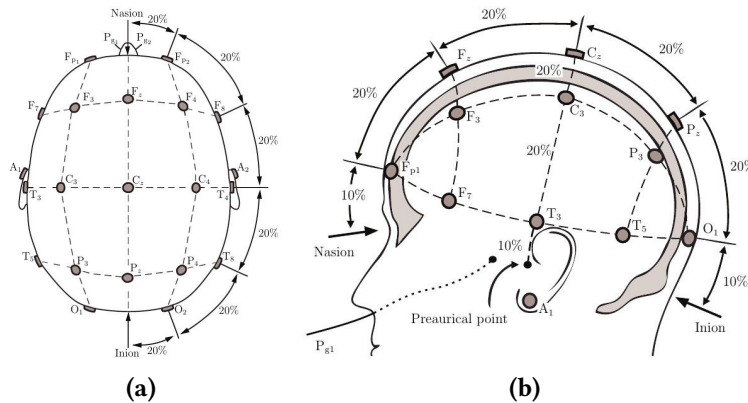
<sup>1</sup><http://www.brainproducts.com/productdetails.php?id=7>

<sup>2</sup><http://www.gtec.at/Products/Hardware-and-Accessories/g.USBamp-Specs-Features>

<sup>3</sup><http://www.emotiv.com/epoc/>

allowed for above chance classification results, which suggested its usability in this particular scenario. According to the authors, this device is suitable for non-critical applications like video-games, but not for medical applications.

Electrical fields emitted by the neurons are thus measured with the help of EEG [Niedermeyer and da Silva, 2005]. These fields are received by electrodes that produce a signal of a weak amplitude. The EEG electrodes are placed on the surface of the head, often attached to a cap. Gel or salted water are used to enhance the conductivity between the head and the electrodes. This implies that a certain amount of time (usually 20 minutes) is needed to setup any system that uses EEG. Electrodes are commonly placed using the 10-20 system (see Figure 1.2).



**Figure 1.2** – The 10-20 international electrodes placement system [Tanner et al., 2011]. (a) Axial view. (b) Sagittal view.

Electroencephalography has also a very good temporal resolution (milliseconds) compared to other methods such as functional magnetic resonance imaging or positron emission tomography (seconds). Unlike functional magnetic resonance imaging, EEG has a bad spatial resolution because of the nature of electric waves and their diffusion. Surface brain activity is easier to detect than internal activity. EEG requires a non-trivial data analysis because of the low signal-to-noise ratio induced by muscular activity. However, some studies have shown that some motion can still be performed while using an EEG-based BCI [Lotte et al., 2009].

### 1.1.2 Common electroencephalography markers used in brain-computer interface setups

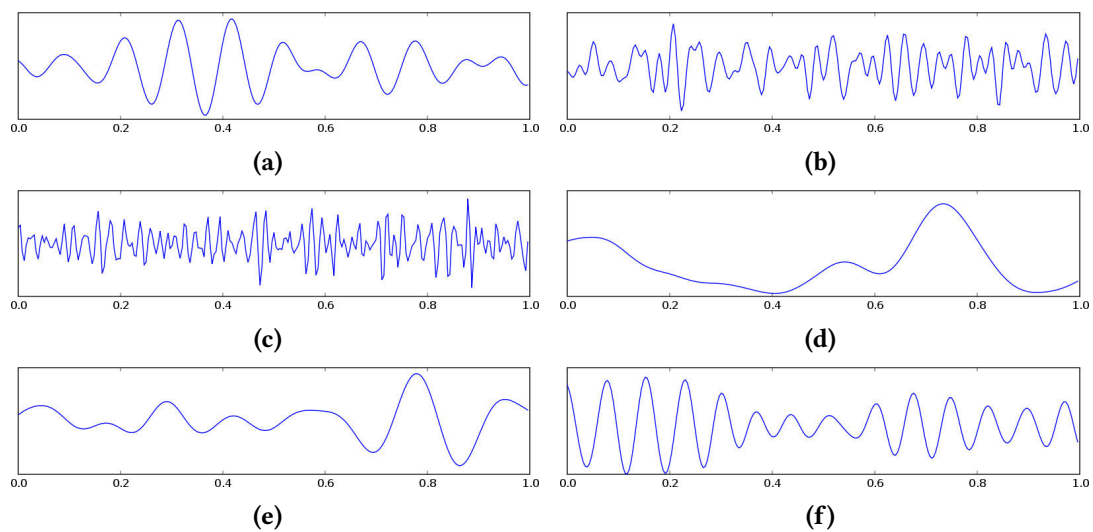
Electroencephalography markers are variations of the signal retrieved from the brain data and exploitable in applications using a brain-computer interface. Commonly used markers in BCIs are: EEG rhythms, event related paradigms, evoked potentials, and concentration/relaxation mental states. These markers will be described thereafter.

#### 1.1.2.1 Electroencephalography rhythms

Rhythms are oscillations that can be observed in specific locations of the brain and at specific frequency bands. They can provide some information about a mental state and can be voluntarily controlled [Niedermeyer, 2004]. These rhythms are called alpha, beta, gamma, delta, theta, and mu.

- **Alpha:** the alpha rhythm (8-13Hz) is present in the posterior (occipital) part of the brain and is higher on the non-dominant side (see Figure 1.3, (a)). It is mostly observed when closing the eyes or being in a relaxed state: higher alertness reduces its amplitude;
- **Beta:** the beta rhythm (13-30Hz) can be detected when the user is awake and conscious and is affected by movements of the user (see Figure 1.3, (b));

- **Gamma:** the gamma rhythm (greater than 30Hz) is linked to cognitive and motor activity and is difficult to measure using scalp-based EEG (see [Figure 1.3, \(c\)](#));
- **Delta:** the delta rhythm (1-4Hz) is mostly observed in adults during deep sleep (see [Figure 1.3, \(d\)](#));
- **Theta:** the theta rhythm (4-8Hz) can be seen in young children during drowsiness and is known to form a spike when the user is trying to repress a response or an action [[Futagi et al., 1998](#)] (see [Figure 1.3, \(e\)](#));
- **Mu:** the mu rhythm (8-13Hz) is motor-based and varies when the user is moving [[Wolpaw and McFarland, 2004](#)] (see [Figure 1.3, \(f\)](#)).



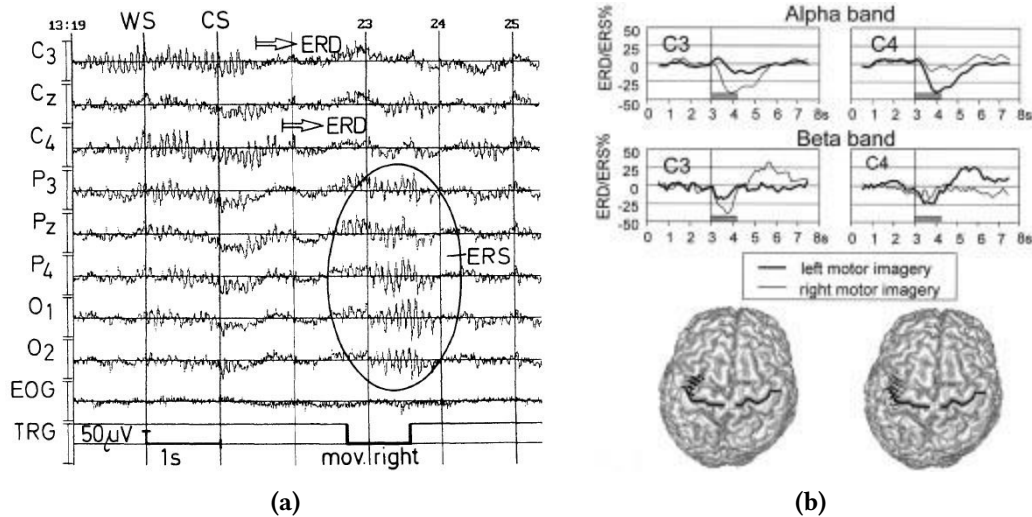
**Figure 1.3** – EEG recordings performed on the Oz position and filtered to show each rhythm. Recording and figures by Hugo Gamboa.

### 1.1.2.2 Event-related potentials

It has been observed that some events such as sensory stimuli, motor activity, and memory tasks have a direct impact on the rhythms described in the previous section [[Pfurtscheller and Lopes da Silva, 1999](#)]. An increase in rhythmic activity is called an “event related synchronization” while a decrease is called an “event related desynchronization”. Event related desynchronizations can be encountered a few milliseconds before a movement is performed, or even imagined (see [Figure 1.4, \(a\)](#)). For example, imagining a right hand movement will trigger an event related desynchronization in the mu and beta rhythms on the left motor cortex.

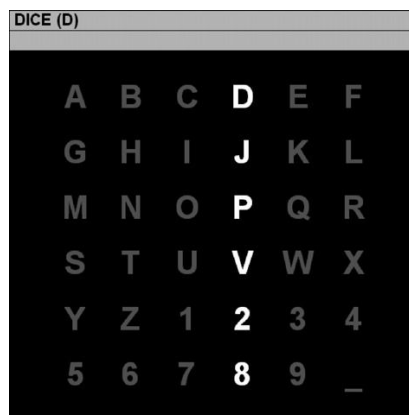
Event related desynchronization is used in a paradigm called “motor imagery”, which mostly relies on the alpha and beta rhythms. While motor imagery represents imagined motor activity, motor execution represents the executed motor activity. After the execution or imagination of a motor action, a so-called alpha- or beta-rebound can be detected (see [Figure 1.4, \(b\)](#)). Motor imagery allows users to send commands to a BCI by imagining performing a movement [[Pfurtscheller and Neuper, 2001](#)].

The P300 is a positive waveform appearing 300 ms after the occurrence of a rare and relevant stimulus [[Donchin et al., 2000](#)]. The P300 paradigm is commonly used with a grid of letters called a “P300 speller” (see [Figure 1.5](#)) [[Krusienski et al., 2008](#)]. This grid is composed of letters that can be either dark or bright (flashing). The user has to focus at one of the letters and mentally counts how



**Figure 1.4** – Two brain activity recordings. (a) Raw EEG data recorded during right finger movement showing event related desynchronization and event related synchronization. A cue stimulus (CS) followed a warning signal (WS) indicating the side of movement (right/left) to be performed (image and caption taken from Pfurtscheller et al. [Pfurtscheller, 1992]). (b) Alpha and beta band (rhythms) variations when using motor imagery [Pfurtscheller and Neuper, 2001].

many times the letter has flashed. This allows the system to detect what the focused letter is. This paradigm has been successfully used on paraplegic patients in a medical context, allowing them to communicate “using thoughts” [Hoffmann et al., 2008].



**Figure 1.5** – A P300 speller grid [Krusienski et al., 2008].

### 1.1.2.3 SSVEP

Steady State Visually Evoked Potential (SSVEP) is a type of evoked potentials that use flickering visual elements whose frequency can be retrieved from the brain electrical signals when the user is looking at them [Müller-Putz et al., 2005]. These elements can be displayed on a computer screen or with light-emitting devices like LEDs. This allows to recognize which element is being looked at, and enables the user to send one command per frequency. A review proposed by Zhu et al. shows that there is no definitive limit on the amount of frequencies that can be used [Zhu et al., 2010]. SSVEP has been employed for navigation control such as in [Lee et al., 2010] or in video-games like in [Lalor et al., 2005] with great efficiency [Beverina et al., 2003]. Legény et al. have designed a system where users have to control a spaceship to destroy targets (see Figure 1.6) [Legény et al., 2013]. Control over the spaceship was performed by looking at its different parts, its wings or its cannon, making it move left/right or fire, respectively.

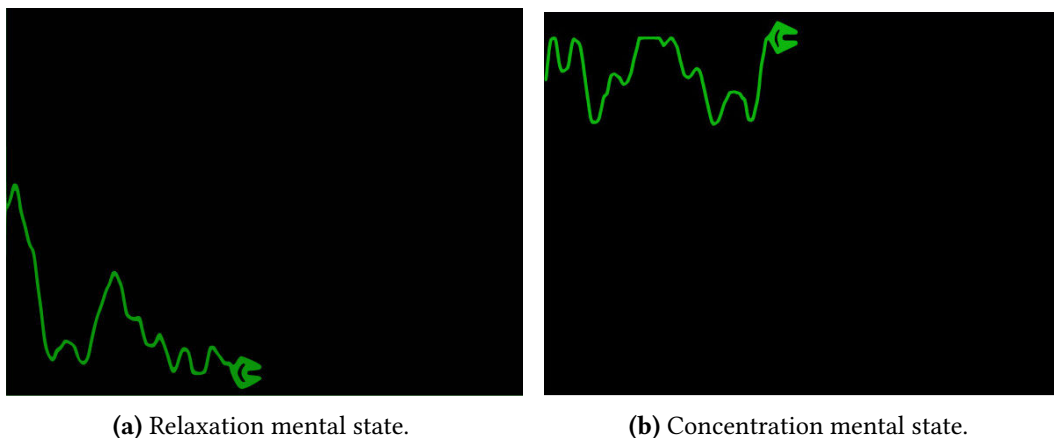




**Figure 1.6** – A system using SSVEP to pilot a spaceship. (a) A user looking at a computer screen displaying the game-like interface. (b) A spaceship driven by SSVEP and three targets that have to be destroyed [Legény et al., 2013].

### 1.1.3 Concentration and relaxation mental states

A BCI can also be used to measure a mental state. For instance, George et al. have designed a system allowing to measure the level of concentration and relaxation [George et al., 2011]. This concentration level can be deduced with the help of ratios or combinations of the alpha, beta and theta rhythms [Lin and John, 2006; Mühl et al., 2010; Hjelm and Browall, 2000]. Another method uses machine learning techniques to classify these mental states [Hamadicharef et al., 2009]. George et al. have compared these two methods and have found that the machine learning technique had a better performance [George et al., 2011]. In addition, they have also determined the best EEG electrode amount and head placement. Their user study was based on a simple game-like 2D environment, where participants were moving a plane up or down depending on their mental state (see Figure 1.7, (a) and (b)).



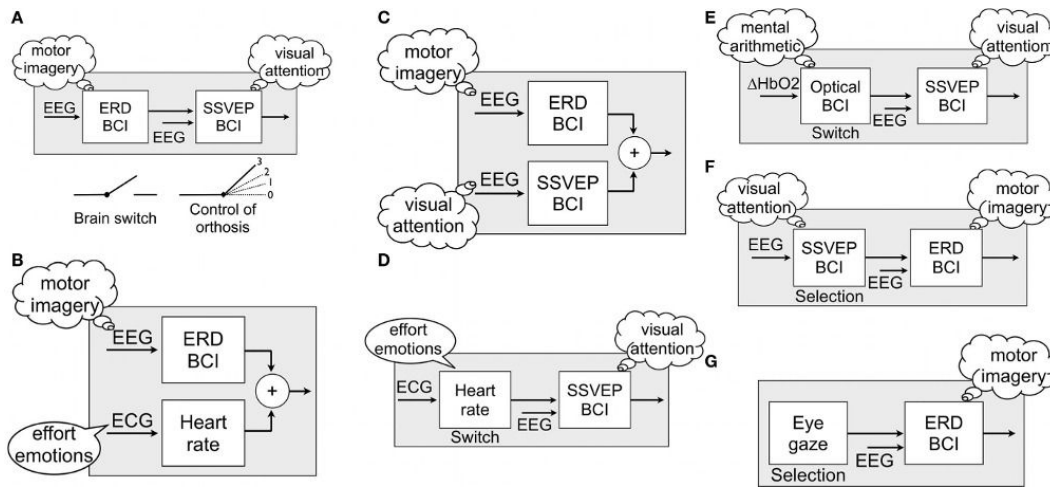
**Figure 1.7** – A simple 2D application used to display the concentration/relaxation mental state detected through a BCI [George et al., 2011].

## 1.2 Combining brain-computer interfaces and other user inputs

The combination of a brain-computer interface with other inputs or another brain-computer interface is often called a “hybrid brain-computer interface”. Hybrid BCIs have been introduced by Pfurtscheller et al.: “Nowadays, everybody knows what a hybrid car is. A hybrid car normally has two engines to enhance energy efficiency and reduce CO<sub>2</sub> output. Similarly, a hybrid BCI is composed of two BCIs, or at least one BCI and another system” [Pfurtscheller, 2010]. A hybrid BCI can

be seen as a combination of devices and paradigms that contains at least one BCI device. In this manuscript we will use the term “component” as a device or a paradigm contained in a hybrid BCI system.

Components of a hybrid BCI system can operate sequentially or simultaneously. Figure 1.8 shows two hybrid BCIs operating simultaneously (B and C) and five operating sequentially (A, D-G). The sequential processing shows the “switch” and the “selection” modes, that could be used to trigger the activity of the second component or make a choice between two other components, respectively. The “fusion” operation is here represented by a “+” sign, showing that the information gathered by these components is “added” to obtain the resulting output. This figure also illustrates the variety of components in a hybrid BCI: a non-EEG BCI device is used in E, an electrocardiography device in B and D, and an eye-tracking device in G. All these devices will be described in the following sections.



**Figure 1.8** – Examples of hybrid BCI components operating sequentially or simultaneously [Pfurtscheller, 2010].

## 1.2.1 Main concepts behind hybrid brain-computer interfaces

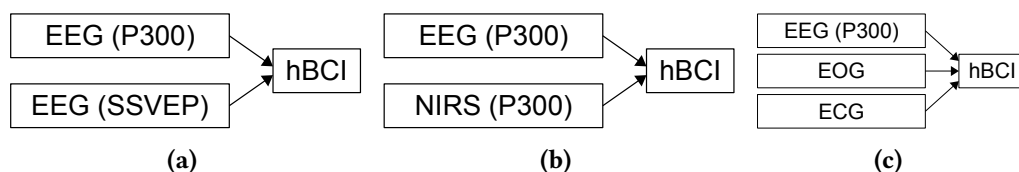
A hybrid brain-computer interface is composed of multiple elements which are associated together to form a system. When BCIs are associated together they are usually “active” as opposed to “passive”, that is, users are actively sending commands through the interface rather than being “monitored” by it. Most BCI setups are considered active in the sense that the user has to deliberately control her brain activity in order to trigger an event or fulfill an objective [George and Lécuyer, 2010]. Active BCIs have a low data transfer rate, usually under 25 bits per minute [Wolpaw et al., 2002]. Passive BCIs are frequently used in combination with other inputs, and, as such, are frequently part of a hybrid BCI.

The first part of this section proposes an overview of the nature of the elements composing the hybrid BCI: “mixed” (a BCI combined with other inputs) or “pure” (only BCIs). The second part of this section will deal with the sequentiality of the data processing, e.g. if the data coming from one component is processed before or at the same time as another one.

### 1.2.1.1 Mixed or pure hybrid brain-computer interfaces

Hybrid brain computer interface systems can be classified in two categories, depending on whether they include only BCI devices or a combination of BCI and non-BCI devices. Hybrid BCI systems using only BCI devices with single or multiple paradigms will be called “pure hybrid BCI” (see

Figure 1.9, (a) and (b)) whereas systems using any non-BCI device will be called “mixed hybrid BCI” (see Figure 1.9, (c)). Section 1.2.2 lists the most common non-BCI devices used in mixed hybrid BCI systems.



**Figure 1.9** – Three possible combinations of components within hybrid BCI systems. (a) Pure hybrid BCI system using two EEG devices with different paradigms. (b) Pure hybrid BCI system making use of two BCI devices with the same paradigm. (c) Mixed hybrid BCI system using one BCI device and two non-BCI devices.

Mixed hybrid BCI systems tend to use electrooculography, electromyography and electrocardiography together with other components (see Section 1.2.2).

### 1.2.1.2 Sequential or simultaneous processing

Hybrid brain computer interfaces can process incoming data sequentially or simultaneously. Sequential processing means that the data gathered from one component will be used before the data retrieved from other components. This has been illustrated by the “brain switch”, where one component is employed to trigger the data processing of another component [Pfurtscheller, 2010]. Pfurtscheller et al. used this brain switch to control an orthosis [Pfurtscheller et al., 2010]. A SSVEP paradigm is used with LEDs to let the user choose which part of the orthosis she wants to move. The motor imagery paradigm is then used to effectively move the orthosis. This reduces the amount of false positives and illustrates one use of a “brain switch”.

Simultaneous processing means that all the data sent by each component is processed at the same time. Li et al. employed this processing method to control a 2D cursor [Li et al., 2010]. Vertical movement was done with the help of the P300 paradigm while horizontal movement was done using motor imagery. Both components interacted on the system at the same time.

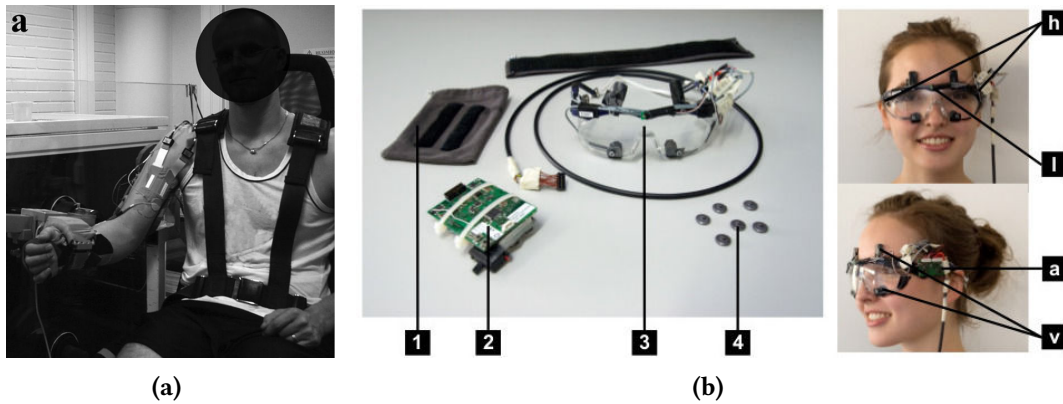
## 1.2.2 Most commonly used input devices in hybrid brain-computer interfaces

Some devices are frequently used in combination with brain-computer interfaces. The following section lists these devices and provides some examples of previous work.

- **Eye trackers:** a first kind of eye tracker, electrooculography, measures the steady electric potential field emitted by eyes, seen as dipoles. The cornea would be the positive pole and the retina the negative pole [Bulling et al., 2008]. Eye movement can be measured by capturing the electric potential field by placing electrodes that will receive a positive or negative signal amplitude, depending on the position of the retina and the cornea. Figure 1.10 shows an electrooculography device. Other types of eye trackers use a special type of contact lens or a video camera [Young and Sheena, 1975]. Eye trackers can be used to measure movements and various events like blinking, saccades and fixations. It has been used with a BCI to allow disabled people to control robots [Wijesoma et al., 2005] or to target an element on a screen such as in a speller.
- **Electromyography:** electromyography measures the electrical activity emitted during muscular activity and can be placed on the surface of the skin or within the muscle. Electromyography is used to retrieve data about muscular activity level and duration [Clancy et al., 2002].



Figure 1.10 shows an electromyography device placed on a subject. The role of electromyography devices in BCIs systems is often to measure the muscle activity during a motor imagery or motor execution task to improve accuracy.



**Figure 1.10** – (a) Electromyography device placed on a user [Piitulainen et al., 2012]. (b) Electrooculography device [Bulling et al., 2008].

- **Electrocardiography:** electrocardiography uses electrodes usually placed on the chest to monitor heart activity [Opie, 2004]. It is used to measure the heart beat rate and regularity, and allows diagnosis of heart damage or abnormalities. One example of electrocardiography usage in hybrid BCI systems is the measurement of effort [Pfurtscheller, 2010]. This effort measurement can then be used to trigger a BCI devices on or off. This system helps preventing false positives.
- **Other input devices:** mice, keyboards, and joysticks are also sometimes used with a BCI. A hybrid setup proposed by Leeb et al. uses a joystick to control the movement of a penguin on a slope while a BCI system is employed to trigger jumps [Leeb et al., 2013]. Kreilinger et al. used a joystick as a device which performance could decrease over time to simulate the users tiredness [Kreilinger et al., 2012]. The user automatically switched from one device to the other depending on a “device score”.

### 1.2.3 Representative examples of hybrid brain-computer interfaces

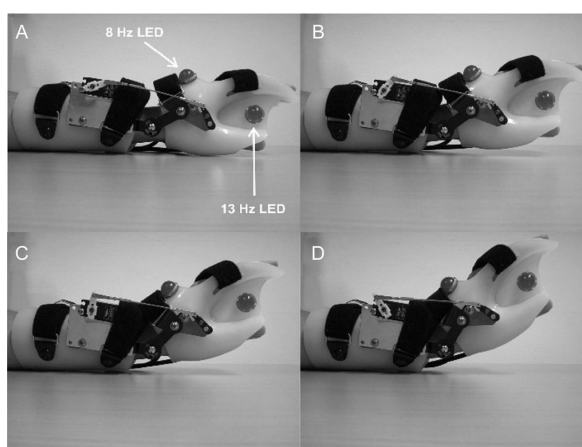
The following section describes a selection of hybrid BCI setups, depending on the nature of their components: pure hybrid BCIs (including only BCI devices and paradigms) and mixed hybrid BCIs (including non-BCI devices).

#### 1.2.3.1 Pure hybrid brain-computer interfaces

This section describes a selection of setups including BCI devices and/or paradigms. In these setups, only BCIs are used to actively record commands or passively gather brain activity data from users.

**Combining motor imagery and P300:** the motor imagery paradigm has been combined with the P300 paradigm in a system designed by Riechmann et al. [Riechmann et al., 2011]. This setup proposes a parallel and asynchronous system including both paradigms. The level of false positives was measured while subjects had to use one paradigm or the other. One target was presented to the user: one of five P300 symbols or one of two motor imagery directions (left or right).

**Combining motor imagery and SSVEP:** a system integrating motor imagery with SSVEP has been proposed by Pfurtscheller et al. [Pfurtscheller et al., 2010]. This setup allowed users to operate a four-step hand orthosis with the help of the SSVEP and the motor imagery paradigms. Two LEDs were placed on the orthosis (see Figure 1.11), one flickering at 8 Hz and the other at 13 Hz. These two LEDs were used by the user to choose which part of the orthosis he wanted to open or close. Motor imagery was then employed to execute the task. Each user executed four different tasks. The first one allowed the user to open or close the orthosis using only the SSVEP paradigm. The second task used a cue on a computer screen to do the training required by the motor imagery paradigm, users were asked to execute fast feet movements. The third one consisted in making use of both paradigms to operate the orthosis in a self-paced way. The last task consisted in using only the SSVEP paradigm and served as a control setup. Only two EEG channels were used, one on the motor cortex and the other on the visual cortex. This hybrid system showed a reduced amount of false positives compared to the continuous use of event related synchronization only.



**Figure 1.11** – A hand orthosis driven using a BCI. The SSVEP paradigm could be used to choose which part of the orthosis should be activated and the motor imagery paradigm could trigger the movement execution. (A), (B), (C) and (D) show four different steps for opening the orthosis [Pfurtscheller et al., 2010].

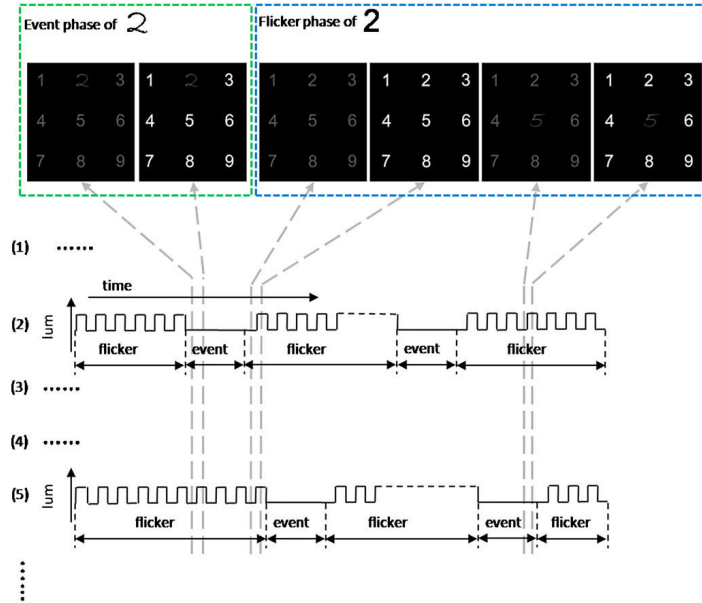
**Combining P300 and SSVEP:** the combination of P300 and SSVEP has been proposed by Xu et al. [Xu et al., 2013]. This setup aimed at improving the performance of a P300 speller by means of hybridization of SSVEP and P300 (see Figure 1.12). Twelve subjects performed an offline spelling with the two approaches. No training has been done beforehand. Six of the subjects used the hybrid configuration first while the other six started by using the P300 paradigm only. A 3x3 matrix was used, showing numbers from 1 to 9 on a computer screen. In the hybrid system, the characters were highlighted in a random sequence. The size and font of the characters were changed to trigger a P300 and flickering was used to trigger a SSVEP reaction. Results showed that spelling performances were largely improved by using the hybrid system.

### 1.2.3.2 Mixed hybrid brain-computer interfaces

This section describes a selection of setups including BCI paradigms combined with non-BCI devices.

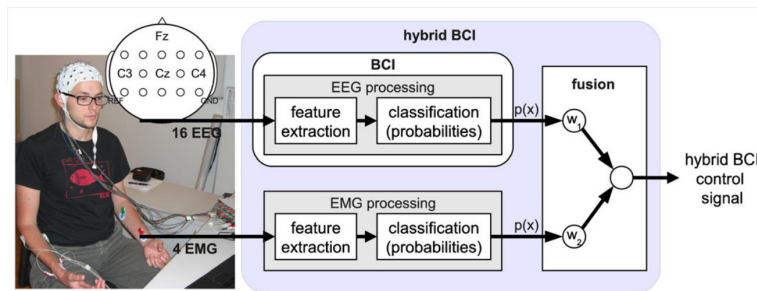
#### **Combining motor imagery with electromyography, eye tracking, or electrocardiography:**

Leeb et al. combined EEG and electromyographic data, allowing partly paralyzed persons to use their residual muscular activity together with motor execution or motor imagery (see Figure 1.13) [Leeb et al., 2011]. In the cases when paralysis is only partial, some residual muscular activity



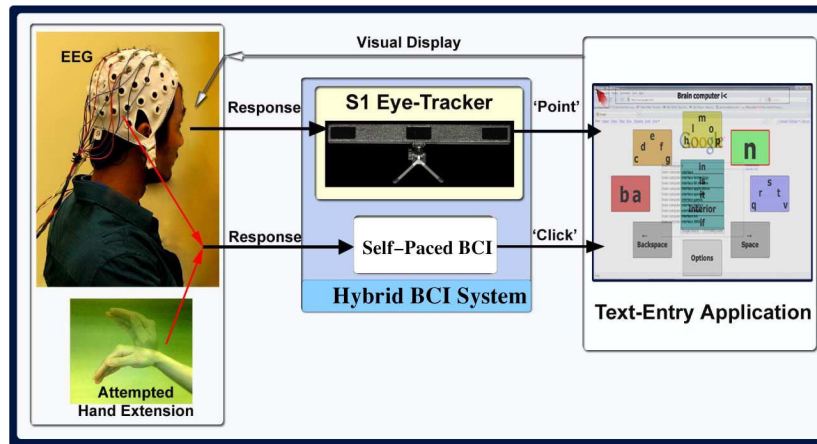
**Figure 1.12** – Time evolution of a P300 speller grid used with both the P300 and the SSVEP paradigms. An “Event phase” is employed to trigger a P300 activity while a “Flicker phase” is used to trigger a SSVEP event [Xu et al., 2013].

can still be used. Each trial consisted in fixating a cross on a computer screen for 3 seconds then a cue for 5 seconds, indicating on which hand motor execution should be performed. EEG and electromyography were recorded at the same time and the fusion of both was done using equally balanced weight and a naive Bayesian technique. The control of this BCI was done using each component or both of them. This setup showed that control can be achieved even when the user is tired. Classification results for the EEG component alone were 73%, 87% for electromyography and 91% for the fusion of both.



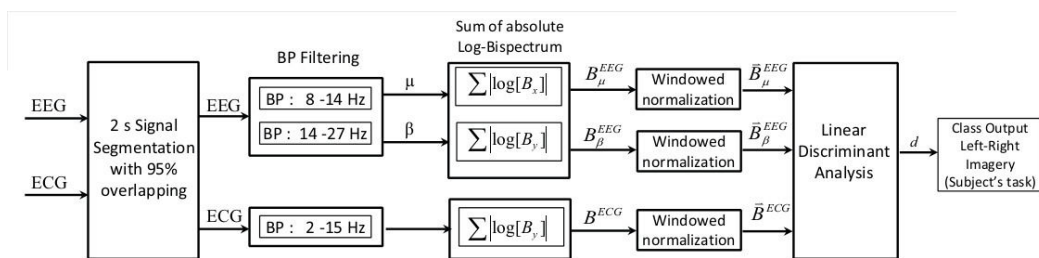
**Figure 1.13** – A person wearing an EEG cap and electromyography electrodes. The diagram shows the different phases of processing and fusion needed for each component of the hybrid BCI [Leeb et al., 2011].

Eye tracking devices can be used to select letters or words. A combination of this device with motor imagery or motor execution has been proposed by Yong et al. [Yong et al., 2011]. This setup used an eye tracking device and motor imagery (or motor execution) to select letters or words (see Figure 1.14). The user had to maintain her gaze on the word or letter she wanted to write during a certain amount of time. The system also had a “sleep mode” that was activated when no letter or word was gazed to reduce the amount of false positives. The classifier used to detect the attempted hand extension was also adaptively updated. This setup was using a program called Dynamic Keyboard that allowed the user to enter text by pressing large buttons and had also a word prediction feature.



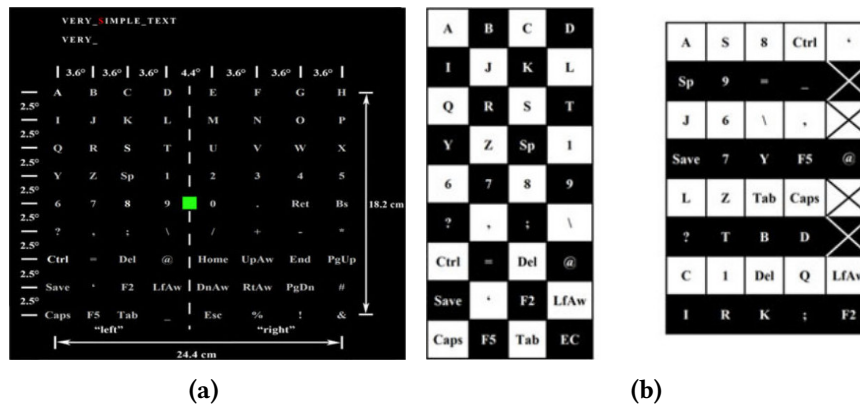
**Figure 1.14** – A person wearing an EEG cap and electrooculography electrodes, using the eye tracker to point a position on the screen and an attempted hand extension (motor execution or motor imagery, depending on the user being able to move her hands) to simulate a mouse click [Yong et al., 2011].

Combining motor imagery with electrocardiography, Shahid et al. proposed to measure if a classification performance could be noticed [Shahid et al., 2011]. Multiple trials were done, each of them lasting 12 seconds: 6 seconds in a relaxed state and 6 seconds where a directional arrow was shown indicating that a left foot or left hand motor imagery task had to be executed. A third symbol represented a rest state. Figure 1.15 shows a block diagram of the processing technique. Two different analyses were performed on the results of a classification between a hand motor imagery task and a rest task. The first one, measuring the average heart rate during a motor imagery task, showed that a 10% heart rate increase could be noticed in that case. The second analysis showed that the simultaneous use of both devices led to an average classification accuracy of 92%, whereas EEG alone produced a classification accuracy of 73%. The fusion of electrocardiography and EEG features enhanced the motor imagery classification in both training and evaluation thanks to the reduced number of false positives.



**Figure 1.15** – A block diagram of a system combining motor imagery and electrocardiography to measure a possible classification performance improvement [Shahid et al., 2011].

**Combining P300 and electrooculography:** a system designed by Postelnicu et al. used a modified stimulus presentation paradigm called the “Half Checker Board Paradigm” to improve the spelling speed thanks to the P300 paradigm and an electrooculography device [Postelnicu and Talaba, 2013]. A 8x9 matrix was divided in areas selected with the help of electrooculography (see Figure 1.16). These areas were composed of multiple characters and symbols that were randomly highlighted. The characters were selected using EEG. An electrooculography calibration phase was required every 2 characters entered. The users had to write a 13 characters long text for calibration and a 16 characters long text for the evaluation. A reduction in the time needed to spell one character was observed when using the half checkerboard paradigm, resulting in a more effective P300 paradigm.



**Figure 1.16** – A character matrix used for spelling. The matrix (a) is divided into areas (b) that can be selected with the help of an electrooculography device while character selection is performed using the P300 paradigm [Postelnicu and Talaba, 2013].

## 1.2.4 Conclusion

In this section we have provided an overview of hybrid brain-computer interfaces, how its BCI components can be characterized, how they can be combined depending on their nature, and how they can be processed in time (sequentially or in parallel). Some examples of commonly used input devices within a hybrid BCI have been presented, as well as representative examples of hybrid BCI systems. In the context of this thesis, hybrid BCIs could provide a way to interact with VR: a BCI could be combined with classical VR input devices. The next section gives an overview of the association between a BCI and a particular output: virtual or augmented reality displays.

## 1.3 Combining brain-computer interfaces and virtual/augmented reality

Brain-computer interfaces and virtual/augmented reality are two different research topics that have been studied for many decades. The combination of both, however, is relatively recent [Lécuyer et al., 2008; Bayliss and Ballard, 2000]. This combination can be seen from two different perspectives [Lotte et al., 2013a]. First, VR can be seen as a testbed for BCI systems and studies [Bayliss and Ballard, 2000]. Second, a BCI can be used as a novel input device for VR systems [Edlinger et al., 2011]. Video-games are one of these VR systems. Literature on the feasibility of associating a BCI and a video-game has increased during the last decade [Lécuyer et al., 2008; Nijholt et al., 2009]. Similarly, the association of BCI with AR has also gained some interest [Escolano et al., 2012; Kansaku, 2011; Scherer et al., 2011], but AR is less studied and more recent. This section provides an overview of the use of BCIs with both VR and AR.

### 1.3.1 Brain-computer interfaces and virtual reality

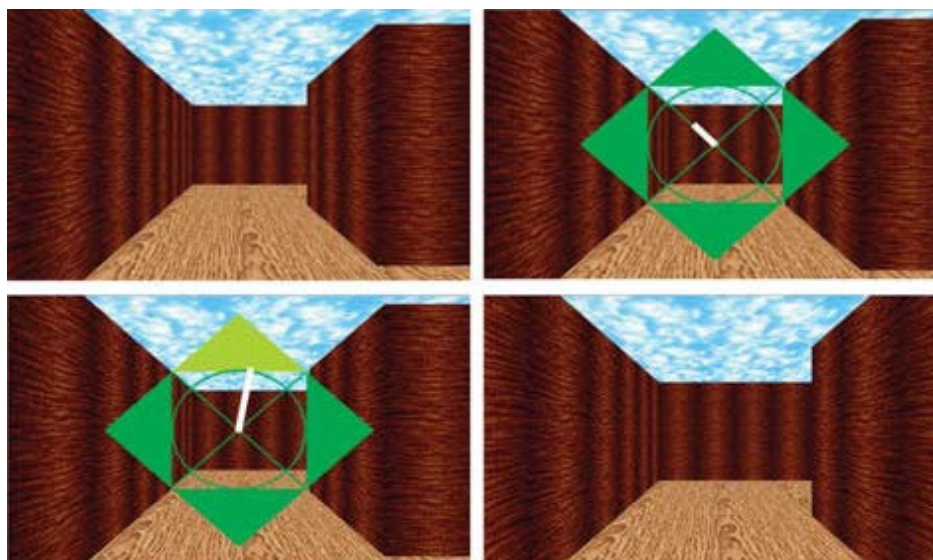
#### 1.3.1.1 Representative examples of virtual reality applications using a brain-computer interface

In this section we present a selection of examples of virtual reality applications making use of a brain-computer interface. The organization of these examples is inspired by the recent work done by Lotte et al. [Lotte et al., 2013a]. Indeed, concerning the VR interaction tasks defined by Bowman et al. and BCI paradigms, they observe that “each BCI paradigm is more or less suitable for each category of interaction task. For instance, motor imagery and SSVEP-based BCIs seem more suitable for navigation tasks and possibly object manipulation because they can issue commands continuously



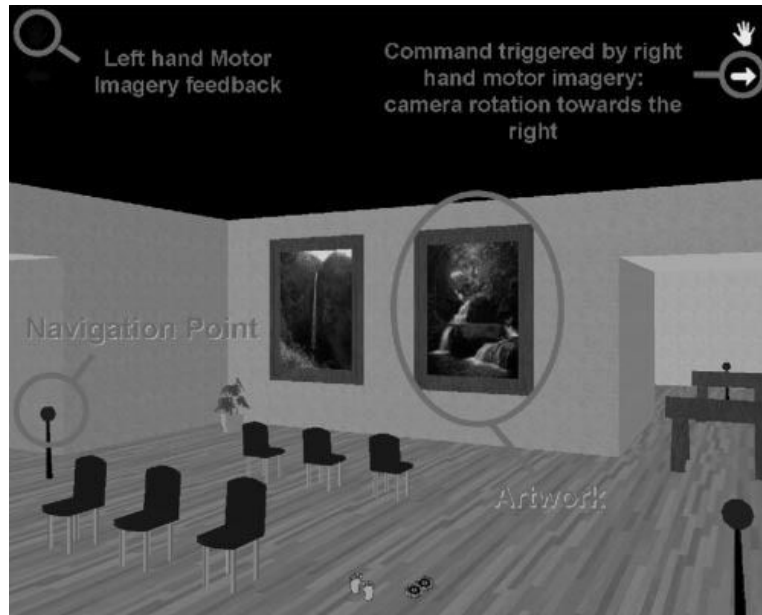
and potentially in a self-paced way. On the other hand, a P300-based BCI let the user pick one item among a list of usually at least four, such a command being issued in a discrete and synchronous way. For this reason, they are more suitable for object selection tasks” [Lotte et al., 2013a]. This underlines the importance of the choice of the BCI paradigm combined with the VR system. The following examples are organized depending on the BCI paradigm they are using. The interested reader can refer to the following book chapter: [Lotte et al., 2013a] and the following articles: [Lécuyer et al., 2008; Lecuyer et al., 2013] for a more complete survey and overview of previous work on BCI and VR.

**Motor imagery:** one possible use for motor imagery within a virtual environment is for navigation purposes. Ron-Angevin et al. have designed a system where users could send four commands: move forward, move backwards, turn left, and turn right [Ron-Angevin et al., 2009]. Their interface comprised a circle, surrounded by symbols representing these commands (see Figure 1.17).



**Figure 1.17** – Interface used for navigation in a virtual environment, comprising a circle and a rotating bar used to select the command to be run. The motor imagery paradigm was used to trigger the command selection [Ron-Angevin et al., 2009].

A bar was continuously rotating in its center, and users could control the length of this bar with the help of two motor imagery tasks. Commands were run each time the bar would reach the corresponding command symbol. This system has been later extended by Velasco-Álvarez et al. [Velasco-Álvarez et al., 2010]. In their setup, users could navigate a wheelchair in a virtual environment using a similar “command circle”, but two steps were required to run a command: select it, and choose the amplitude of the movement. This choice was achieved thanks to the same rotating bar: the length of the bar represented the amplitude. While the previous commands can be seen as being “low-level”, Lotte et al. proposed “high-level” commands as an alternative [Lotte et al., 2010]. In their system, users could navigate within a virtual museum with the help of points of interest that were generated automatically depending on the geometry of the virtual environment. Users had to select a destination instead of issuing basic commands like moving in a straight line or rotating (see Figure 1.18).



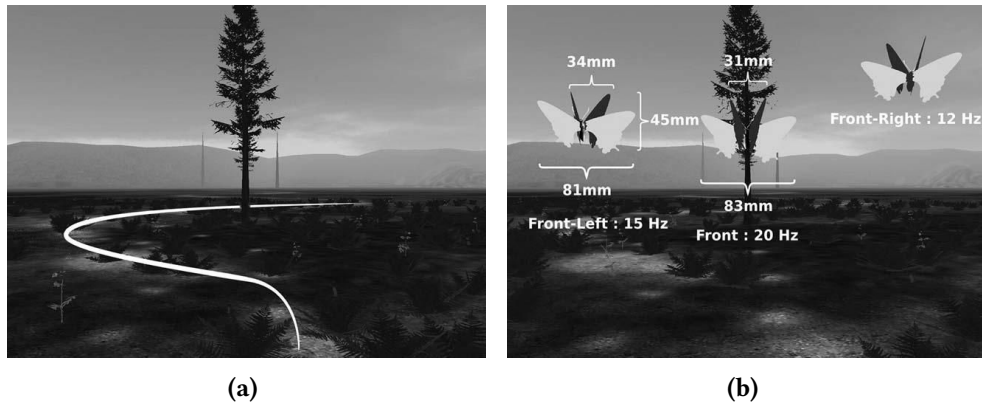
**Figure 1.18** – Virtual museum navigation based on a BCI and associated user interface proposed in Lotte et al. [Lotte et al., 2010].

**SSVEP:** making use of SSVEP in a VR environment was first proposed by Lalor et al. [Lalor et al., 2005]. Their system was composed of a 3D animated character that had to walk on a tightrope within a virtual environment. The movement of the character was conditioned by the output of the BCI. Users had to look at one of two checkerboards placed on each side of the screen so that the character would keep its balance (see Figure 1.19). A user study showed that the visually rich environment allowed for a reliable control using SSVEP.



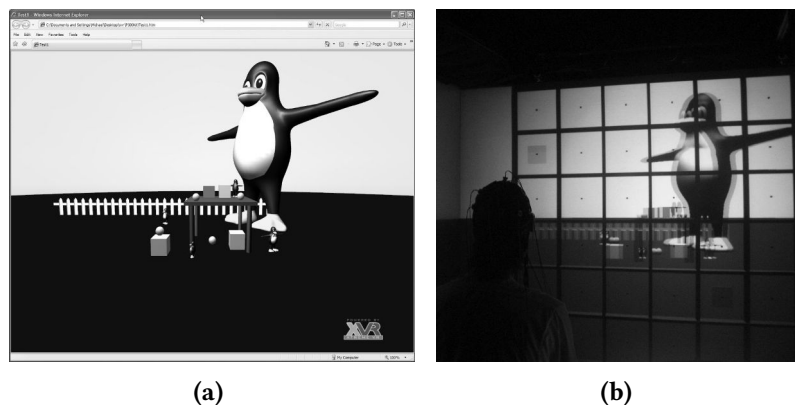
**Figure 1.19** – Mind-Balance game showing the use of a SSVEP-based BCI with a virtual environment [Lalor et al., 2005].

An ecological way of using SSVEP in a virtual world has been shown by Legény et al. [Legény et al., 2011]. In this case the user had to focus on butterflies to navigate in a virtual forest (see Figure 1.20). Each butterfly was flickering at a specific frequency and its antennae were used to represent the intensity of the command as detected by the BCI.



**Figure 1.20** – Navigation in a virtual environment using SSVEP. (a) Virtual environment with a path that had to be followed. (b) Three butterflies used as flickering targets for the SSVEP paradigm [Legény et al., 2011].

**P300:** an illustration of P300 usage in a VR environment was proposed by Donnerer et al. [Donnerer and Steed, 2010]. Their setup included a Cave Automatic Virtual Environment (CAVE)-like environment where various 3D objects were displayed. A selection task was asked from the users. Two variants were tested: selecting a blinking object or selecting a cell from a grid overlayed on the whole scene (see Figure 1.21). A user study, performed with this setup, showed that both selection tasks could be performed efficiently within a virtual environment.



**Figure 1.21** – Selection of objects from a scene or a cell from a grid based on P300 in a CAVE. (a) Object selection. One of the cubes is blinking. (b) Cell selection [Donnerer and Steed, 2010].

**Concentration/relaxation:** the association of the concentration/relaxation BCI paradigm with VR has been described by Lécuyer et al. [Lécuyer et al., 2013] in the form of a system called “Virtual Dagobah”. Their system used a CAVE environment to display a well known scenery from the movie “The Empire Strikes Back” where Luke Skywalker trains to become a Jedi. Users were wearing an EEG headset and could lift various objects such as a helmet, a robot, or a spaceship by performing a mental concentration task (see Figure 1.22). Each object had a particular weight which proportionally increased the difficulty and the concentration level required to lift it.

Considering the previous systems, we can observe that some paradigms have been used for some particular VR tasks, meaning that they may be more appropriate for these. According to Lotte et al., SSVEP and P300 were mostly used in previous work for selection or manipulation tasks because they enable the selection of objects by paying attention to them. Motor imagery and SSVEP seems more natural for navigation or manipulation tasks because they can issue commands continuously.





**Figure 1.22** – Cave Automatic Virtual Environment (CAVE) environment application using the concentration/relaxation BCI paradigm to lift objects by concentration [George, 2012].

### 1.3.1.2 Passive brain-computer interfaces and virtual reality

Passive brain-computer interfaces are used to monitor the brain activity of users while they are performing a task. A passive BCI can be used to adapt certain parts of a virtual environment, for instance changing the difficulty of a VR task when a high cognitive activity is detected. The following systems have associated a passive BCI with VR.

The “Alpha WoW” system integrated a passive BCI to the “World of Warcraft” video-game [Nijholt et al., 2009]. The BCI was used to evaluate the players stress level, and changed accordingly the appearance of their avatar from an elf to a bear (see Figure 1.23).



**Figure 1.23** – “Alpha WoW” application where a user avatar can transform itself in a bear depending on the users stress level [Nijholt et al., 2009].

The “Bacteria Hunt” system uses a passive BCI to adapt the controllability of a game-like application where users control an amoeba and have to eat bacteria moving on a field [Mühl et al., 2010]. The passive BCI was used to measure the players relaxation level using the alpha frequency band. Movement of the players avatar was done with the help of conventional input devices such as a keyboard and a mouse while an active SSVEP-type BCI was used to trigger the “eating phase” of the amoeba.

### 1.3.1.3 Hybrid brain-computer interface and virtual reality

Control within a virtual environment can be characterized by the tasks that users can perform within the virtual environment. Bowman proposed four tasks: selection of virtual objects, manipulation of these objects, navigation in the environment, and control of the application [Bowman, 1999]. Each one of these tasks could be performed using an element composing a hybrid BCI. This section proposes a selection of applications combining a hybrid BCI with a virtual environment and describes which VR task was performed with each hybrid BCI element.

**Combining P300 and SSVEP:** controlling home automation devices has been achieved by Edlinger et al. by combining P300 with SSVEP in a virtual environment (see Figure 1.24) [Edlinger et al., 2011]. The SSVEP paradigm was used to enable/disable the detection of P300 events. The SSVEP system used flickering LEDs or flickering symbols on a computer screen. There were 7 different control masks: light, music, phone, temperature, TV, move and go to. This system showed that the hybrid use of the P300 and SSVEP paradigms to select options from a panel presented a very good level of reliability and accuracy.



**Figure 1.24** – Home automation in VR driven by P300 and SSVEP. (a) A TV control mask, selection was achieved using the P300 paradigm. (b) Person issuing a command in the virtual environment [Edlinger et al., 2011].

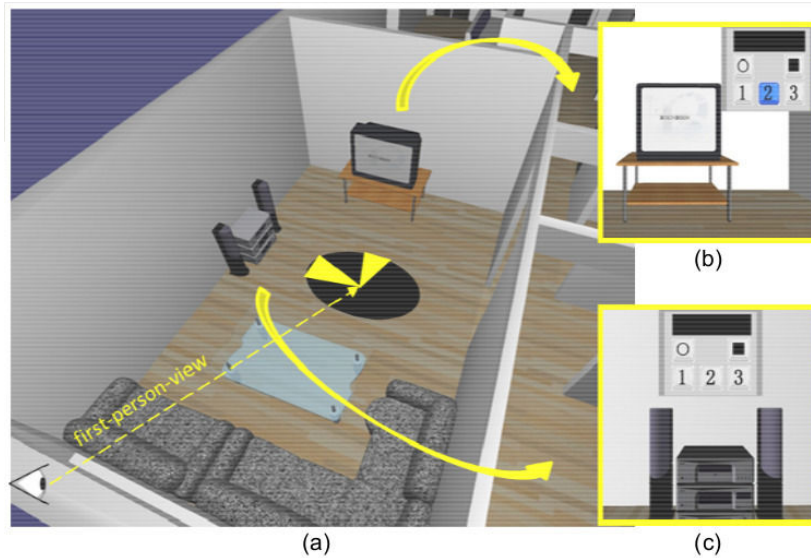
**Combining motor imagery and P300:** the motor imagery paradigm has been combined with the P300 paradigm to move and to control objects in a virtual environment (see Figure 1.25) [Su et al., 2011]. Motor imagery was used to move around in several rooms by allowing the user to imagine left or right hand movements. The P300 paradigm was used to operate virtual objects that were present in each room. A state switch was used to determine which paradigm should be detected. The control state was activated when the user was moving close to an object that could be controlled. The navigation state could be reached again by pressing a button. This system showed that the combination of motor imagery with the P300 paradigm could be successful in terms of BCI performance.

#### 1.3.1.4 Motor activity, brain-computer interfaces, and virtual reality

Using a brain-computer interface while performing a motor activity such as using a virtual reality device carries a risk of producing artifacts in the EEG signal [De Clercq et al., 2006].

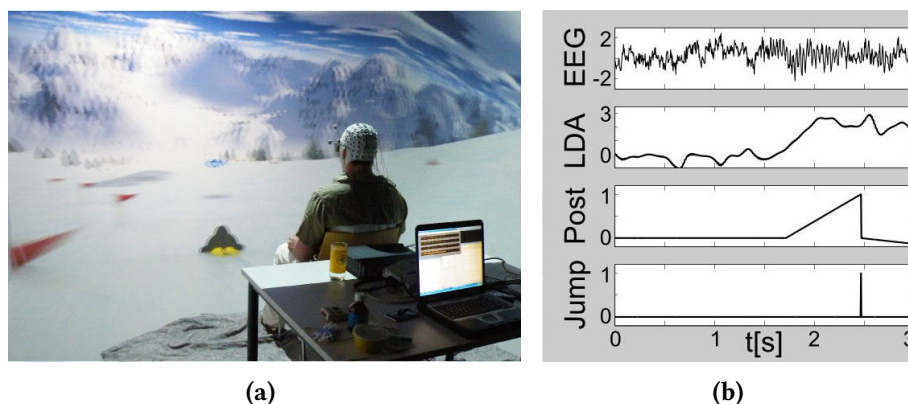
Motor activity can be triggered by the use of common input devices like a mouse or a joystick. The combined use of BCIs with other input devices such as a mouse has been rarely studied in BCI or VR scientific communities. But a recent example of this is an application called “Bacteria Hunt” in which the controllability of a mouse was impaired proportionally to the level of alpha band power, which was in this application correlated to relaxed wakefulness [Mühl et al., 2010]. In “AlphaWow”, which is based on the video-game World of Warcraft, the user’s avatar transforms itself from an elf to a bear according to the measured level of alpha activity [Nijholt et al., 2009]. However, the authors of these studies did not specifically compare the use of their setup with and without the manipulation of the mouse.

In the context of virtual environments, two other representative studies reported on setups combining a joystick and BCI. First, Kreiling et al. proposed to switch alternatively from joystick to BCI to provide a continuous source of reliable control [Kreiling et al., 2012]. Both devices were not used simultaneously. The VR entertaining application consisted in controlling a car to collect



**Figure 1.25** – A virtual environment where various objects can be controlled with the help of motor imagery and P300. (a) up-down view of one room of the virtual environment. (b) a TV object than can be controlled using the P300 paradigm. (c) a stereo object that can be controlled. The three numbered buttons correspond to channels or songs that can be selected. The circle button triggers the exit of the control state while the square button stops the playing of a channel or song [Su et al., 2011].

coins and avoid obstacles. A reliability score was computed for both devices, allowing the selection of the most reliable device at any time. The switching between BCI and joystick was found to improve the user experience, allowing participants to control the car even after losing control of one of the devices. Combining motor imagery with a joystick, Leeb et al. proposed a hybrid BCI system using a virtual environment and consisting of a track and a penguin sliding on it [Leeb et al., 2013]. A mountainous background was displayed to further enhance the users immersivity. A motor imagery paradigm was used to make the penguin jump to catch one of multiple fish laying on the track. While the BCI task was the primary task, users also had to perform a secondary task: controlling the trajectory of the penguin thanks to a joystick. The environment was displayed within a CAVE system. The virtual environment of the CAVE system increased the motivation of the users to get a better score and thus to improve their performance. This hybrid interaction scheme was found globally efficient and well appreciated by the participants. However, the mutual influence of motor and mental activities is not the main purpose of this article.



**Figure 1.26** – A game-like virtual environment where users had to control a penguin by using a joystick and make it jump thanks to a BCI. (a) A user in front of the virtual environment. (b) Data gathered and processed during a virtual jump attempt [Leeb et al., 2013].

### 1.3.2 Neurofeedback and virtual reality

The last decade has seen an increase of interest in using VR as a motivating feedback for neurofeedback systems. According to Heinrich et al., neurofeedback can be defined as “a form of behavioural training aimed at developing skills for self-regulation of brain activity” [Heinrich et al., 2007]. For this self-regulation to operate, users have to get a real-time feedback about their brain activity. While a BCI is a way to send data to a computer, neurofeedback proposes a loop of information between the computer and the user. For example, users could be sitting in front of a computer screen, looking at a gauge representing their brain activity in a particular frequency band [Neuper and Pfurtscheller, 2010]. Their objective would then be to maximize this activity by performing a cognitive task related to this frequency band. Users would then learn to elicit this type of brain activity and see their performance improve over time. Neurofeedback has been used to help curing epilepsy, anxiety, and alcoholism [Hammond, 2007], and provides an alternative to stimulant medication for some treatments like attention deficit hyperactivity disorder [Fuchs et al., 2003].

Virtual reality can be used to improve neurofeedback results for attention deficits, as shown by Cho et al. [Cho et al., 2004]. They have designed a virtual classroom where participants were asked to perform a continuous performance task, which “provides measurements of the ability to respond and pay attention” [Cho et al., 2004].

It has also been shown that using a virtual environment in neurofeedback systems can improve the performance of the BCI (and thus neurofeedback performance) by providing additional information about the underlying brain activity [Lotte et al., 2013b].

### 1.3.3 Brain-computer interfaces and augmented reality

The idea of combining a brain-computer interface with augmented reality has been proposed by Navarro [Navarro, 2004]. The purpose of the author was to find a way to incorporate BCIs “into daily life” by designing a “wearable BCI”. According to her, the limitations of BCI systems were “slow users response times, excessive error rates, high cost, actual appearance and long initial training periods”. Based on the results of the BCI Competition at Graz University of Technology in 2003 [Blankertz et al., 2004], she suggested the use of the P300 paradigm for its low error rate. Acknowledging a possible issue with the selection time, she also mentioned the SSVEP paradigm as an alternative. The author expressed the issue of using a BCI in a highly changing environment. Navarro thus proposed the use of AR as a way to obtain a “transparent coupling” of the BCI in the varying environments.

The following sections will present the systems including a BCI and AR depending on their main objective: the manipulation of real objects, the manipulation of virtual objects, and the visualization and analysis of brain activity. The systems are then organized depending on the BCI paradigm they are using: motor imagery, SSVEP, or P300.

#### 1.3.3.1 Manipulation of real objects

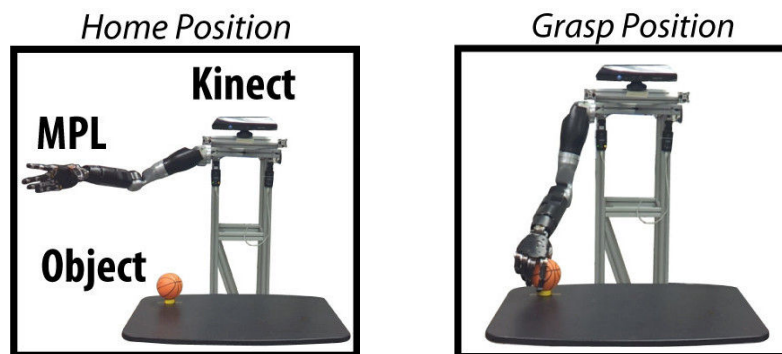
Several systems combining augmented reality and a brain-computer interface aim at manipulating mechanical devices like robots or mechanical arms, as well as other electronic devices like electrical home appliances.

**Motor imagery:** making use of dry EEG electrodes, Lampe et al. proposed a setup where users were manipulating a robotic arm using a BCI [Lampe et al., 2014]. Users were controlling the arm from another location. The data coming from the BCI and image data coming from a camera placed on the arm were transferred through the Internet. They used a neural network classification system to obtain commands from the BCI. These commands were sent through an AR interface. A reaching-grasping task was carried out. A user study has shown that both tasks could be performed whith



dry EEG electrodes, however the online motor imagery classification showed above chance results for only three of the five participants.

A more invasive setup, relying on electrocorticography, has been designed by McMullen et al. and Katyal et al. (see Figure 1.27) [McMullen et al., 2014; Katyal et al., 2013, 2014]. Their systems made use of a framework called “HARMONIE”, which can be used with EEG and electrocorticography based BCIs. This framework integrates AR computer vision to perform object recognition and a modular user interface that uses AR to control a robotic arm for tasks like reaching or grasping objects. While the experiment carried out by McMullen et al. used the motor imagery paradigm, Katyal et al. used the SSVEP paradigm in addition.



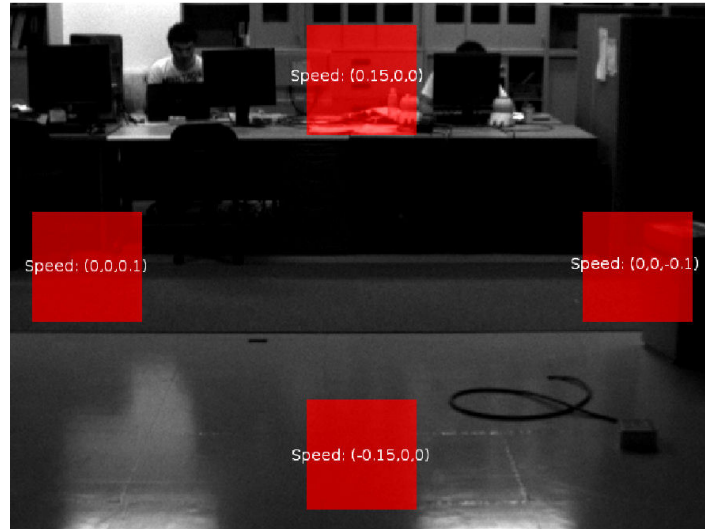
**Figure 1.27** – A prosthetic limb driven by several input devices in AR, including a BCI [Katyal et al., 2013].

**SSVEP:** the SSVEP BCI paradigm has been used by Gergondet et al. to allow users to steer a robot by looking in four different directions: forward (up), backward (down), left, and right (see Figure 1.28) [Gergondet et al., 2011]. Users could see on a computer screen the images taken by a camera placed on the robot. The four directions were displayed overlaid on the video feed.

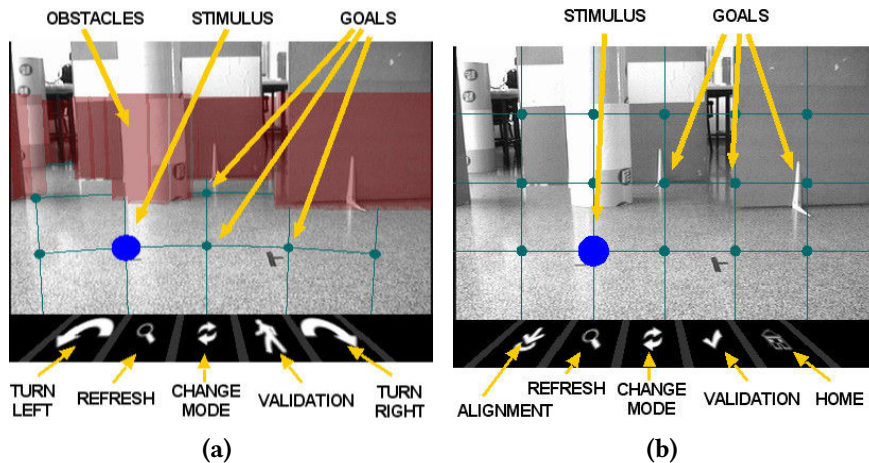
Another system proposing to manipulate a robot was designed by Petit et al. in a similar setup where the robot would see the user and interact with her with the help of AR markers [Petit et al., 2014]. Users were wearing a Head-Mounted Display (HMD) as well as an EEG cap fitted with electrodes. Tasks ranged from navigation to touching a marker placed on the user’s arm. Instead of a robot, a robotic arm has been used by Martens et al., driven thanks to the SSVEP paradigm. The robotic arm was used to insert a key in a keyhole, in order to open a door [Martens et al., 2012]. Their setup also included the P300 paradigm, where users had to manipulate a robotic arm to move objects on a field. This manipulation was achieved using a P300 speller grid to select both the object to move and the target position. Finally, Blum et al. have studied the use of a BCI and SSVEP combined with a gaze-tracker and AR to pilot an X-ray device [Blum et al., 2012b]. Their objective was to allow physicians to use the X-ray device without having to use their hands. The pilot study performed by Blum et al. included the BCI device, but the brain activity data was not recorded.

**P300:** systems using the P300 BCI paradigm combined with AR can be divided into three groups depending on how the AR interface is being displayed to the users.

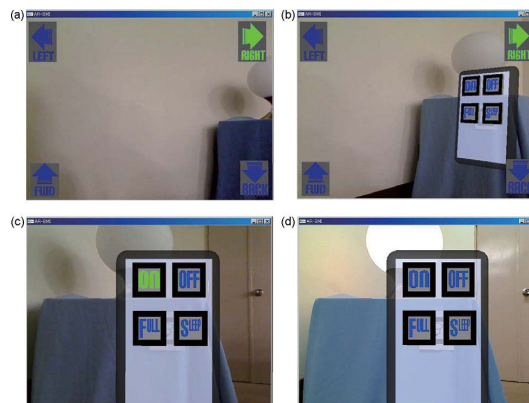
In the first group, systems use a regular computer screen to display the interface. Two systems designed by Escolano et al. allow users to pilot a robot with the help of a 2D grid of circles that can be selected using P300 and is overlaid to the video feed recorded by the robot’s camera (see Figure 1.29) [Escolano et al., 2009, 2012]. Users could experience telepresence, since they were controlling a robot whose commands input and video feed output were transferred through the Internet. In a similar setup, Kansaku et al. designed a system where the user seeing through the robot’s camera could interact with various home appliances thanks to virtual buttons overlaid to real-world AR markers (see Figure 1.30) [Kansaku et al., 2010].



**Figure 1.28** – An AR display used to control the steering of a robot. Four squares were flickering on each side of the display to allow selection using the SSVEP paradigm [Gergondet et al., 2011].



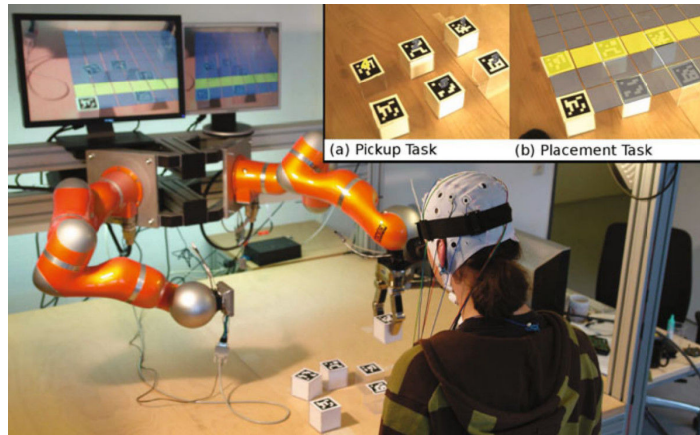
**Figure 1.29** – An AR interface allowing to steer a robot using P300. (a) Navigation mode. (b) Camera control mode [Escolano et al., 2009].



**Figure 1.30** – An AR interface allowing the control of multiple home appliances using a moving robot [Kansaku et al., 2010].

In the second group, users were wearing a see-through HMD. This has been illustrated by Lenhardt et al. in a setup where users visualized a set of cubes under AR markers (see Figure 1.31)

[Lenhardt and Ritter, 2010]. This system required users to select and manipulate these cubes to move them in a particular fashion with the help of a pair of robotic arms placed in front of the user. The P300 paradigm was used for both tasks.



**Figure 1.31** – A robotic arm driven using the P300 paradigm, as well as objects to be picked-up and placed, overlaid in AR [Lenhardt and Ritter, 2010].

The last group contains systems including both a computer screen and a HMD. Both systems by Kansaku and Takano et al. proposed to use either devices to display an AR interface, either as a video feed recorded by a robot’s camera, or using a see-through HMD (see Figure 1.32) [Kansaku, 2011; Takano et al., 2011]. Their systems allow the triggering of various home appliances.



**Figure 1.32** – An AR system allowing users to look at various appliances and sending commands to them using a BCI [Kansaku, 2011].

### 1.3.3.2 Manipulation of virtual objects

Manipulation of virtual objects is also an objective that has been achieved in previous work combining AR and a BCI. Goals range from selecting a cube in a 3D grid to control the movement of a virtual avatar overlaid on a real-world table. This previous work is presented hereafter, divided into three groups, depending on which BCI paradigm is being used: motor imagery, SSVEP, or P300.

**Motor imagery:** controlling virtual hands overlaid on top of the user's hands, Chin et al. proposed a setup where users could reach and grasp objects using the motor imagery BCI paradigm (see Figure 1.33) [Chin et al., 2010]. They performed a user-study comparing the AR feedback to a simple 2D progress bar, and found that users felt that AR was more engaging and motivating. In addition, they found that the performance of the BCI was not impacted by the AR setup.

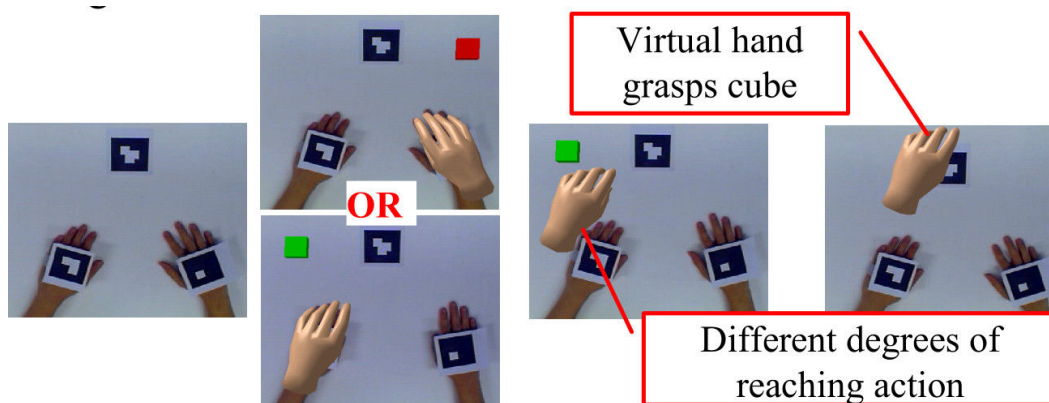


Figure 1.33 – Real hands overlaid by virtual hands that are controlled using a BCI [Chin et al., 2010].

**SSVEP:** using the SSVEP paradigm, Faller et al. used both VR and AR to display virtual and augmented environments (see Figure 1.34) [Faller et al., 2010]. They conducted a user study which comprised multiple scenarios where users had to control an avatar with the help of the SSVEP paradigm. One of these scenarios used AR to display the avatar on top of a real-world table. Users were wearing a HMD. Their objective was to move the avatar through a series of points in the 3D environment, each one of them being represented by the SSVEP flickering targets.

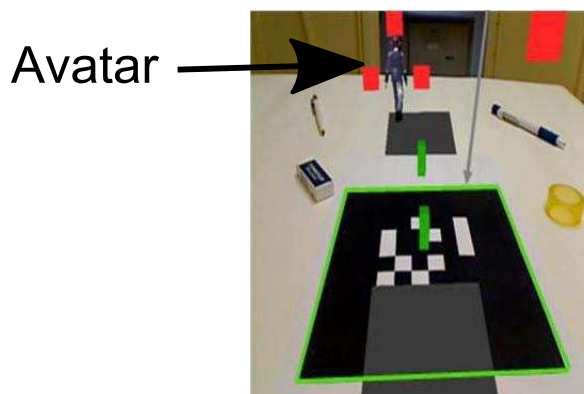
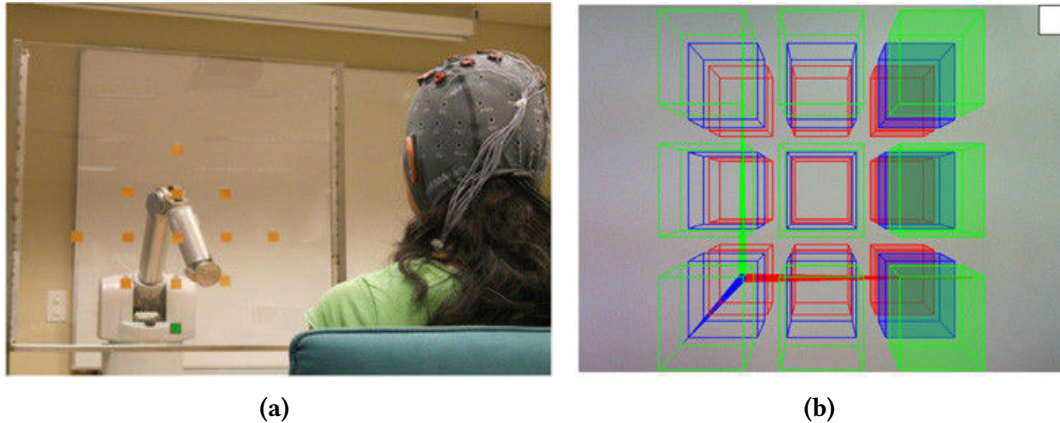


Figure 1.34 – A virtual avatar overlaid on a table using AR and controlled with SSVEP [Faller et al., 2010].

**P300:** using both the P300 paradigm and the detection of error potentials, which are “neural correlates to error awareness” [Buttfield et al., 2006], Iturrate et al. studied how latency variations could affect various BCI applications (see Figure 1.35) [Iturrate et al., 2014]. To this end, they designed multiple experiments, one of them involving AR. In this experiment, users had to select a cube from a 3D grid with the P300 paradigm and manipulate a robotic arm using error potentials. Both manipulation used a transparent panel as an AR support.





**Figure 1.35** – Two applications using either error potentials (a) or P300 (b) combined with AR [Iturrate et al., 2014].

Some work on brain-computer interfaces and augmented reality have also studied applications other than controlling robotic elements, home appliances or virtual objects. The following systems are using a BCI to record and display information rather than sending commands.

### 1.3.3.3 Brain activity visualization and analysis

Brain activity measurement and visualization based on AR and EEG have been performed by Frey et al. in the form of a “Tangible EEG Interface” (see Figure 1.36) [Frey et al., 2014]. The main purpose of their application is educational: users get to learn how an EEG-based BCI works and understand which kind of brain activity can be detected with EEG. Their system called “Teegi” consisted of a figurine serving as a support for a projector-based AR. The brain activity of users was recorded using an EEG cap and displayed on the head of the figurine. Users could watch their brain activity in real-time and interact with it. Moving this character on specific areas on a desk would let users select which kind of activity was monitored: meditation, vision, or motor activity.



**Figure 1.36** – Teegi system: a tangible character whose head is overlaid by a dynamic representation of the brain activity of the main user wearing an EEG cap [Frey et al., 2014].

A study performed by Acar et al. evaluated the use of “Virtual Reality Exposure Therapy” to help curing phobias and obsessions [Acar et al., 2014]. Their system displayed AR elements on a smartphone like a bee or a non-symmetric painting, so that users suffering from a phobia against insects or having an obsession for symmetry could train overcoming their fear. A BCI using EEG was used to measure various frequency bands.



**Figure 1.37** – An application using AR with a smart phone together with a BCI to treat anxiety disorders. A virtual insect can be seen in the hand of a user [Acar et al., 2014].

#### 1.3.3.4 Discussion

In this section, we proposed an overview of the related work concerning systems combining a BCI with AR. Table 1.1 summarizes the properties of such systems combining BCI with AR. We described these systems using two criteria: their main objective and the BCI paradigm that has been used. This overview shows that most of the objectives of the aforementioned systems was to allow users to manipulate robotic devices or control home appliances with the help of a BCI. This could be explained by the fact that robots and mechanical arms are commonly used by paralyzed or physically impaired persons, so as BCIs. In this use-case AR seems equally appropriate because it allows users to have a third-person view of the operation being carried out. Concerning the BCI device, this overview shows that almost all setups used an EEG-based BCI. Table 1.1 also shows that the selection task has been performed with the BCI most of the time. Both manipulation and navigation tasks were performed less frequently. Selection tasks are most frequently achieved thanks to the P300 BCI paradigm, followed by SSVEP. Navigation tasks have been performed with P300 and SSVEP, while manipulation tasks have been mostly executed with motor imagery or motor execution. The control task has only been performed once using SSVEP, but the setup did not make use of the BCI, so only subjective results are available. Concerning the AR devices, computer screens have been used most of the time, followed by HMDs. Finally, this overview also shows that the combination of a BCI and AR is usually performed with the P300, SSVEP, or motor imagery BCI paradigms, with a few exceptions [Frey et al., 2014; Acar et al., 2014]. Likewise, these systems are using an active BCI to send commands to a device.

System	Objective	BCI device	BCI paradigm	3D task	AR device
[Escolano et al., 2009]	Manip. a robot	EEG	P300	Select./Nav.	CS
[Lenhardt and Ritter, 2010]	Manip. a robotic arm	EEG	P300	Select./Manip.	HMD <sup>1</sup>
[Kansaku et al., 2010]	Manip. a robot	EEG	P300	Select.	CS
[Faller et al., 2010]	Avatar control in 3D env.	EEG	SSVEP	Select./Nav.	HMD
[Chin et al., 2010]	Manipulation virtual objects	EEG	MI	Manipulation	CS
[Kansaku, 2011]	Manip. a robot	EEG	P300	Select./Nav.	CS/HMD <sup>1</sup>
[Takano et al., 2011]	Home automation	EEG	P300	Select.	CS/HMD <sup>1</sup>
[Gergondet et al., 2011]	Manip. a robot	EEG	SSVEP	Select./Nav.	CS
[Escolano et al., 2012]	Manip. a robot	EEG	P300	Select./Nav.	CS
[Blum et al., 2012b]	X-ray device manipulation	EEG	SSVEP <sup>2</sup>	Control	CS/HMD <sup>1</sup>
[Martens et al., 2012]	“pick-and-place” task Manip. a robotic arm	EEG	P300/SSVEP	Manipulation	HMD
[Katyal et al., 2013]	Manip. a robotic arm	EEG/ECoG	SSVEP/MI/ME	Select./Manip.	CS
[McMullen et al., 2014]	Manip. a robotic arm	ECoG	ME	Select./Manip.	CS
[Lampe et al., 2014]	Manip. a robotic arm	EEG	MI/ME	Select./Manip.	CS
[Katyal et al., 2014]	Manip. a robotic arm	EEG/ECoG	SSVEP/MI/ME	Select./Manip.	CS
[Iturrate et al., 2014]	Virtual object selection	EEG	P300/evoked potentials	Select.	Transp. panel <sup>1</sup>
[Petit et al., 2014]	Manip. a robot	EEG	SSVEP	Select./Nav.	HMD
[Frey et al., 2014]	Visualize the brain activity	EEG	Brain activ. topology	None	Video-projector
[Acar et al., 2014]	Fear treatment	EEG	Freq. band meas.	None	Smartphone

**Table 1.1** – Systems combining a BCI and AR. ECoG denotes Electrocochography, MI denotes Motor Imagery, ME denotes Motor Execution, and CS denotes Computer Screen.

<sup>1</sup> AR device with a see-through design.

<sup>2</sup> BCI set up but not used, subjective results only.

## **1.4 Conclusion**

This chapter presented an overview of the previous work on BCIs and their use in combination with other inputs and in particular with VR/AR systems. A short description of the brain structure and how brain data acquisition can be achieved have been provided. An overview of common EEG markers and how they are used in BCI setups has been proposed. Then, an overview of the combination of BCIs with other BCIs or other input devices has been provided. Hybrid BCIs have been described, together with a presentation of some illustrative and representative systems. Finally, the combination of BCIs with VR and AR has been studied and presented in the final part of this chapter.

## Chapter 2

# Can we use a brain-computer interface and manipulate another input device at the same time?

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As of today, very few studies have combined a brain-computer interface with other and more standard input devices such as mice, joysticks or gamepads [Leeb et al., 2013; Mühl et al., 2010]. One main reason is that muscular activity is known to add artifacts in electrical signals that can considerably impair the process of identifying brain activity. Several approaches have been proposed to detect and remove muscular artifacts, like the independent component analysis or the principal component analysis [Lee and Choi, 2003]. But these approaches are not always effective. Thus, the BCI user is often asked to remain motionless and is not free to use other interaction devices based on her motor activity. As a result, the integration of a BCI with VR technologies, and their combination with other 3D interaction techniques remain at a very early stage.

There have been few specific studies on the influence of additional motor activity on the performance of a BCI. First, Lotte et al. reported on a preliminary study evaluating the influence of locomotion and ambulatory motor activities on the performance of a BCI based on P300 [Lotte et al., 2009]. Three different locomotion conditions were tested with different ambulatory motions: sitting, standing and walking. Successful classification of auditory P300 signals could be achieved off-line in every condition and the best mean classification score was obtained in standing condition. In another study, Gürkök et al. found out that the control of a BCI was not impaired by speaking [Gürkök et al., 2010]. The experiment involved left hand versus right hand motor imagery, with and without speaking. It was established that the (facial) muscular activities involved when speaking had no major impact on the classification results.

This chapter aims at studying whether a BCI could be used in the context of interacting with a virtual environment in combination with mouse manipulation. With this goal in mind, we have designed a virtual environment using a BCI that relies on alpha brainwaves to discriminate between two classes of mental activity: concentrated versus relaxed mental activity.

The remainder of this chapter is organized as follows. The objectives and experimental protocol of our study are presented in Section 2.1. The Section 2.2 details the main results, which are then discussed in Section 2.3. The chapter ends with a general conclusion.

## 2.1 Experimental method

Our objective is to study if and how mouse manipulation and its related motor activity could influence the performance of a BCI when interacting with a virtual environment. This virtual environment is based on the Pac-Man video-game where the player is chased by ghosts and has to eat pellets. Control over the player's position is achieved with a mouse (a motor activity) while the eating of pellets is controlled using a mental activity through a BCI. Three complexity levels of motor activity are proposed:  $C_{MO1}$  (no motor activity, control condition),  $C_{MO2}$  (a semi-automatic motor activity, secondary task with no influence on gameplay) and  $C_{MO3}$  (a highly-demanding motor activity, the mouse is used for a primary task, i.e., controlling the position of a virtual character). The experiment makes use of a simple two-class BCI measuring the mental activity of the user related to either a relaxed mental activity ( $C_{ME-R}$ ) or a concentrated mental activity ( $C_{ME-C}$ ). Our purpose is to observe the evolution of BCI performance (i.e., the discrimination rate between relaxed and concentrated mental activities by the BCI system) according to the different levels of motor activity. The subjective preferences of the participants are also gathered.

### 2.1.1 Population

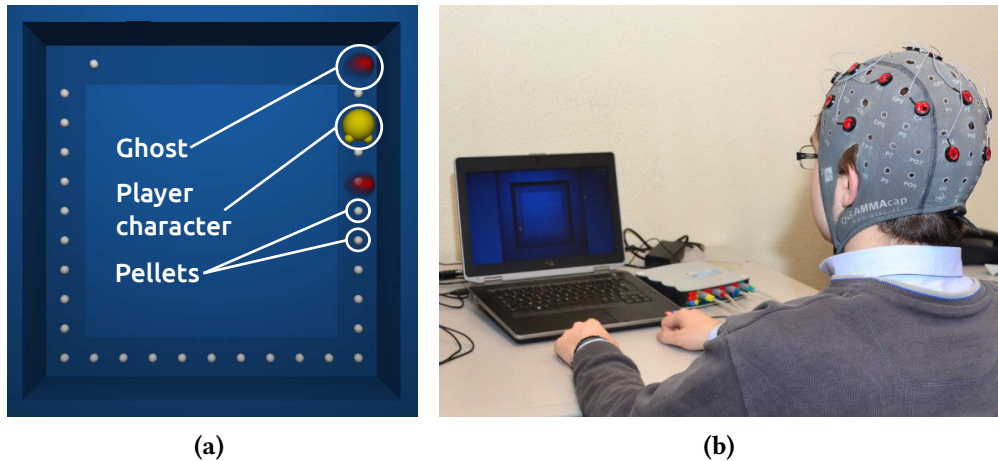
Eight healthy participants (1 female and 7 males, aged from 21 to 28, mean=24, sd=2.1) took part in the experiment. All participants except one were right-handed.

### 2.1.2 Experimental apparatus

The virtual environment application is a simplified variant of the Pac-Man video-game (see [Figure 2.1](#)), designed with the Unity3D game engine ([unity3d.com](http://unity3d.com)). Video-games are known to be a motivating environment for BCI experiments [[Lécuyer et al., 2008](#)]. The user controls a yellow blob in a maze and has to eat pellets to gain points while avoiding contact with two ghosts (two red blobs surrounding the yellow character). The game is controlled both with a mouse and a BCI system to control the eating of virtual pellets. The experiment was conducted in a room without environmental noise or other source of distraction.

Electroencephalographic activity was gathered with a g.USBamp (g.tec company, Austria) amplifier sampled at 512 Hz. Sixteen electrodes were used to gather EEG signals and one additional electrode was used as a reference. A ground electrode was placed on the user's left ear lobe. Electrodes were placed on positions Fp1, Fp2, F7, F8, T7, T8, F3, F4, C3, C4, P3, P4, O1, O2, Pz and Cz of the international 10-20 system. The reference electrode was placed on position FCz. EEG signals acquisition, processing and classification were done using the OpenViBE software platform [[Renard et al., 2010](#)]. The relaxed and concentrated mental activities of the user were determined with the alpha activity which is known to increase during relaxation and can be measured on the posterior half of the head [[Niedermeyer and da Silva, 2005](#)]. The alpha activity was quantified thanks to a band power technique [[Pfurtscheller and Lopes da Silva, 1999](#)]. Band power was computed 16 times per second on a moving window of 1 second (windows could overlap). We have used the same signal-processing pipeline as in George et al. [[George et al., 2011](#)]. The signal-processing pipeline provides





**Figure 2.1** – Experimental setup. (a) Screenshot of our simplified version of the Pac-Man video-game. (b) Participant wearing an EEG cap in front of a monitor screen.

a two-class output that represents the level of relaxation/concentration. A negative (respectively positive) value means that the user has a relaxed (respectively concentrated) mental activity. The absolute value of the classifier output represents the intensity of the mental activity. For instance a value of -1.0 would indicate that the user is completely relaxed. A value of 0 would indicate that the user is not especially relaxed or concentrated.

### 2.1.3 Experimental plan

Three different levels of motor activity were used with a progressive complexity:

- $C_{M01}$ : no motor activity was executed. The player character was going forward automatically. If the BCI system detected the correct mental activity then the player character could eat pellets and was colored in yellow. Otherwise it was colored in gray.
- $C_{M02}$ : a semi-automatic motor activity was executed: the participant had to move the mouse continuously in circles. The player character was going forward automatically. If not enough mouse movement was measured then the character appeared blue and was earning fewer points when eating pellets. If the BCI system detected the correct mental activity then the player character could eat pellets and was colored in yellow instead of gray.
- $C_{M03}$ : a highly-demanding motor activity was executed: the participant had to move the mouse in the same direction as the player character along the square path (see [Figure 2.1](#)). The mouse movements actually controlled the motion of the character. The movements had to be at the right speed, to avoid two ghosts following and preceding the character and advancing at a constant speed. If the BCI system detected the correct mental activity and if the player character was correctly located between the two ghosts, pellets could be eaten and the character was colored in yellow instead of gray. If the player was too slow or too fast and moved behind or in front of the ghosts then she could not eat any pellet and the character was colored in red.

Two different mental activities were proposed:  $C_{ME-R}$  for the Relaxed mental activity and  $C_{ME-C}$  for the Concentrated mental activity. In each case participants were instructed to remain in the given mental state (Relaxed or Concentrated) during the whole trial, in order to collect and eat pellets.

### 2.1.4 Procedure

Each participant was informed about the complete test procedure which included a training phase. During the training phase, users had to watch a static cross on a computer screen and successively relax and concentrate for 30 seconds (see Figure 2.2). The gathered data was used to train the BCI classifier. Then the experiment involved 6 conditions corresponding to the combinations of 3 motor activity conditions ( $C_{MO1}$ ,  $C_{MO2}$ ,  $C_{MO3}$ ) and 2 mental activity conditions ( $C_{ME-R}$ ,  $C_{ME-C}$ ). The order of presentation of the 6 conditions was randomized. Each trial lasted around 1 minute and 30 seconds. The 6 conditions were run two times, ending up with  $(3 C_{MO}) * (2 C_{ME}) * (2 \text{ repetitions}) = 12$  trials, for a total duration of about 18 minutes.

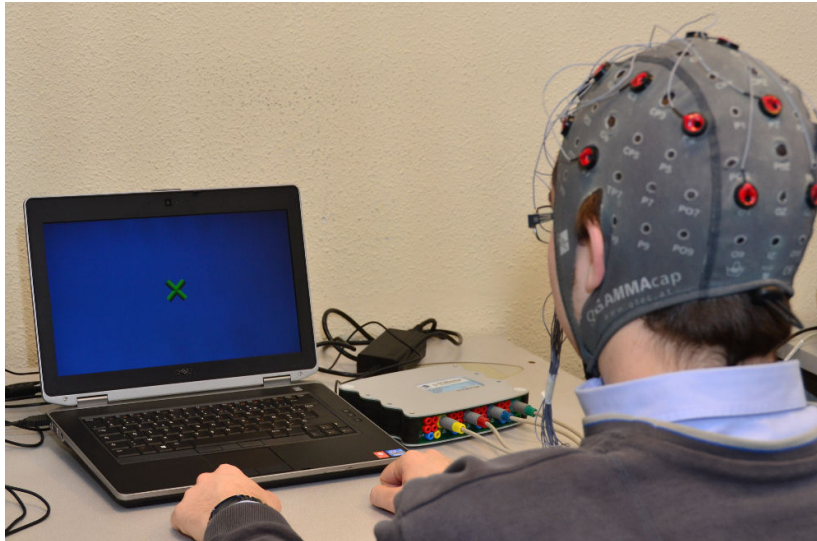


Figure 2.2 – A participant in our user study during the training phase.

### 2.1.5 Collected data

For each trial and each participant, we recorded the BCI classifier output (between -1, completely relaxed and 1, completely concentrated) resulting from the signal-processing pipeline. At the end of the experiment, participants had to fill out a subjective questionnaire with a 7-point Likert-scale. Criteria used were: (1) the ability for the user to generate the appropriate mental activity (1: no ability, 7: complete ability), (2) the ability of the BCI system to detect the mental activity of the user (1: no ability, 7: complete ability), (3) the appreciation of game conditions (1: did not like the conditions, 7: liked the conditions), and (4) the fatigue (1: very fatigued, 7: no fatigue at all).

## 2.2 Results

### 2.2.1 Classifier results

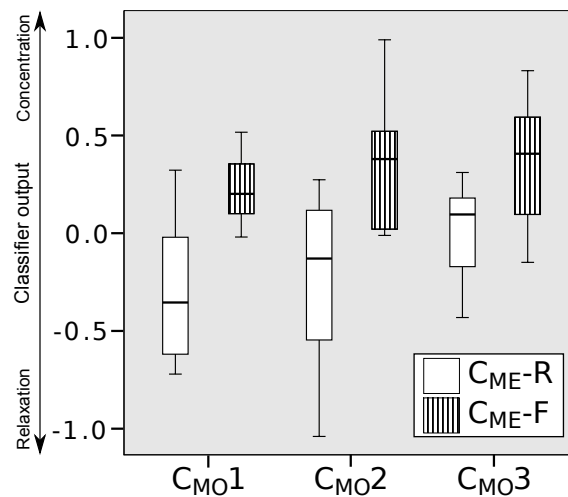
A mixed between-within subjects ANOVA was conducted to assess the impact of the three motor activities and the two mental activities on the BCI classifier output. We found a significant effect of the mental activity condition on the classifier output ( $F(1, 7) = 4.57, p = 0.005$ ). The mean value for the  $C_{ME-R}$  condition was  $-0.17$  ( $SD = 0.38$ ), while the mean value for the  $C_{ME-C}$  condition was  $0.31$  ( $SD = 0.29$ ). A paired-sample t-test showed a significant difference between  $C_{ME-R}$  and  $C_{ME-C}$  for all motor activity conditions:  $C_{MO1}$  ( $t(7) = -3.65, p = 0.008$ ),  $C_{MO2}$  ( $t(7) = -4.07, p = 0.005$ ) and  $C_{MO3}$  ( $t(7) = -3.02, p = 0.019$ ). The effect of the motor activity condition was not found significant ( $F(2, 6) = 3.63, p = 0.09$ ) and no significant interaction between motor activity and mental activity conditions was observed ( $F(2, 6) = 4.57, p = 0.06$ ). Classifier output for



each participant and each motor and mental activity condition are provided in [Table 2.1](#). [Figure 2.3](#) provides the boxplots for all participants and the different combinations of motor and mental activity conditions.

**Table 2.1** – Mean value of the classifier output for each participant (P1 to P8) and for each combination of motor and mental activities. The global mean and standard deviation are also provided. The classifier output values represent the concentrated (positive value) or relaxed (negative value) mental states.

	$C_{MO1}$ $C_{ME-R}$	$C_{MO1}$ $C_{ME-C}$	$C_{MO2}$ $C_{ME-R}$	$C_{MO2}$ $C_{ME-C}$	$C_{MO3}$ $C_{ME-R}$	$C_{MO3}$ $C_{ME-C}$
P1	-0.44	0.23	0.27	0.43	0.18	0.07
P2	0.32	0.52	0.24	0.99	0.31	0.83
P3	-0.26	0.04	-0.40	0.05	-0.43	-0.15
P4	-0.72	0.17	-1.04	-0.01	-0.32	0.59
P5	-0.56	0.29	-0.11	0.45	0.15	0.60
P6	-0.68	0.42	-0.69	0.59	-0.02	0.53
P7	0.20	0.16	-0.01	0.33	0.18	0.28
P8	-0.24	-0.02	-0.15	-0.01	0.04	0.12
<b>Mean</b>	-0.30	0.23	-0.24	0.35	0.01	0.36
<b>SD</b>	0.39	0.18	0.45	0.34	0.26	0.33



**Figure 2.3** – Boxplots of classifier output for each combination of motor and mental activities. They are delimited by the quartile (25% / 75%) of the distribution over all participants. The median is also represented for each boxplot.

## 2.2.2 Questionnaire results

Mean values of participant answers to the subjective questionnaire are provided in [Table 2.2](#). A Friedman test showed no significant difference between the different conditions for all criteria. From the results it seems that whatever the motor activity condition, the participants felt able to generate the appropriate mental activity depending on the instructions. Moreover, the participants globally

found that the BCI system correctly detected their mental activity. Results also indicate that participants enjoyed the different conditions of interaction with the game and have not found it to be too tiring.

**Table 2.2** – Mean values (and standard deviations in brackets) of answers to the subjective questionnaire, with respect to the conditions (7-point Likert-scale). The criteria are: (C1) the ability for the user to generate the appropriate mental activity, (C2) the ability of the BCI system to detect the mental activity, (C3) the appreciation of game, and (C4) the fatigue. Mental activities are differentiated for the two first criteria (relaxed and concentrated mental activity in this order).

	$C_{MO1}$	$C_{MO2}$	$C_{MO3}$
C1: Rel./Con.	5.62 (0.92)/4.62 (0.92)	4.87 (1.36)/4.87 (1.13)	4.37 (1.69)/5.62 (0.74)
C2: Rel./Con.	4.87 (1.89)/4.87 (1.64)	4.5 (1.77)/4.75 (1.83)	4.62 (1.69)/4.87 (1.46)
C3	5.25 (1.39)	4.25 (1.58)	5.62 (1.77)
C4	4.87 (1.13)	5 (1.41)	4.87 (1.89)

## 2.3 Discussion

Considering the analysis of the classifier output, a significant difference was found between the two mental activity conditions  $C_{ME-R}$  and  $C_{ME-C}$ , whatever the motor activity condition ( $C_{MO1}$ ,  $C_{MO2}$  or  $C_{MO3}$ ). Thus, the mental activity was correctly detected, even when participants were executing a highly-demanding motor activity with the mouse ( $C_{MO3}$ ). Participants were able to adapt their mental activity independently of any motor activity, showing the effectiveness of the BCI-based interaction proposed in this study.

Looking at Table 2.1, we can observe that the average values between  $C_{ME-R}$  and  $C_{ME-C}$  are closer when the motor activity is highly demanding ( $C_{MO3}$ ). It suggests that the BCI is less effective in  $C_{MO3}$  than in the other motor activity conditions. The mean classification value for the combination of the conditions  $C_{MO3}$  and  $C_{ME-R}$  suggests that participants had some difficulties executing a highly-demanding motor activity while trying to achieve a relaxed mental activity. However, no significant difference was found in the subjective questionnaire for the subjective ability to generate the appropriate activity. This suggests that the user’s subjective perception of the BCI-based interaction was not considerably affected by the motor activity condition.

## 2.4 Conclusion

In this chapter, we have presented a study on the influence of motor activity and mouse manipulation on the performance of a simple BCI for controlling a virtual environment. Different levels of motor activity were tested: no motor activity, a semi-automatic motor activity and a highly-demanding motor activity. Our results show that our simple 2-class BCI could be successfully used in each case, even in presence of a highly demanding motor activity (when the users were carefully controlling the 2D position of a virtual character with the mouse). Moreover, participants subjectively felt that they were able to control their mental activity in all cases, and enjoyed the entertaining and hybrid mouse/BCI interaction with the virtual environment. These results pave the way not only for future experimental studies with more complex mental and motor activities but also for novel 3D interaction paradigms that could mix BCIs and other input devices for VR and video-game applications.

## Chapter 3

# Real-time brain activity visualization using augmented reality

### Contents

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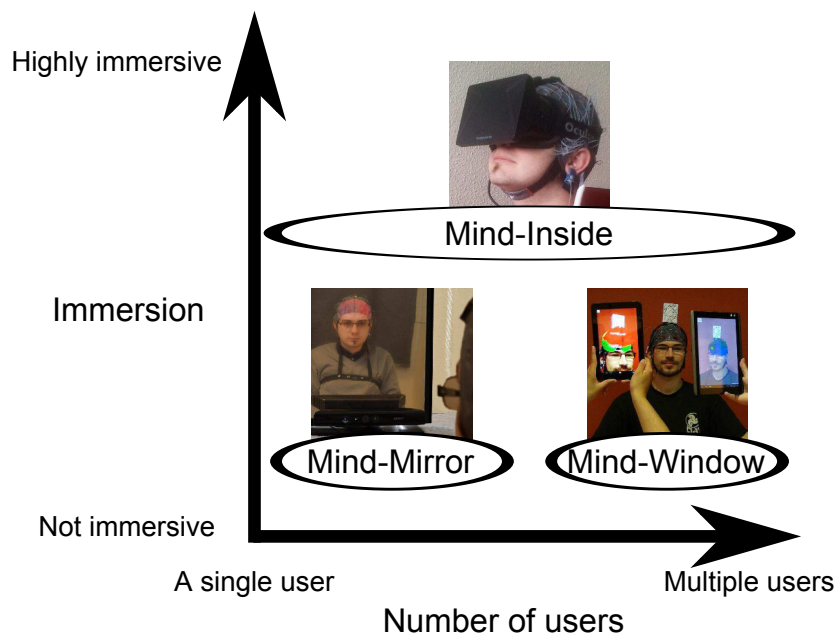
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This chapter presents three novel systems for the visualization of brain activity in real-time based on electroencephalography and virtual/augmented reality. These approaches could allow users to better learn how to control their brain activity. The first system is the “Mind-Mirror”, which provides a way for users to visualize their own brain activity in real-time as if they were looking in a mirror. We then propose to allow more than one user: the Mind-Window allows multiple users to view their own brain activity or the one of other persons. This visualization is still performed using AR, but with the help of tablet PCs. Our third contribution is a system improving immersion: the Mind-Inside. This system uses VR instead of AR, resulting in an improved sensation of immersion. The Mind-Inside uses a HMD and allows to be immersed inside one's brain, i.e. a volumetric display of brain activity. [Figure 3.1](#) presents a decomposition of our three systems. Thus our objective is here to study different levels of immersion and different cases on interaction (single or multiple users).

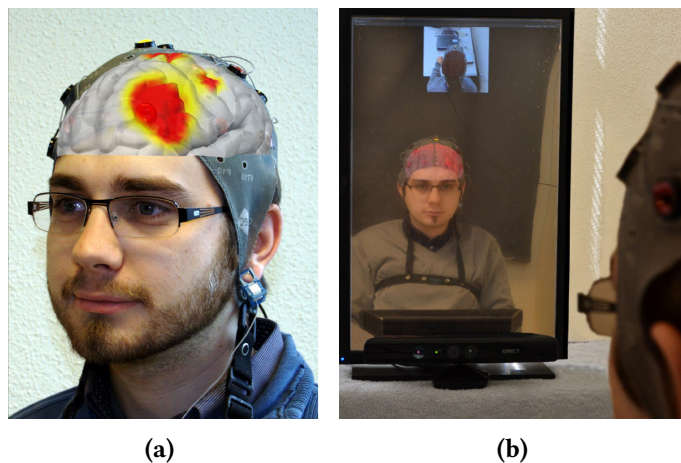
### 3.1 Mind-Mirror: view your brain in activity as in a mirror

Our first setup called “Mind-Mirror” enables the visualization of our own brain activity “inside our own head” by superimposition (see [Figure 3.2](#), (a)). The brain activity is extracted in real-time using



**Figure 3.1** – Decomposition of our three systems for the visualization of brain activity in real-time in terms of immersion and interaction with other people.

an EEG acquisition machine and is displayed in a mirror-based AR setup in front of the user's skull in semi-transparency. The Mind-Mirror could therefore be used for entertaining or educational activities, or for neurofeedback applications, i.e., training to control our brain while being in a more natural, engaging, and immersive environment.



**Figure 3.2** – The Mind-Mirror prototype. (a) A virtual brain superimposed onto the real user's image (photomontage). (b) Our mirror-based augmented reality setup.

### 3.1.1 Related work on mirror-based augmented reality

Since the beginning of augmented reality the properties of half-silvered screens have been used to superimpose various graphics on top of real objects. These objects could be buttons [Knowlton, 1977] or virtual enemies in a video-game [Piekarski and Thomas, 2002]. In both cases, displayed objects would seem very realistic to the user since they are superimposed over real objects. These virtual objects are not directly dependent on the mental state of the user. A recent paper has shown that a high quality display of flames and smoke on a user's hand in AR could induce a heat sensation [Weir et al., 2012]. Thus the realistic display of a virtual stimulation on a body part seems to have a

strong impact on the sensations of users.

Mirror-based systems have already been used to show virtual objects mapped on users in so-called “magic mirror” augmented reality [Maes et al., 1995]. For instance Maes et al. designed the “Artificial Life Interactive Video Environment” (ALIVE) that allowed interaction between an autonomous virtual agent, e.g. a dog, and the real user. Users could perform gestures and see themselves in a magic mirror while the virtual agent would respond with different actions depending on the gesture of the user. In some cases, the mirror can be used to display virtual objects “inside” the user’s real body. For instance Blum et al. used a 3D camera and a screen to show various organs in situ [Blum et al., 2012a]. However, the displayed organs were static and not dependent on the state of the real organs, since no device was used to capture their activity.

We believe that the Mind-Mirror represents a novel tool for the real-time visualization of brain activity. Its realistic rendering of a virtual brain in situ should provide users with a motivating feedback about their brain activity.

In the following section we introduce our approach relying on AR and 3D interaction for real-time brain activity visualization in a magic-mirror setup.

The remainder of this section is organized as follows. Section 3.1.2 introduces the Mind-Mirror system and details its main components. Section 3.1.3 presents a pilot study comparing the Mind-Mirror to a classical 2D visualization used in current neurofeedback applications. The section ends with a general discussion and a conclusion.

### 3.1.2 The Mind-Mirror system

#### 3.1.2.1 Concept

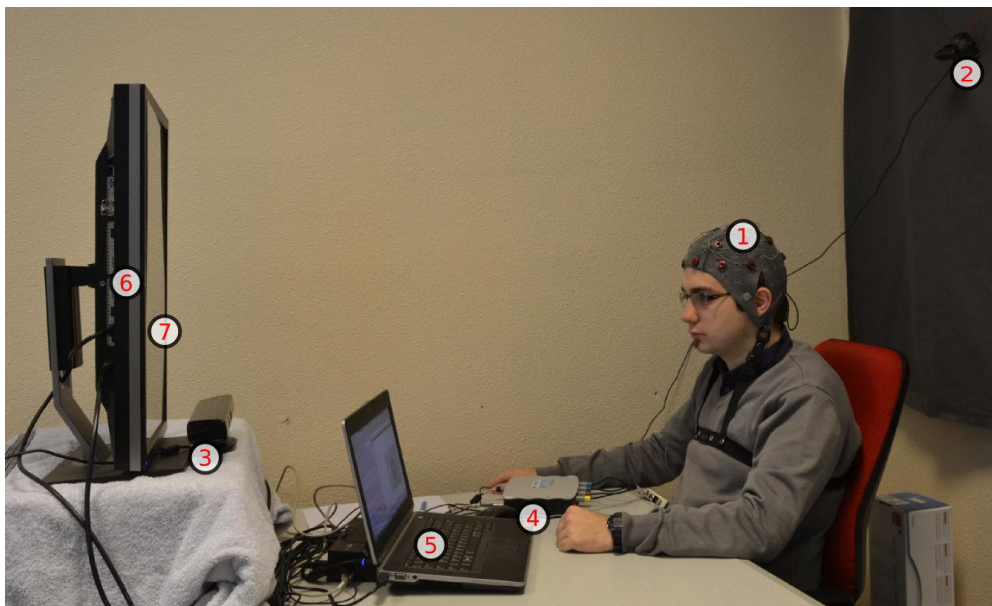
The Mind-Mirror is an augmented reality paradigm that enables users to see in a mirror both their real head and a virtual display of their brain in activity and perfectly superimposed onto their real head. In other words, when using the Mind-Mirror, users can see “through their own head”, visualizing their brain “in action and in situ”.

#### 3.1.2.2 System description

Our approach relies on the use of a semi-transparent mirror positioned in front of a computer screen. A virtual brain is displayed on-screen and automatically follows the head movements using an optical face-tracking system. The brain activity is extracted and processed in real-time thanks to an EEG cap worn by the user. Since a mirror alone can only show the frontal parts of the brain, we have also added a rear-view. This view uses a webcam placed behind and above the head of the user.

The Mind-Mirror system is composed of several components which are displayed in [Figure 3.3](#):

- **Electroencephalography recording and amplification:** electroencephalography acquisition and amplification is performed with a set of electrodes mounted on a cap (1) and an EEG amplifier (g.tec, g.USBamp) (4).
- **Webcam:** a webcam is used and positioned on a wall behind the user (2) in order to capture the image of the back of the user’s head and display it in a rear-view window on the Mind-Mirror.
- **Face and head tracking:** face and head tracking are achieved with a Microsoft Kinect camera (3) and its development kit. It is used to overprint the virtual brain at the position of the user’s head in real-time. The Kinect development kit uses here depth and color sensing of the camera to track the human face using proprietary algorithms.



**Figure 3.3** – Mind-Mirror system overview. Components: (1) EEG cap, (2) webcam, (3) Microsoft Kinect camera, (4) g.tec g.USBamp EEG amplifier, (5) laptop PC, (6) computer screen, (7) half-silvered foil.

- **Signal-processing:** signal processing is done on a computer (5) using the OpenViBE software platform [Renard et al., 2010].
- **Display:** the display system consists of a computer screen (6) that supports a half-silvered foil (7) applied onto a thin plastic plate. Due to the half-silvered foil only the bright screen parts can be seen. The rest of the screen surface appears opaque and reflective, as with a classical mirror. Using a real mirror enables users to see themselves directly, which would not be possible with a camera-based AR setup.

Electroencephalographic data acquired with OpenViBE software [Renard et al., 2010] and head movement data from the Kinect are retrieved and processed within a Unity3D-based application that simulates and displays the virtual brain. Virtual brain activity visualizations are displayed in real-time (framerates between 25 and 80 Hz depending on the visualization type). Face-tracking and head movements are detected and processed with a latency of less than 500 ms.

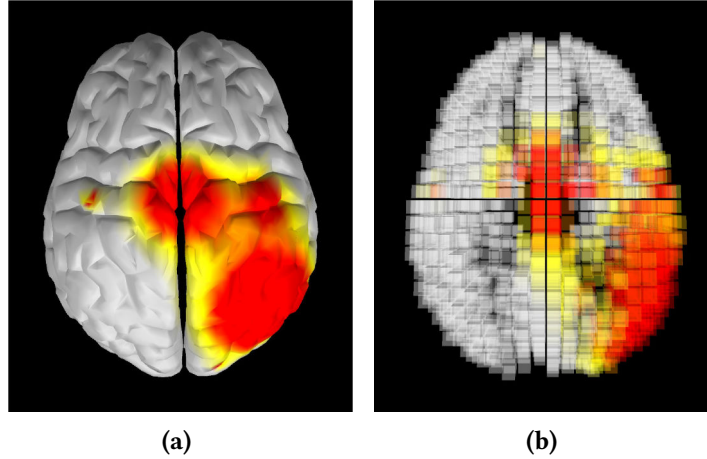
### 3.1.2.3 Visualization tools

As mentioned previously, the Mind-Mirror can be used to display the brain in action and in situ. Different visualization techniques can be used. We have explored the following ones for the Mind-Mirror.

**Brain topography:** the brain topography visualization enables the display of the EEG signal power over the brain surface, as shown in Figure 3.4, (a). This representation allows a quick overview of the most active brain areas, i.e., the areas with the largest EEG signal power.

**3D volumetric representation using inverse solution:** electroencephalographic signals correspond to brain activity at the surface of the scalp. Fortunately, it is possible to estimate the brain activity in the whole brain volume with the help of algorithms known as inverse solutions [Pascual-Marqui, 1999]. The volumetric brain activity hence estimated can then be displayed with a 3D model of the brain using voxels. This visualization allows a comprehensive 3D view of the brain activity, as shown in Figure 3.4, (b).





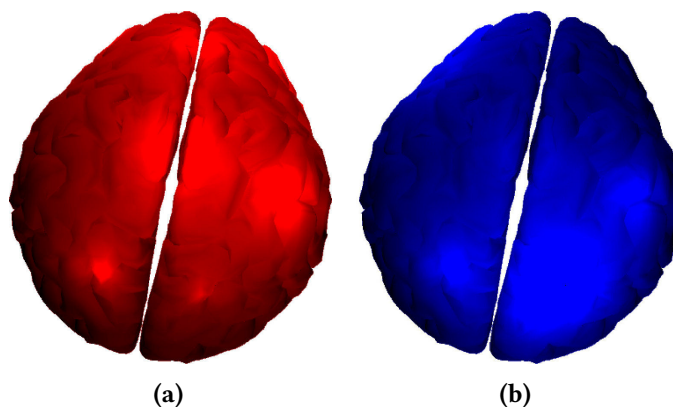
**Figure 3.4** – Brain visualization techniques. (a) Topography display of surface brain activity. (b) Volumetric display of brain activity using voxels. Red and yellow colors correspond to the high-activity spots.

**Visualization integrating mental state classification:** we propose a new brain activity visualization technique that 1) provides information about the underlying brain activity, using surface topography, and highlights some specific brain areas that are relevant for the targeted mental state classification, and 2) displays simultaneously the mental state currently identified by the BCI, which altogether is expected to help users identifying the relevant features of their brain activity in order to control more efficiently the targeted brain activity. With this new representation, the whole virtual brain is colored according to the mental state of the user, as identified by the BCI system. Currently, we have explored this approach with a BCI that estimates the concentration and relaxation level of the user. When the system detects that the user is relaxed the whole virtual brain is colored in blue, otherwise it is colored in red. Moreover, the more blue the brain is displayed, the more confident the BCI system is in the corresponding mental state estimation. This confidence is computed using the output of the linear regression used in the BCI system: the larger the absolute value of the linear regression output, the more confident the estimation [George et al., 2011]. Then, in order to help the user pay attention to the most relevant information and not overwhelm her, the most important brain areas for the estimation of the mental states are displayed with a more intense color, as shown in Figure 3.5.

We have used machine learning tools to display the most important brain areas. In particular, the surface topography only displays the EEG signals in the frequency band that is the most relevant for classification (i.e., the most discriminative frequency band in the Filter Bank Common Spatial Pattern algorithm [Ang et al., 2012]), and only the most relevant channels (i.e., the channels with the largest absolute weights in the Common Spatial Patterns filters for this frequency band) are displayed with more intense colors.

Surface topography is displayed on a 3D mesh of a brain using vertex coloration. In our current implementation the surface topography is computed as follows: the color of vertex  $j$  ( $V_j$ ) is defined using Equation 3.1. A state color  $S$  is defined as red if the detected mental state is concentrated, blue otherwise. Electrode Relevance ( $R_i$ ) represents the relevance of the electrode  $i$  for one mental state, computed during the initial calibration phase.  $P_i$  represents the EEG band power at electrode  $i$  and  $D_{i,j}$  the distance between electrode  $i$  and vertex  $j$ . The electrode positions used are those of the international 10-20 system. Note that other computations could be used such as Surface Laplacians [Renard et al., 2010].

$$V_j = S \cdot \sum_{i=1}^n \frac{R_i \cdot P_i}{D_{i,j}} \quad (3.1)$$



**Figure 3.5** – Brain activity visualization integrating concentration/relaxation classification. (a) Concentrated mental state (red color). (b) Relaxed state (blue color). A brighter color represents a more intense electrical activity.

**Rear-view:** the rear-view, which allows users to see what is happening on the rear parts of their brain, is displayed on top of our mirror (see [Figure 3.6](#)). This rear-view makes use of a standard computer webcam placed above and behind the user. Another virtual brain is used here and also superimposed over the image recorded by the webcam.

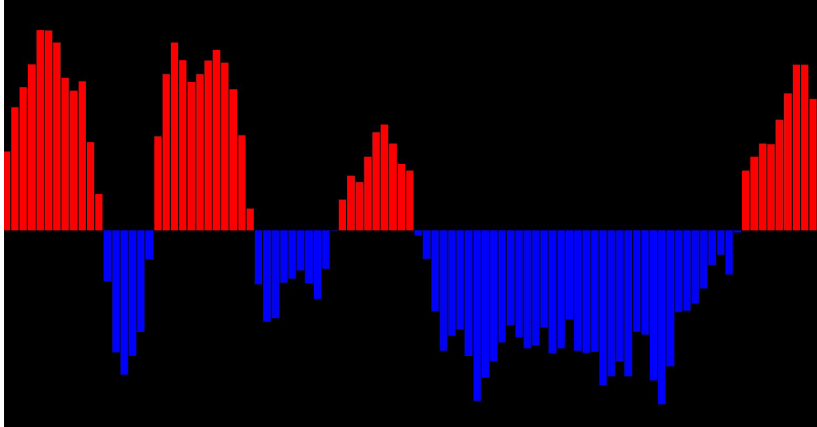


**Figure 3.6** – Rear-view window: a virtual brain is superimposed onto the back of the user's head. It follows its orientation and enables the perception of what happens at the back of the head (brain).

### 3.1.3 Pilot study

In order to assess our Mind-Mirror system, we performed a pilot study in which the participants used it as feedback in a BCI based on the concentration and relaxation levels. More precisely, with this BCI, participants had to put themselves in a relaxed or in a concentrated state, these mental states being analyzed and identified by the BCI in real-time. We studied both the performance (in terms of successfully recognized mental state) and preference (with the help of subjective questionnaires) of the participants using the Mind-Mirror to visualize their brain activity in real-time while using the BCI. We also compared the Mind-Mirror to a temporal gauge, a typical representation used within the BCI and neurofeedback community (see [Figure 3.7](#)). This indeed enabled us to study the impact of the more complex but also more immersive and informative brain activity representation that is the Mind-Mirror on participants' experience and BCI performance.





**Figure 3.7** – The temporal gauge display. The red and blue bars respectively represent the evolution of the concentration and relaxation levels in time.

### 3.1.3.1 Experimental apparatus

The experiment was conducted in a room without environmental noise or other source of distraction. The participants were comfortably seated in front of a computer screen.

Electroencephalographic signals were acquired with a sampling frequency of 512Hz using a 16-channels g.USBamp acquisition system. EEG were recorded at channel locations T7, T8, F7, F8, Fp1, Fp2, C3, Cz, C4, O1, O2, F3, F4, P3, Pz and P4 according to the international 10-20 system. The ground electrode was placed on position FCz, and the reference electrode on the participant's left earlobe.

The concentration level of each participant was estimated using a subject-specific model obtained with machine learning [George et al., 2011].

More precisely, the Filter-Bank Common Spatial Pattern (FBCSP) algorithm [Ang et al., 2012] was used to identify the most relevant EEG frequency bands and channels to discriminate the concentrated from the relaxed mental state [George et al., 2011]. Only frequency bands within the theta (4-7Hz) and alpha (8-14Hz) rhythms range were explored. Indeed, from a neurophysiological point of view, these rhythms are expected to be correlated with concentration [Niedermeyer and da Silva, 2005], and are less likely than higher frequency bands to be contaminated by muscle artifacts [George et al., 2011]. The FBCSP algorithm was optimized on training EEG signals collected during the initial calibration phase. Then, FBCSP features were used to train a linear regression algorithm to estimate the participant's concentration level.

Once the BCI is calibrated in this way, it can be used online. To do so, the FBCSP features were extracted from the EEG signals over the last 2s (using a sliding window scheme, with a 0.1s overlap between consecutive windows) and used as input for the linear regression, which output indicates the participant's concentration level. More precisely, a negative (respectively positive) output value means that the participant is in a relaxed (respectively concentrated) mental state.

### 3.1.3.2 Population

Twelve participants (aged from 21 to 30, mean=25, sd=2.8) took part in the experiment.

### 3.1.3.3 Experimental plan

A calibration phase took place before the experiment. Participants were asked to concentrate for 60 seconds and then relax for 60 seconds without having any visual feedback. Participants were free to choose any cognitive activity for the concentration task. Several suggestions were made such as

a “mental computation” task. The EEG data collected during this phase were used to calibrate the signal processing pipeline.

Two different representations were then compared: the Mind-Mirror and the temporal gauge. As the participants were concentrating or relaxing, the brain activity representations would show the current level of concentration or relaxation, respectively.

The experiment was divided into 12 trials. Each trial comprised a relaxation phase followed by a concentration phase, each of them lasting 25 seconds. The experiment lasted 10 minutes per representation and so 20 minutes for the whole experiment. The two brain activity representations were used by each participant. The half-silvered foil was manually applied on the monitor screen for the Mind-Mirror condition, and removed for the gauge condition. Participants were divided into two groups. The first group started with the Mind-Mirror and the second group started with the temporal gauge.

### 3.1.3.4 Collected data

For each trial and each participant, we recorded the BCI classifier output values resulting from the signal-processing pipeline. At the end of the experiment and for each representation, participants had to fill out a subjective Likert-scale questionnaire (1: strongly disagree to 7: strongly agree). Questions were: “Do you think that the representation is  $x$ ”, where  $x$  was one of the following criteria: (1) Comprehensible, (2) Motivating, (3) Simple, (4) Clear, (5) Innovative, (6) Original.

## 3.1.4 Results

### 3.1.4.1 Classification performance results

We conducted a statistical analysis in order to assess the BCI classification performance for each brain activity representation. To do so, we first compared the linear regression output between the relaxed state and the concentrated state for each of the two visualizations separately, in order to assess whether participants could control the BCI with them. A paired t-test showed significant differences in BCI output between the concentrated and relaxed states for the gauge visualization ( $t(11)=-4.82$ ,  $p=0.0005$ ) as well as for the Mind-Mirror visualization ( $t(11)=-2.73$ ,  $p=0.02$ ). We also compared the classification performances obtained with the two visualizations with a paired t-test. These classification performances were assessed using the average difference between the linear regression output during the concentration and relaxation conditions, as in George et al. [George et al., 2011]. The larger the difference, the better the discrimination between the two mental states. We found no significant difference ( $p=0.19$ ) between the classification performance with the Mind-Mirror condition (average difference: 0.31,  $SD=0.39$ ) and the gauge condition (average difference: 0.46,  $SD=0.33$ ), although there might be a slight trend towards better performances with the gauge. The average values of the linear regression output for each mental state are provided in Table 3.1.

**Table 3.1** – Classification performance results. Average values of the linear regression output and standard deviation are provided for each representation (Gauge; Mind-Mirror) and each state (Concentration; Relaxation), as well as the difference between the two states (Diff.)

	Gauge			Mind-Mirror		
	Con.	Relax.	Diff.	Con.	Relax.	Diff.
Mean	0.21	-0.25	0.46	-0.004	-0.31	0.31
SD	1.44	1.50	0.33	1.1	1.22	0.39

### 3.1.4.2 Questionnaire results

We performed a Wilcoxon test on the visual representations for the different criteria. We found a significant effect for 4 criteria: Simplicity ( $z=-1.981$ ,  $p=0.048$ ), Clarity ( $z=-2.089$ ,  $p=0.037$ ), Innovation ( $z=-2.890$ ,  $p=0.004$ ) and Originality ( $z=-2.924$ ,  $p=0.003$ ). The participants found the Mind-Mirror less simple, less clear but more innovative and more original than the gauge representation. [Table 3.2](#) summarizes the questionnaire results for the 6 criteria.

**Table 3.2** – Subjective questionnaire results for the 6 criteria (1: worst to 7: best). Average values of mark and standard deviation were provided for each representation.

	Gauge		Mind-Mirror	
	Mean	SD	Mean	SD
Comprehensibility	5.67	1.37	5.17	0.94
Motivation	4.75	1.05	4.67	1.37
Simplicity	5.92	1.68	4.92	1.31
Clarity	5.83	1.27	4.83	1.11
Innovation	3.17	1.11	5.5	1.09
Originality	3.25	1.14	5.5	0.8

### 3.1.5 Discussion

The results obtained from the classification analysis and from the questionnaires enabled us to assess the pros and cons of the Mind-Mirror.

Concerning the pros, results from the classification analysis suggested that the participants had no problem putting themselves either in a concentrated or in a relaxed mental state with the Mind-Mirror representation. This shows that participants can successfully use the Mind-Mirror as a feedback for a neurofeedback/BCI application. Results also suggested that the Mind-Mirror, albeit more complex than a classical gauge, does not seem to lead to substantially lower BCI performance, although there might be a trend towards slightly better performance with the gauge. Further studies with a larger population would be required to confirm this point. Results from the questionnaire suggested that participants found the Mind-Mirror to be more original and innovative than traditional BCI feedback (i.e., the gauge). In other words, this means that the Mind-Mirror provides a higher quality experience than a gauge, with a more engaging feedback environment. Moreover, as compared to the gauge, the Mind-Mirror provides more information, since it indicates in real-time which brain areas are active. The participants quoted the Mind-Mirror as “clear and easy to understand”, “quite precise”, “gives a good indication of the activated zones, without being too complex”. The Mind-Mirror thus provides an explanatory feedback, informing about what is going on in the user’s brain, whereas the gauge only provides a corrective feedback, only indicating whether the user is correctly relaxed or concentrated. These two feedback properties, namely, being engaging and explanatory, are recommended properties for the efficient learning of a skill such as the ability to control brain activity [[Lotte et al., 2013b](#)].

The evaluation reported in this section is a short-term one, focused on feedback perception and usability. As such longer-term learning effects are unlikely to occur. In future work, it would be interesting to compare the classical gauge to the Mind-Mirror during multiple neurofeedback sessions, over several days. This would enable us to assess the users’ learning curves (i.e., performance improvements over time), and confirm whether the Mind-Mirror - due to its properties - provides a faster and better learning experience, as is theoretically expected [[Lotte et al., 2013b](#)].

Concerning the Mind-Mirror cons, the user study highlighted that it was significantly more difficult to understand and to use than the classical gauge, at least for first-time users who qualified it as having a “slight lack of readability”. This result is not unexpected since the Mind-mirror is a rich multidimensional feedback, thus a more complex one than the mono-dimensional gauge feedback. Users therefore need more time to get used to the Mind-Mirror feedback, to understand how it works and how to handle it.

This might explain why the classification analysis revealed no increase in BCI performance with the Mind-Mirror. An alternative interpretation that could explain this performance is that the Mind-Mirror displays rich instantaneous information, but no temporal information, whereas the gauge displays an instantaneous information, more precisely the regression output, but also the previous outputs, hence showing a short history describing temporal variations. In the future it would be interesting to add this temporal information to the Mind-Mirror. This could be done, e.g., by displaying the last few surface topographies as well as the current one, with the older ones displayed in dimmer colors or steam-like appearance, and slowly fading away as time passes. It would also be interesting to perform a follow-up longer-term study, in order to assess users’ performance and preference once they got used to the Mind-Mirror principle. Still regarding possible improvements to the Mind-Mirror design, some participants reported that they enjoyed the mirror principle with AR (“easier to control the movement without interfering with the task”, “nice to look at and entertaining”), but that it made visually focusing on the brain or the user’s reflection more difficult (“the virtual brain appears on the foreground whereas the reflection seems to be on the background”). In the future, it could be relevant to compare this mirror AR approach to a more classical AR design with a webcam filming the user and overlaying the brain, without the use of a mirror. This would prevent users from looking themselves into the eyes as in a real mirror but could make the brain activity display easier to watch and to focus on.

The Mind-Mirror has the potential to be used for multiple other applications, notably education, entertainment and neurofeedback training. Indeed, the Mind-Mirror could have educational purposes, as a support tool to teach brain biology and anatomy. For instance, users could select the brain area they are interested in by pointing to it using their own hands. The Mind-Mirror could also be used for entertainment, as a motivating feedback in BCI-based video-games for instance [Lécuyer et al., 2008]. It could also be used in serious games involving the brain, such as video-games for brain fitness or for treating Attention Deficit Hyper Activity Disorders [Lim et al., 2010]. Finally, and maybe more importantly, the Mind-Mirror could be a very powerful tool for Neurofeedback training, either for medical applications or for BCI control. A patent has been published based on the Mind-Mirror setup [Lécuyer et al., 2013].

## 3.2 Mind-Window: multi-user visualization of brain activity

The Mind-Mirror, as presented in the previous section, allows the visualization of brain activity in AR in real-time. It is, however, meant for only one user at a time, equipped with an EEG cap and facing her own virtual brain “in action in situ”. We think that the Mind-Mirror could be enhanced to allow multiple users at the same time.

### 3.2.1 Concept

In this section, we propose a novel approach for real-time visualization of brain activity called the “Mind-Window”. Our approach enables single or multiple users to directly look at the brain activity of an “augmented” person thanks to a tablet-based augmented reality. Tablet computers are directed towards the head of a person wearing an EEG cap. These tablets are used as windows, displaying a video stream recorded by their frontal camera. A 3D virtual brain is displayed on top of the recorded

video stream at the position of the head which is tracked using an AR marker (see [Figure 3.8](#)). The electrical activity of the brain is extracted and processed in real-time thanks to an EEG cap worn by the user. One objective of the Mind-Window is to display real-time brain activity while being simple to use. EEG was chosen because of its well-known high temporal resolution, and because of the relative low-cost and ease of use of EEG caps. Displaying a virtual brain at the same position as it would be if the observee's head was transparent requires retrieving the position and orientation of the head. The computed position and orientation of the observee's head are used to render the virtual brain superimposed onto the camera feed recovered from the tablet PC. The tablets allow a portable wireless display that can be positioned at will by the observers. The Mind-Window application retrieves EEG data from one or several EEG caps. It outputs on one or several tablets the images of the users wearing the caps superimposed with the virtual 3D brain models. The orientation and position of each virtual brain are computed according to the specific viewpoint of the tablet on the AR marker. Compared to the Mind-Mirror, the Mind-Window is a multi-user portable setup based on tablets. It can display multiple points of view of the same brain activity.



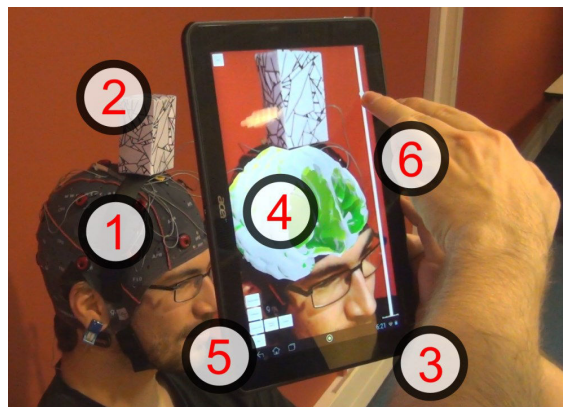
**Figure 3.8** – The “Mind-Window” approach enables single or multiple users to visualize in situ the brain activity of a person in real-time by using tablets and augmented reality. The display of the virtual brain is updated in real-time according to the real brain activity of the person which is measured thanks to an electroencephalography (EEG) cap.

### 3.2.2 System description

The Mind-Window system is composed of multiple components which are displayed in [Figure 3.9](#).

- **Brain activity recording and processing:** one objective of the Mind-Window is to display real-time brain activity while being simple to use. EEG was chosen because of its well-known high temporal resolution, and because of the relative low-cost and ease of use of EEG caps.
- **Augmented reality tracking:** displaying a virtual brain at the same position as it would be if the observee's head was transparent requires retrieving the position and orientation of the head. Of the acoustic, mechanical, magnetic and optical solutions, an optical marker tracking system was chosen for its simplicity, low-cost and compatibility with BCIs. Modern tablet PCs usually have a camera that allows the use of this kind of AR paradigm. Tablets have already been used as support for a marker-based AR [[Gherghina et al., 2013](#)], but not in relation with brain activity.





**Figure 3.9** – Mind-Window system overview. (1) EEG cap, (2) 3D AR marker, (3) tablet PC, (4) virtual brain representation, GUI: (5) button bar, (6) slider.

- **Display on tablets:** the computed position and orientation of the observee’s head are used to render a virtual brain superimposed onto the camera feed recovered from the tablet PC. The tablets allow a very mobile and portable wireless display that can be positioned at will by the observers.
- **Graphical user interface:** our approach can benefit from touch inputs of the tablet. A Graphical User Interface (GUI) can then be overlaid over the surface of the tablet. The Mind-Window GUI features large buttons that can be clicked to activate or deactivate several features like the virtual brain representation or various calibration parameters.

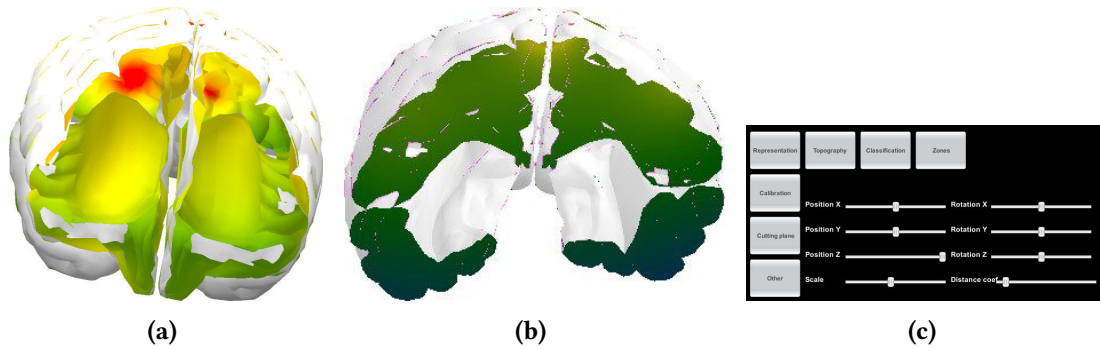
All tablets are computing locally a display of the virtual brain and only the brain activity data are sent from the computer performing the EEG signal processing to the tablets. This network-based approach allows the use of both multiple tablets and multiple EEG caps at the same time.

### 3.2.3 Visualization techniques

Several visualization techniques have been designed for the real-time display of brain activity with the Mind-Window.

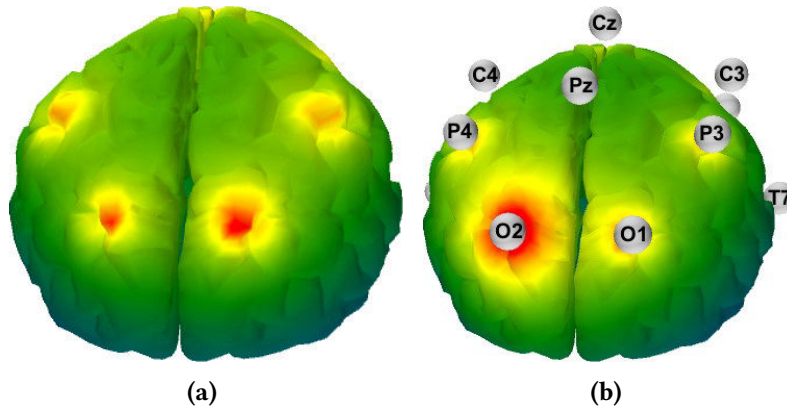
- **Brain topography:** viewing the most and least active brain areas is possible using a surface topography with colors ranging from blue/green (low activity) to red (high activity) (see [Figure 3.11](#), (a)). The brain topography can be set up to display the raw signal or to focus on well-known EEG frequency bands such as alpha (8-15 Hz) and beta (16-31 Hz). These frequency bands can be changed and selected in real-time.
- **Cutting plane:** brain topographies often display only the surface activity of the brain. It could be useful, in a medical context for instance, to view the brain activity below the surface. A virtual cutting plane allows the viewer to cut the virtual brain at any desired position (see [Figure 3.10](#), (a) and (b)). A slider control allows changing the position of the cutting plane along the viewpoint axis whereas the orientation of the tablet PC controls the orientation of the plane (see [Figure 3.10](#), (c)). A button allows the viewer to freeze the rotation of the cutting plane.





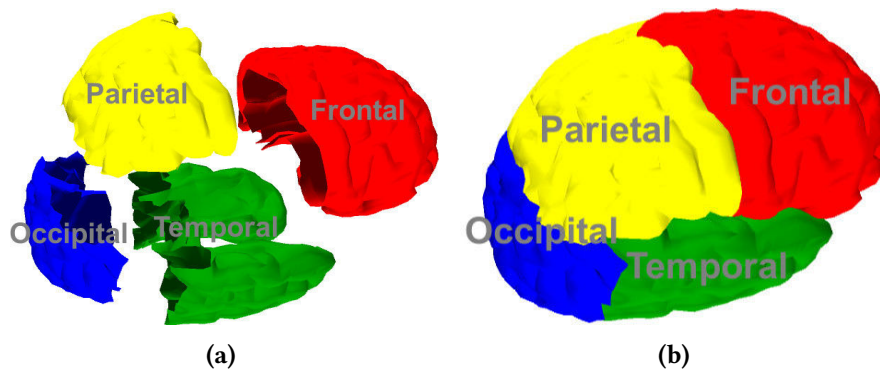
**Figure 3.10** – A cutting plane allows users to see the inside of the virtual brain. (a) and (b) Two cut brains. (c) Our graphical user interface allowing to change cutting parameters.

- **Electrodes:** the electroencephalographic cap used to capture the brain activity is composed of several electrodes placed on well-known positions on the head (see [Figure 3.11](#), (b)). Learning the localization and name of these electrodes and being able to link them with any brain activity could be useful for educational purposes.



**Figure 3.11** – Brain surface topography. (a) Brain surface topography, showing the most active parts of the brain in red and the least active ones in blue and green. (b) The EEG electrodes and their name can also be displayed to let users check the placement of the electrodes and learn how to place them.

- **Brain anatomy:** a human brain is divided into several regions that are known to correspond to specific functions. Learning how to localize them could be useful within an educational context. Those regions can be distinguished using the Mind-Window because they can be displayed with different colors. (see [Figure 3.12](#)).



**Figure 3.12** – Brain anatomy. (a) Brain cartography showing the four main brain regions. (b) The brain regions shifted in different directions.

- **Visualization integrating mental state classification:** surface topographies only show the areas that are most used at a given point in time, but do not provide any information about the user's mental state. In order to display both an information about the mental state of the user and a localization of the brain activity, we have also implemented a visualization integrating the level of concentration and relaxation of the user [George et al., 2011].

### 3.2.4 Implementation

Brain activity measurements are performed with electrodes mounted on a cap and connected to an EEG amplifier (g.tec, g.USBamp). Signal processing is performed within the OpenViBE software [Renard et al., 2010] using filters to reduce noise and process the raw signal.

Resulting brain activity recordings are then transmitted as floating point numbers to a middle-ware application developed with the help of the Qt5 framework that acts as a server for all the tablet PCs connecting to it. Communication between the server and the tablet PCs is done thanks to a network layer implemented using UDP and transmitted over a Wi-Fi connection, allowing our system to be wireless. Tablet PCs (Acer Iconia Tab A500 and A700 running on the Android operating system) then detect the position of the 3D marker to deduce the virtual brain position and orientation.

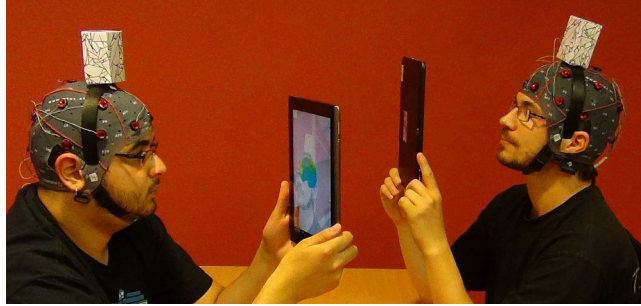
Brain surface color is computed within a pixel and vertex shader written in the CG language, allowing the system to keep an average frame-rate of 30 Hz even on a low-end tablet PC.

### 3.2.5 Use cases and applications

The Mind-Window allows interaction with multiple users at the same time. We could identify different use cases depending on the number of users.

- **One user (one observer, one observee):** one user could see her own brain activity by holding a tablet in front of her head and target a 3D marker. This could be used in Neurofeedback applications.
- **Two users (one observer, one observee):** one person could be observing the brain activity of another person, moving around her while holding a tablet. This configuration could be useful within the medical field to view the brain activity.
- **Three or more users (two or more observers, one observee):** one person is wearing an EEG cap and other persons are watching her brain activity, each one of them having one tablet PC. This setup could be suitable for educational purposes, where the observers are watching the individual's brain activity and have the ability to learn its localization (see Figure 3.8).
- **Two users (two observers, two observees):** two users could both act as observer and observee, each one of them having an EEG cap, a 3D marker, and a tablet PC (see Figure 3.13). This setup allows the users to see the brain activity of one another, e.g. during a brain-enabled video-conference.

We believe that the Mind-Window could have applications in different fields such as medicine, education, or entertainment. The Mind-Window could represent an alternative way for physicians to visualize the brain activity. Typical medical brain visualizations are off-line [Wolters et al., 2006]. Our approach allows an online visualization of the brain activity. For teachers wanting to show how certain parts of the brain work, the Mind-Window could be a way to illustrate their lessons in real-time. The Mind-Window has also some entertaining potential and could be used to enhance the traditional videoconferencing by displaying the brain activity of each participant.



**Figure 3.13** – Multi-user visualization of brain activity: two users are visualizing each other's brain activity in real-time using two tablet PCs.

### 3.3 Mind-Inside: telepresence inside one's brain

In order to increase the immersion of users, we propose a third system for the visualization of the brain activity using VR instead of AR.

This system allows users to visualize brain activity while being immersed inside a virtual brain. Users have to wear an EEG cap and a HMD that are used to record and display the brain activity within a virtual environment. A multi-user setup is also possible, one user wearing the EEG cap and another user wearing the HMD.

#### 3.3.1 Introduction

The Mind-Inside system uses a similar approach as our previous systems, the “Mind-Mirror” and the “Mind-Window”: users are able to visualize their own brain activity or the brain activity of another person in real-time. However, this prototype proposes to “immerse” users within a virtual brain, allowing them to navigate within a representation of their brain or another person's brain. This representation displays the most active parts, so that users can observe the effects of various mental tasks. Possible uses include neurofeedback, entertainment, or education.

Using an HMD, users are completely immersed within the virtual environment, and are not subject to external visual noise. Thus, this could improve the engagement and the motivation of the users, as well as the BCI performance [Pausch et al., 1997].

#### 3.3.2 System

Users are wearing an EEG cap that records their brain activity, as well as an HMD (see Figure 3.14). The virtual environment consists of a virtual brain that surrounds the user, and is filled with voxels. The user's viewpoint is located at the center of the virtual brain and can rotate to any direction when rotating the head. Each one of the voxels is transparent and bears a color related to the level of brain activity at a particular position in the brain. Brain activity reconstruction is achieved using an inverse model, allowing to infer the internal brain activity with the only help of surface electrodes.

The Mind-Inside system comprises several components (see Figure 3.15, (a)) which are described in the following section.

- **Static reference frame:** a static 3D reference frame is displayed, allowing users to localize their position in the virtual brain (see Figure 3.15, (a)).
- **Top and side view compasses:** our system displays two brain representations at the bottom of the screen (see Figure 3.16). They represent the top- and side-views of the brain. A red arrow displays the current orientation of the user's view. These compasses are expected to help users identifying the current part of the brain they are looking at.



Figure 3.14 – A Mind-Inside user wearing an HMD together with an EEG cap.

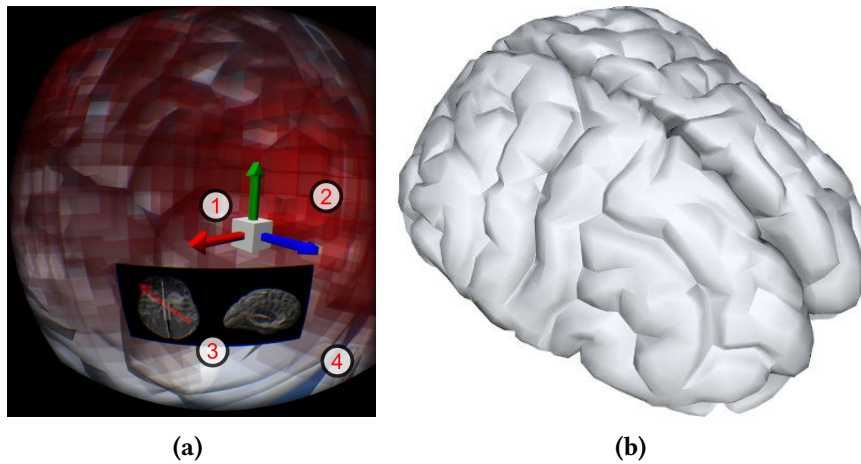


Figure 3.15 – Two viewpoints on the virtual brain. (a) User's view of the virtual brain, as displayed in the HMD. (1) A reference frame helps users to orient themselves within the virtual environment. (2) Red voxels display the most active brain areas in a bright red color. (3) Two compasses display the current orientation in two embedded additional 2D views. (4) The brain structure can be seen in the background. (b) The virtual brain, seen from the outside.

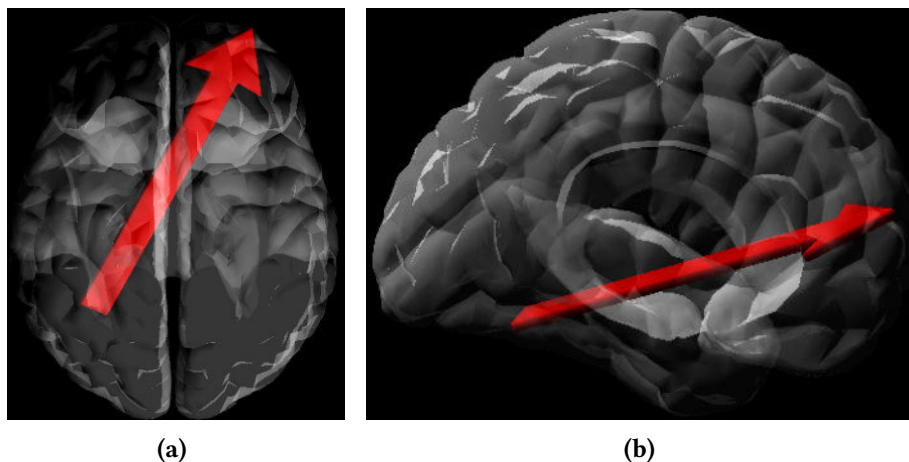
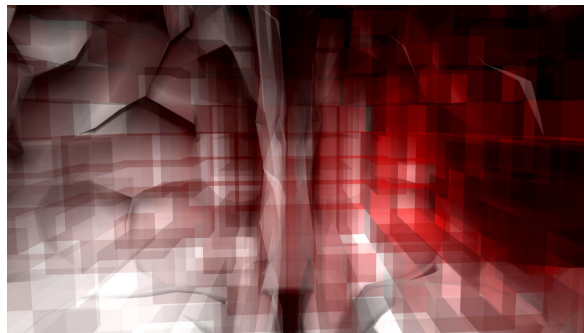


Figure 3.16 – The two compasses. A red arrow represents the user's viewing direction in the 3D brain. (a) Top view. (b) Side view.



- **Internal brain surface:** the user's point of view is located in the center of a virtual brain. The shape of the brain can be identified from the inside. [Figure 3.15](#), (b) displays the virtual brain.
- **Voxel display of brain activity:** brain activity is gathered with an EEG-based BCI. EEG electrodes are placed on the surface of the scalp. Signal processing is achieved with the help of the NeuroRT Studio software<sup>1</sup> from the Mensia Technologies company. The internal brain activity is computed with a source reconstruction algorithm based on sLORETA algorithm [[Pascual-Marqui et al., 2002](#)]. This algorithm produces an array of 2394 values corresponding to the brain activity at known positions inside the brain, using only EEG data from the surface of the head. Voxels are then displayed within a virtual environment using the Unity3D game engine<sup>2</sup>. Voxels located in an active area of the brain are displayed in an opaque red color, while non-active or less-active voxels are transparent and white (see [Figure 3.17](#)).

This display allows users to navigate inside the brain volume and see the brain activity at any position, not only at the surface of the brain but also inside it.



**Figure 3.17** – Voxel-based representation of brain activity. The most active areas of the brain appear opaque and bright red. The internal areas of the virtual brain model can be seen in the background.

### 3.4 Conclusion

This chapter has presented three approaches for the visualization of brain activity in real-time based on VR/AR. These approaches addressed different levels of immersion and different contexts of users (single or multiple users).

The Mind-Mirror has been presented first. This system combines AR and EEG in order to enable users to visualize their own brain operating inside their head as in a mirror. We proposed various brain activity visualization tools for this system. Different use-cases could be identified, including education, entertainment, and neurofeedback. We also conducted a user study to compare feedback provided using the Mind-Mirror to a classical gauge feedback in a BCI neurofeedback experiment. Results suggested that participants found the Mind-Mirror to be more innovative and engaging than a classical gauge but also more complex to use and understand. This complexity did not lead to a statistically significant drop in BCI performance.

Another system, the Mind-Window was presented second. This system enables to visualize brain activity in real-time using augmented reality and single or multiple tablet PCs. A virtual brain model is displayed at the level of the skull of the real user and its representation is updated as a function of EEG recordings. We have designed several visualization techniques and tools such as a 3D cutting plane that can be directly controlled with the tablet thanks to gestural and touch inputs.

<sup>1</sup><http://www.mensiatech.com/development-tools/>

<sup>2</sup><http://unity3d.com>

Our approach is highly versatile and portable and could be used by single or multiple users in various applications in the fields of medicine, education, or entertainment.

Finally, a third system called Mind-Inside has also been presented for immersive brain activity visualization. Our system lets the users visualize brain activity from within a representation a brain. They can visualize their own or another person's brain activity. The brain activity is displayed as colored voxels, as measured with a BCI and localized using a source reconstruction algorithm. Some tools have been designed to ease the navigation within the virtual brain, like virtual compasses. The Mind-Inside could be used for neurofeedback applications, or for educational or entertainment purposes.



## Chapter 4

# Towards smart clothes based on brain-computer interfaces and augmented reality

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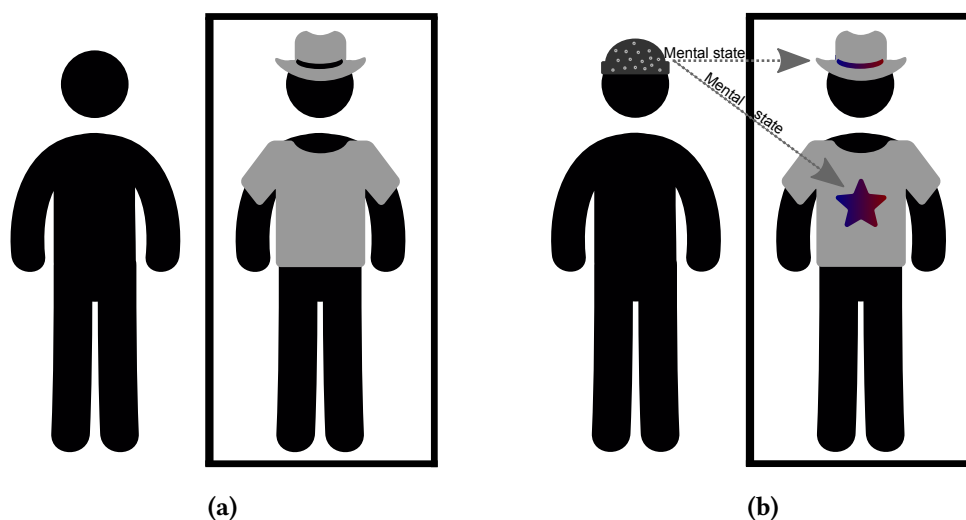
The objective of this chapter is to study the potential use of brain-computer interfaces in the context of smart clothes. Smart clothes are “regular” clothes combined with electrical components such as sensors or actuators, as well as computers.

Smart clothes have been described by Pentland as being “like a personal assistant. They are like a person who travels with you, seeing and hearing everything that you do, and who tries to anticipate your needs and generally smooth your way” [Pentland, 1998]. Pentland proposes some use-cases: smart clothes could provide information about the wearer’s surroundings, the name of a person could appear in front of the wearer’s eyes through glasses, or directions to the next meeting. For him, the key idea is that the piece of smart clothing has some knowledge about its surroundings that allows it to react intelligently. As an example, a wearable sensor badge and a sensor jacket have been conceived by Farringdon et al. [Farringdon et al., 1999]. Their sensor badge was able to detect various states of the wearer: walking, running, standing, sitting, or lying down, using accelerometers. Their sensor jacket used knitted sensor strips to detect the position of the elbows and wrists of the wearer. Another example of smart clothes, Axisa et al. conceived two garments that could be used within a medical environment [Axisa et al., 2003]. First, a smart T-shirt able to measure breathing, temperature, and body heat flow. Second, a smart glove, used to measure skin potential, conductance, and temperature. This previous work on smart clothes provides some examples of systems in which BCIs may be integrated. BCIs could provide a new input device for smart clothes: they could for instance measure the mental state of a person and adapt the smart clothes accordingly.

In this chapter we present our experimental platform for the integration of a BCI with smart clothes. We begin by presenting a virtual dressing room where users can experience wearing and interacting with virtual clothes. We propose the use of augmented reality to mitigate the costs of producing smart clothes, as well as allowing to quickly prototype systems integrating a BCI to them. We then add an EEG-based BCI to the virtual dressing room so that users can control the appearance of the virtual clothes by using their mental state. Last, we introduce a virtual Invisibility Cloak, inspired by the Harry Potter universe. Users can become invisible by wearing a real cloak and reaching a particular mental state.

## 4.1 The virtual dressing room

In this section we present a testbed based on AR allowing users to “virtually wear” clothes, as if they were in a dressing room. The virtual dressing room allows users to see themselves as in a mirror, allowing them to try various clothes and other wearable objects or garments (see Figure 4.1, (a)). The virtual objects follow users as they move in front of the mirror, overlaying the user’s reflected image. A BCI cap worn by users can then be added and allows them to alter the appearance of the virtual clothes and/or garments depending on their mental state (see Figure 4.1, (b)). Our system uses a 3D camera to track users without the need for any AR markers.



**Figure 4.1** – Our experimental platform allowing users to wear virtual clothes controlled by their mental state. (a) AR-based dressing room: the user (left) can see herself wearing virtual clothes (right). (b) BCI-based control: the user, wearing an EEG-based BCI cap (left), can change the appearance of the virtual clothes by changing her mental state (right).

### 4.1.1 Previous work related to mirror-based virtual dressing rooms

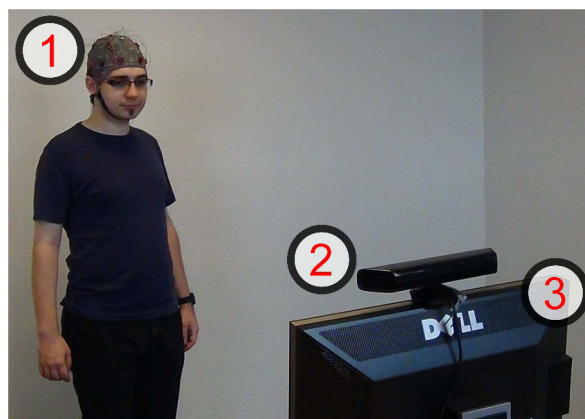
Augmented reality markers have been used in setups to record the position and orientation of the users. A “magic mirror” proposed by Fiala used these markers to display virtual clothes on the user, such as a medieval armor, or a sports suit [Fiala, 2007]. Markers could also be placed on the user’s head, allowing the placement of virtual garments like hats, or helmets. This system is similar to our virtual dressing room in that it allows the user to wear body and head garments, but with the help of AR markers. The “Virtual Mirror” proposed to overlay virtual shoes on top of the user’s feet [Eisert et al., 2008]. This system used a 3D motion tracker to extract the feet’s silhouette from a camera’s video feed. A 3D model was then superposed on top of the user’s feet and the resulting image was displayed on a large screen in real-time. The work proposed by Eisert et al. did not use any AR

marker to track the position and orientation of the feet, similarly to what our virtual dressing room does. However, it only tracked the user's feet and not other body parts. More recently, organs have also been overlaid on users [Blum et al., 2012a]. The setup presented by Blum et al. proposed to display organs in situ for educational purposes. Using markerless tracking with a 3D camera, their system displayed a magic mirror where users could visualize medical scans on themselves. This system was close to our virtual dressing room, in that it displayed virtual objects on users without markers. It did not depend on the state of the displayed organs. The literature does not show any association of a BCI and AR for the control of smart clothes (see Section 1.3.3). Nonetheless, Acar et al. used the association of a BCI with AR to display virtual insects on top of the user's hands [Acar et al., 2014]. These insects would follow the hands of the users, as would virtual gloves or other hand worn garments. Their objective was to provide a way to treat phobias and obsessions by using virtual objects displayed on a smartphone. An EEG-based BCI was used to measure various frequency bands, but they did not adapt the appearance of the insects depending on the output of the BCI. To sum up, our approach concerning the virtual dressing room is similar to this previous work in that it uses a camera to track users and display virtual 3D elements on the user's image, as in a mirror. However, our contribution consists in the addition of a BCI that allows to adapt the appearance of the virtual clothes depending on the mental state of the user.

Compared to our Mind-Mirror setup (Chapter 3), our virtual dressing room also uses AR to superimpose virtual objects on users. However, the virtual dressing room overlays virtual clothes instead of a brain. Both systems use a 3D camera to track the user's head and body, as well as BCI to record the user's mental state and adapt the overlaid virtual objects.

#### 4.1.2 System description

Our virtual dressing room system uses a 3D camera to record the position of users standing in front of it. Tracking is achieved thanks to a depth sensor and a proprietary algorithm within a development kit provided with the camera. A screen displays the video feed provided by the camera, overlaid with virtual 3D garments. The position of these garments is set up using the coordinates computed with the help of body and face tracking. Since the body tracking provides 3D coordinates, the virtual garments can be rotated and scaled to some extent, being only constrained by the limitations of the tracking algorithm provided with the 3D camera. The appearance of the virtual garments depends on the mental state of the users (see Figure 4.2).



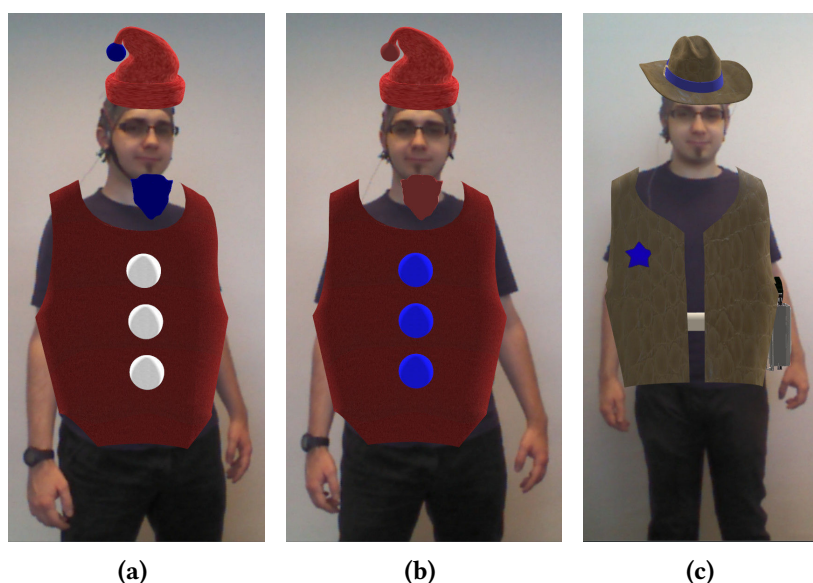
**Figure 4.2** – Our virtual dressing room. An EEG cap (1) records the brain activity of the users. A 3D camera (2) records color and depth information used for head and body tracking. Finally, a computer screen (3) displays the augmented environment.

**Image processing and tracking:** an optical tracking system (1) records 640x480 pixels color images and 320x240 pixels depth images at a frequency of 30 Hz. The tracking of the user is achieved using the color and depth recordings with the help of the Kinect development kit. An application running the Unity3D engine processes the final rendered image containing the image of the user and virtual clothes/garments. Rendering is achieved at a frequency of approximately 25 Hz.

**Display:** a computer screen set up like a mirror (2) displays the real scene in which the user is standing.

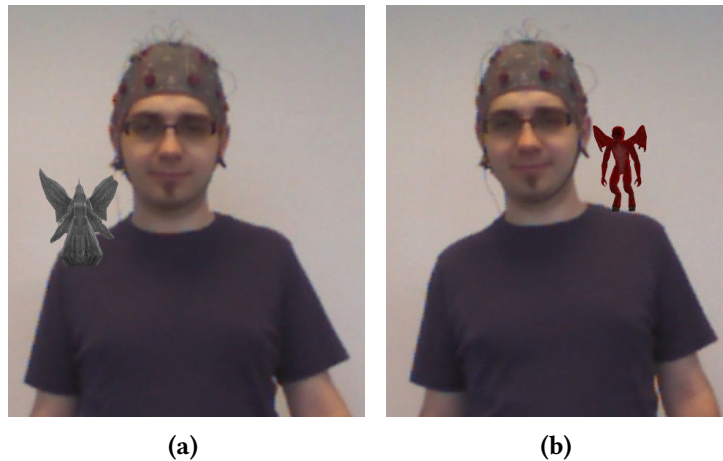
**Electroencephalographic acquisition/processing:** electroencephalographic data is acquired at a frequency of 512Hz with a cap fitted with 16 electrodes and transmitted to a computer through a g.USBamp acquisition system. EEG electrodes are placed at positions T7, T8, F7, F8, Fp1, Fp2, C3, Cz, C4, O1, O2, F3, F4, P3, Pz and P4 according to the international 10-20 system. A subject-specific model obtained using machine learning similar to [George et al., 2011] is used to estimate the concentration level of the users at any moment. This processing pipeline uses training data to compute a linear regression's coefficients that outputs a single value which represents the user's concentration level. Expected values ranged from -1 to 1, a lower value (respectively higher) means that the participant is in a relaxed (respectively concentrated) mental state. The signal processing is done on the OpenViBE software platform [Renard et al., 2010].

**Virtual objects:** we have proposed three categories of virtual objects that can be displayed on the user. The first category corresponds to the clothes and other garments that could later be produced as real smart clothes. Figure 4.3 shows two costumes: a "Santa Claus" costume comprising a cap, a beard, and a vest, and a "sheriff" costume comprising a hat, a vest, and a revolver. Their color can gradually change depending on the user's detected mental state. The beard and the cap's tassel vary from blue to red, depending on whether the user is considered as relaxed (a) or concentrated (b), respectively. The vest's tassels vary from white to blue. These virtual clothes illustrate the use of our system as a testbed for smart clothes.



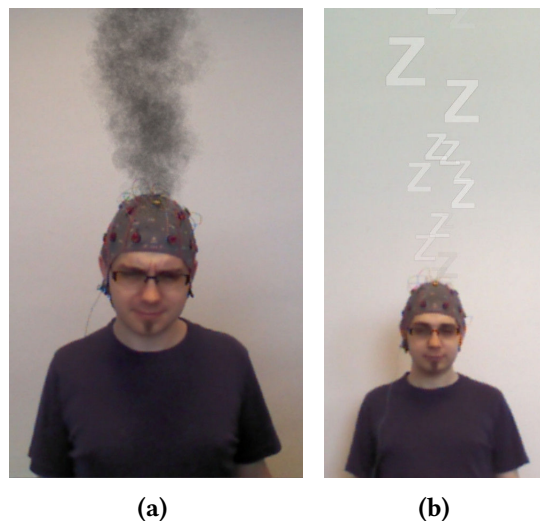
**Figure 4.3** – Virtual clothes that can be displayed on users. (a) and (b) A "Santa Claus" costume comprising a cap, a beard, and a vest. (c) A "sheriff" costume comprising a hat, a vest, and a revolver.

Our second category comprises animated characters that can be displayed on the shoulders of the users. In this case, an angel appears when users are relaxed and a devil appears when they are concentrated (see pictures (a) and (b) of [Figure 4.4](#)). These virtual characters illustrate another possible use of our system in entertainment. Users could interact with these characters with the BCI or in addition to other more conventional controls and interactions.



**Figure 4.4** – 3D animated characters. (a) An angel, displayed when users are relaxed. (b) A devil, displayed when they are concentrated.

Finally, our third category represents special effects that can follow the users. [Figure 4.5](#) shows puffs of smoke appearing above the head of the users when they are concentrated (see picture (a)). Other effects, such as “Z” letters appearing when the users are relaxed can also be displayed (see picture (b)). Similarly to our second category, these effects could be used for entertainment purposes.



**Figure 4.5** – Special effects. (a) Smoke appears if users are concentrated. (b) “Z” letters appear when users are relaxed.

Thus, we have introduced a system allowing users to wear virtual clothes in a mirror-like setup. This system lets users adapt the appearance of virtual clothes as their mental state change. This system could allow users to try various clothes and other wearable elements that would not need to be produced in order to be tested on users, hereby reducing costs.



## 4.2 The Invisibility Cloak and the B-C-Invisibility Power

The objective of this section is to further study the use of a BCI to interact with and/or control virtual and smart clothes. We want to study and propose here novel concepts of smart clothes based on a BCI.

### 4.2.1 The Invisibility Cloak

#### 4.2.1.1 Concept

We introduce the “Invisibility Cloak”, driven by EEG. This Invisibility Cloak is inspired by the Harry Potter universe (see [Figure 4.6](#)). Users have to put the hood of the Invisibility Cloak on their head and concentrate to become invisible from a ghost. Removing the hood makes them visible again regardless of their concentration state, in order to be visible by a friendly owl.



**Figure 4.6** – An Invisibility Cloak illustrates an entertaining concept of smart clothes controlled by a BCI freely inspired by the Harry Potter universe. In this case, the user puts on the cloak’s hood and concentrates to become invisible. Removing it prevents any level of invisibility. A particle effect appears each time users put the hood on their head.

The Invisibility Cloak provides the user with the power of invisibility (see [Figure 4.7](#)). Here this power is driven by the mental state of the user by means of a BCI. This is what we propose to call the “B-C-Invisibility Power”.



**Figure 4.7** – The B-C-Invisibility Power enables users to become virtually invisible by performing mental tasks. Brain signals are extracted using EEG electrodes and analyzed within the BCI.



#### 4.2.1.2 Related work and positioning

Virtual reality or augmented reality technologies can sometimes provide a feeling of having “super-powers” allowing users to perform actions that no human being would be able to do. One of these super-powers is the “power of invisibility”, i.e., being able to be surrounded by other individuals without being seen. This old dream could have come true several years ago with the appearance of “optical camouflage” [Inami et al., 2003].

Several attempts have already been made in virtual reality to provide humans with super-powers. This has been illustrated by Ishibashi et al. [Ishibashi et al., 2009] in VR. In their experiment, participants could use a super-power (launching a virtual web) to jump from one virtual building to another. Bailenson et al. [Rosenberg et al., 2013] provided users with the super-power of flying in a virtual environment. Participants had to help a diabetic child or tour a virtual city. They had either the flight super-power or were a passenger in a helicopter. The experimenter then provoked a non-virtual event needing help from the participant: she would let some pens fall from a table. The experiment demonstrated that users given the virtual super-power of flight had an increased helping behavior.

“Optical camouflage” has been defined by Inami et al. [Inami et al., 2003] as a type of active camouflage that uses optical projection. Their system worked by projecting an object’s background on itself to make it almost invisible. A camera was placed behind the object that was to become camouflaged to record its background. A projector then rendered an image on the object, as seen from a particular viewpoint. Inami et al. [Inami et al., 2000] also applied an optical camouflage on objects using AR. Their objective was to hide a haptic interface with the help of a head-mounted projector. Users could manipulate virtual objects and even cause occlusions.

In our system, instead of projecting background elements on a person to make her disappear, an outlined image of her body is separated from the background and overprinted on another image. This outlined image can be overprinted with various levels of transparency, allowing users to camouflage themselves within the virtual environment. A BCI allows users to control their invisibility level depending on their concentration level. Compared to the literature, our setup provides a new way of controlling optical camouflage by using only mental activity, in order to give a greater feeling of having a super-power. We propose a novel virtual Invisibility Cloak based on AR and BCIs.

The remainder of this section is organized as follows. First we will introduce our B-C-Invisibility Power. Then we will present a pilot study comparing two input devices used to control a level of camouflage: a BCI (and our B-C-Invisibility Power) and a keyboard. The section ends with a discussion and a conclusion.

### 4.2.2 The B-C-Invisibility Power

#### 4.2.2.1 Concept

The B-C-Invisibility Power aims at allowing users to control the power of becoming virtually invisible by camouflaging themselves. This “super-power” is mind-controlled, so that they can experience invisibility without having to move any muscle, only by controlling a mental activity (here concentrate or relax). Users see themselves on a screen as in a mirror, a reflection of their body following their movements and being displayed with a varying level of transparency (see Figure 4.8).

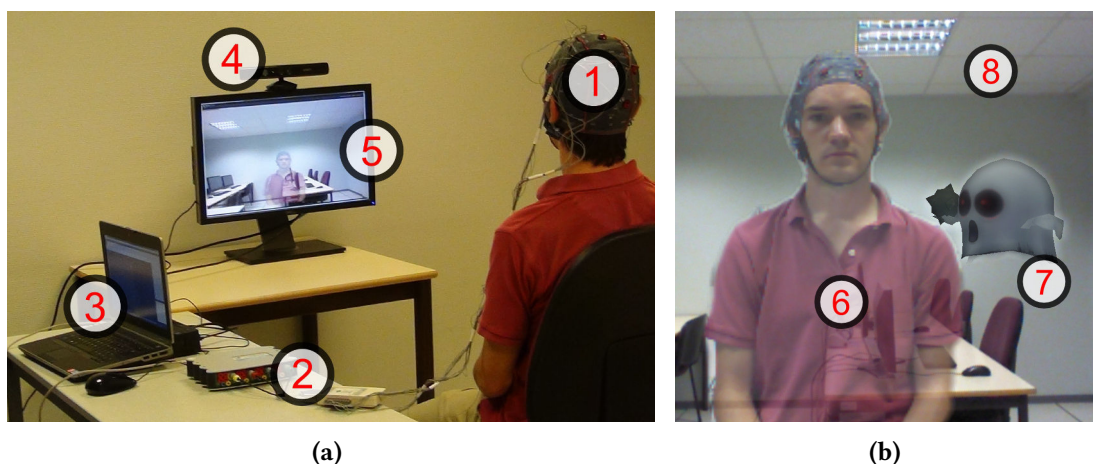
#### 4.2.2.2 System description

Our system comprises various components which are displayed in Figure 4.9, (a). These components are the same as the ones used in our dressing room controlled by a BCI (see previous section), with the addition of a pre-captured background image used for the invisibility effect. An EEG cap records the brain activity (1), an EEG amplifier pre-processes the recorded data (2), a computer performs

additional signal processing (3), an optical tracking system records color and depth images (4), and a computer screen displays the resulting image (5).



**Figure 4.8** – Users can see themselves with various levels of transparency.



**Figure 4.9** – B-C-Invisibility Power overview. (a) System overview; (1) EEG cap, (2) EEG amplifier (g.USBamp, g.tec), (3) computer, (4) optical tracking system (Kinect camera), (5) computer screen. (b) Experimental environment overview; (6) participant's cut out image, (7) virtual entity: a ghost, (8) pre-captured background image of the real background scene in which the participant is standing.

A middleware application receives the BCI information and the video feed from the 3D camera. This information is then sent to the Unity3D engine that performs the rendering of the static background overlaid by an image of the user.

### 4.2.3 Pilot study

We have designed a pilot study comparing the performance of a BCI compared to a more conventional interface i.e., a keyboard. The participant's task was to control the B-C-Invisibility Power, i.e. our optical camouflage system, with both interfaces. We focused on both task performance and user experience.

A video-game inspired prototype was presented to the participants. They had to be visible when seeing a friendly owl and invisible when seeing an evil ghost. With the keyboard, participants had to press two different keys to increase or decrease their invisibility level. With the BCI, participants had to be concentrated or relaxed to achieve total visibility or total invisibility. These mental states were identified in real-time by the signal processing pipeline. Both the task performance and the preference of the participants have been evaluated, using the detected concentration level and a subjective questionnaire.

Our hypotheses were that the use of a BCI would be more motivating for participants while the keyboard would perform better (e.g. participants would have a higher success rate in controlling their camouflage).

#### 4.2.3.1 Experiment description

Participants were seated in front of a computer screen. Two different input devices (keyboard or BCI) were available to the participants. Twelve participants (3 females and 9 males, aged from 20 to 36, average=28.42, SD=4.5) took part in the experiment.

The signal processing pipeline for the BCI used in this study requires a calibration phase so that the system is able to recognize the two mental states. During this calibration phase, participants were asked to concentrate and afterwards relax during 2 minutes while having no visual feedback. Participants were free to choose any cognitive activity for both mental states (concentration and relaxation), but suggestions were made such as “performing a mathematical computation” (concentration) versus “thinking about nothing” (relaxation).

The experiment comprised 4 blocks involving a device (keyboard or BCI) and one of two tasks. Participants were split equally into 4 groups corresponding to the order of the different blocks. Each task (“become invisible” or “become visible”) was dependent on the device. For the keyboard it would be “press the Up key” or “press the Down key”. For the BCI it would be “concentrate” or “relax”. Each block included 20 trials of 12 seconds. Only the last 8 seconds were used to compute the trial’s result. At the beginning of each trial an animated 3D model appeared in one corner of the screen and moved progressively towards the image of the participant following a spiral shaped path. The 3D model could be either a ghost, in which case participants had to become invisible, or an owl, in which case they had to become visible (see [Figure 4.9](#), (b)). The presentation order of the 10 ghosts and 10 owls within each block was randomized. The level of transparency of the participant’s image depended on the current task’s success rate.

At the end of the experiment, participants had to fill out a questionnaire and grade the 2 input devices (keyboard/BCI) according to the following criteria: (a) Controllability, (b) Innovation, (c) Motivation, (d) Time to become invisible, (e) Stress level, (f) Fatigue level, (g) Feeling of having a super-power. They were also asked to provide open comments about the keyboard and the BCI usages.

#### 4.2.3.2 Results

The average and standard deviation values of the linear regression output for each device are provided in [Table 4.1](#).

A statistical analysis has been conducted on the BCI classification results for each trial, in order to evaluate the amount of control that participants had on the B-C-Invisibility Power. A mixed model analysis was performed to evaluate the effects of the task (“concentrate” versus “relax”), the objective (“become invisible” versus “become visible”), and the individuals (considered as random). A significant difference between the two tasks has been found ( $F(1,11)=14.37$ ,  $p=0.003$ ). However, no significant difference has been found between the two objectives ( $F(1,11)=0.365$ ,  $p=0.56$ ). Finally, a significant difference has been found on the effect of the interaction between the task and the objective ( $F(1,443)=5.62$ ,  $p=0.02$ ). The average output for the concentration task was 0.49 (SD=0.34) for the “become invisible” objective and 0.54 (SD=0.29) for the “become visible” objective. For the relaxation task, the average output was 0.26 (SD=0.23) for the “become invisible” objective and 0.24 (SD=0.24) for the “become visible” objective. Comparing the average value of successful trials (out of 20) shows that the keyboard has a higher rate (99.15%, SD: 1.9%) than the BCI (66.9%, SD: 17.6%).

A paired-wise t-test has been performed on the results of the subjective questionnaire (see [Figure 4.10](#)). The “controllable” ( $p < 0.001$ ) and “time to become invisible” ( $p = 0.001$ ) criteria have been found to be significantly better for the keyboard. The “innovative” ( $p < 0.001$ ) and “feeling of having a super-power” ( $p = 0.009$ ) criteria, on the other hand, have been found to be significantly better for the BCI. The “motivating” ( $p = 0.073$ ), “stress level” ( $p = 0.19$ ) and “fatigue level” ( $p = 0.772$ ) criteria have not been found as being significant.

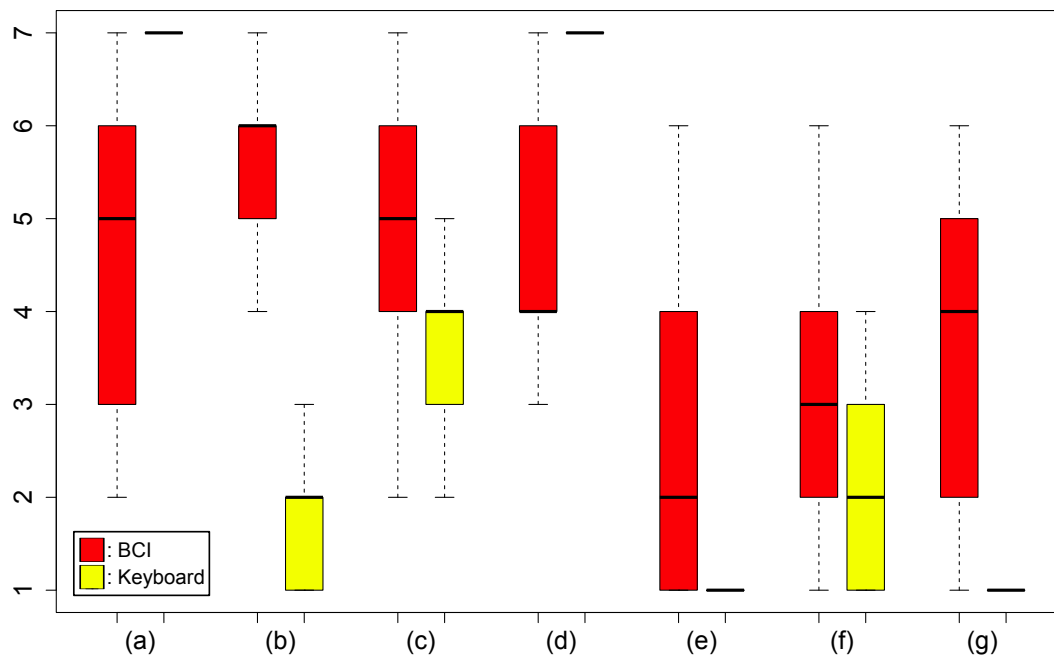
**Table 4.1** – Performance results per participant (P1–P12). Average values and standard deviation of the amount of successful trials are provided for each device.

	Keyboard		BCI	
	Mean	SD	Mean	SD
P1	19.5	0.71	13	2.83
P2	20	0	9.5	0.71
P3	20	0	13	1.41
P4	20	0	11	1.41
P5	19.5	0.71	11	1.41
P6	19	0	16	0
P7	20	0	20	0
P8	20	0	12.5	2.12
P9	20	0	11	0
P10	20	0	15	4.24
P11	20	0	18.5	0.71
P12	20	0	10	0
Mean	19.83		13.38	
SD	0.38		3.52	

#### 4.2.4 Discussion

Our user study enables us to compare the BCI and the keyboard as means of controlling the B-C-Invisibility Power. As expected, performance results confirmed that participants using the keyboard almost never failed at any trial, whereas participants were more challenged when using the BCI. The lower performance obtained with the BCI could be explained by the fact that the virtual environment was not visible during the calibration phase compared to the rest of the experiment.

A statistical analysis of the questionnaire results shows that the BCI was perceived to be more innovative than the keyboard, and to give a better feeling of having a super-power. On the other hand, the keyboard has been perceived as being easier to control and gave participants more time to switch between being visible or invisible. Having super-powers, being “augmented”, often means being able to control these extra-ordinary elements by intuitive means. Having the ability to become invisible without having to manipulate any physical object is likely to be more intuitive than using a keyboard. Additionally, the statistical analysis shows that the system was always able to distinguish between the “concentrate” versus “relax” tasks, regardless of the objective, and that it was also able to better distinguish between the two tasks when the user was asked to become visible rather than invisible.



**Figure 4.10** – Subjective questionnaire results for the different criteria; (a) Controllability, (b) Innovation, (c) Motivation, (d) Time to become invisible, (e) Stress level, (f) Fatigue level, (g) Feeling of having a super-power.

At the end of the experiment participants were invited to write down comments about their user experience regarding the BCI and the keyboard. Participants were also asked what strategy they used to reach the concentrated and relaxed mental states. Eight participants indicated that they “used a mathematical computation” task during the concentration phases. Two participants used other tasks such as “trying to be afraid of the ghost” or “reciting passages from a book”. As for the relaxation phases, some participants have indicated “thinking about nothing”, “breathing slowly”, or “imagining being in another place”. Participants have tried other tasks than the suggested one, with various success. It could be interesting to let the participants try these tasks during a post-calibration phase, so that they can select the one that is most efficient for them.

While our study provided valuable results, it also showed some limitations. First of all, the rich content of the virtual environment seemed to have an impact on the BCI performance because of its distractive nature. Performing the calibration while the user can see this virtual environment could help improving the BCI performance. Our setup also had a limited mobility since participants had to wear a BCI cap connected to a computer using wires. Wearing a wireless cap would let users move more freely during the experiment, which could increase their immersion.

### 4.3 Conclusion

This chapter presented our experimental approach for the design of smart clothes integrating a brain-computer interface, as well as our concept of an “Invisibility Cloak”. Our objective was to design a framework for prototyping smart clothes in AR using a BCI as a novel input device.

First, we designed an experimental platform consisting of an AR-based dressing room where users could wear virtual clothes in front of a virtual mirror. Thanks to an EEG cap the appearance of the virtual clothes could change depending on an estimation of the mental state of the wearer (concentrated or relaxed). The virtual dressing room uses a 3D camera to track the user’s body and head position and orientation. A game engine is used to combine the image recorded by the camera with virtual objects, clothes and other garments. Within the Homo Textilus project, this

experimental platform showed that the virtual clothes could be adapted depending on the mental state of the user. It was then expected that the appearance or features of real smart clothes could also be altered in a similar way.

Second, we studied the design of novel smart clothes based on a BCI. We notably introduced the concept of an Invisibility Cloak. One objective was then to study how well users could interact with smart clothes with the help of a BCI, compared to a classical input device. We introduced the “B-C-Invisibility Power”, representing the “super-power of becoming invisible” using a BCI. Our system proposed a novel approach for optical camouflage using AR, and was based on our previous virtual dressing room controlled by a BCI. We designed and performed a user study evaluating if and how well a BCI could be used to control this “super-power” and, by extension, smart clothes. Results from a pilot study comparing the BCI to a keyboard to control an optical camouflage suggested that while the BCI was more challenging to control than the keyboard, participants have found the BCI to be more innovative. Compared to the keyboard, the BCI has provided participants with a stronger feeling of having a super-power. These results, therefore, indicate that the BCI could be fruitfully used as an alternative to the keyboard to control an invisibility power or smart clothes such as our Invisibility Cloak.



## Chapter 5

# Conclusion

In this manuscript, we have studied the use of BCIs in both VR and AR. Our objectives were: 1) to evaluate the compatibility between BCI and VR/AR setups, 2) to propose novel tools for the visualization of brain activity based on VR/AR, and 3) to propose novel uses for BCIs, especially in combination with smart clothes.

### 5.1 Contributions

To fulfill these objectives, we have first designed and performed a feasibility study concerning the combination of a BCI with VR/AR (see Chapter 2). More specifically, our objective was to find out if a BCI could be used simultaneously with another input device. We have designed a game-like system serving as a support for a user study on the effects of muscular activity on the BCI performance. Various levels of muscular activity were performed while participants had to execute a mental task: concentrate or relax. Our results have shown that this particular 2-class BCI can be successfully used, even when participants are performing a highly demanding muscular activity. Participants expressed the feeling that they were able to keep control of their super-power through the BCI at every level of muscular activity.

We have also proposed visualization tools related to brain activity based on AR/VR and EEG (see Chapter 3). Our first system called the “Mind-Mirror” allowed users to see themselves as in a mirror while visualizing their brain activity in real-time through a virtual brain. This virtual brain was overlaid on top of the reflection of the user’s head using AR. Our system provided multiple visualization tools for the brain activity. We have performed a user study comparing the Mind-Mirror display to a classical neurofeedback display based on a 2D gauge. Our study has shown that even with the additional complexity due to the AR display, no statistically significant drop in the BCI performance was found. Participants have felt the Mind-Mirror to be more innovative and more engaging than the classical gauge display. Our second contribution was called the “Mind-Window”. This system extends the Mind-Mirror by allowing multiple viewpoints on a brain activity recording. We proposed the use of tablet PCs as windows, allowing users to move around a person wearing an EEG cap and being able to see any part of her brain activity in real-time. We have designed multiple display methods including a topography showing the most active parts of the brain, but also displaying the position and name of the EEG electrodes, and a virtual brain divided in well-known areas. Our last contribution is called “Mind-Inside” and allows users to visualize brain activity in real-time by being immersed in a virtual brain. Users are wearing both an EEG cap to record their brain activity and a HMD to display a 3D environment. They are surrounded by a virtual brain filled with voxels which are changing in color depending on the reconstructed brain activity.

Finally, we have studied how BCIs and VR/AR could be applied to the field of smart clothes (see Chapter 4). Our objective was to find novel uses of BCIs integrated with smart clothes. We have

proposed the use of AR-based virtual clothes to mitigate the costs of producing real smart clothes. We have first designed an experimental platform comprising a virtual dressing room integrating a BCI. This BCI, based on EEG, was used to record and evaluate the mental state of the users. Second, we have designed an “Invisibility Cloak” inspired by the Harry Potter universe. This virtual cloak allowed users to become camouflaged in AR by controlling their mental state. A pilot study comparing the BCI to a keyboard for the control of the invisibility effect (called the “B-C-Invisibility Power”) has shown that users found the BCI to be more innovative than the keyboard, although the keyboard was logically found to perform better.

## 5.2 Future work

The work presented in this manuscript has left some unanswered questions concerning the combination of brain-computer interfaces and virtual and augmented reality.

Concerning Chapter 2, further investigation on the combination of BCIs and input devices could be performed. This investigation could confirm our results for the introduction of motor activity while using a BCI within a virtual environment. Mental activities other than motor imagery, such as the P300 or SSVEP BCI paradigms, could be studied as well as other 3D tasks. Additional experiments could be performed within a 3D virtual environment with a higher level of immersion, or with users being allowed to stand and walk during the experiment.

Concerning Chapter 3, other evaluations of the Mind-Mirror could be performed for BCI and neurofeedback applications. This implies formal experiments in other application contexts (e.g., game or education), as well as further studies to identify the best display parameters (e.g., color maps, contrasts, use of the mirror, etc.) for an optimal visualization and learning experience. The positioning of the virtual brain displayed in the Mind-Window could be improved by adding an automatic scaling feature. A markerless tracking could also be implemented. This could allow observers to display the lower areas of the brain. Lastly, a user study could compare the Mind-Window to a classical brain activity visualization tool. The Mind-Inside could also be improved by adding more or different visual guides indicating the position and orientation of the viewer within the virtual brain. Finally, the Mind-Inside could also benefit from a user study to compare this approach to previous work.

Concerning Chapter 4, future work could include a way for users of our virtual dressing room to combine our approach with gestural interaction. The BCI-augmented dressing room could also be extended by adding other BCI paradigms such as the P300. This paradigm could be used to make a selection from a menu in order to give users the ability to change the virtual elements or alter their appearance (shape or color) by making a selection from a list. Finally, concerning the B-C-Invisibility Power, future work could include further user studies as well as multi-user scenarios involving multiple BCIs and camouflages.

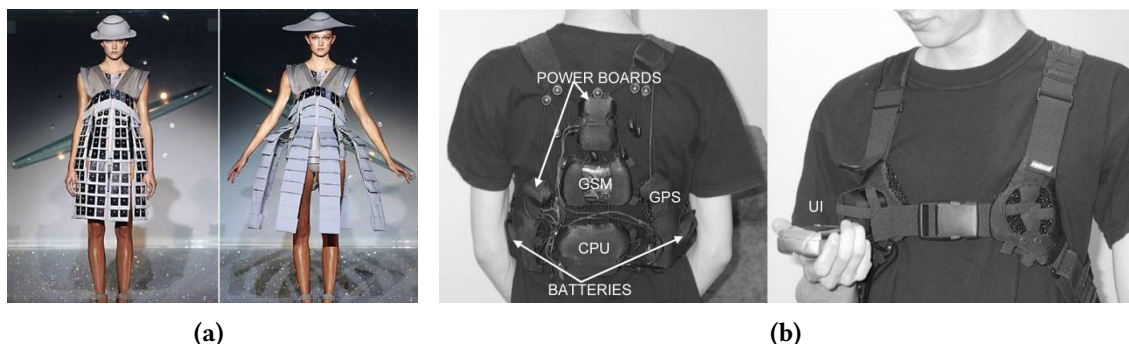
We believe that the work described in this document paves the way for future research on BCIs used to interact with real smart clothes in AR. Real smart clothes could integrate EEG electrodes within a hood and include AR glasses. A portable projector could also be used to change the appearance of the smart clothes depending on the mental state of the wearer.

## **Appendix A**

### **French abstract**

L'OBJECTIF de cette thèse est de proposer une contribution à l'association des interfaces cerveau-ordinateur à la réalité virtuelle ou augmentée.

Le travail présenté dans ce manuscrit a été réalisé dans le contexte d'un projet de recherche collaboratif nommé Homo-Textilus (Février 2012 – Septembre 2015). Son but était d'étudier l'impact sociologique de la prochaine génération de vêtements intelligents. Plus particulièrement, son objectif était d'étudier comment les vêtements intelligents peuvent être acceptés par les utilisateurs, lister les limitations technologiques et les défis, produire un état de l'art sur ces vêtements et finalement concevoir et développer des prototypes. Les textiles intelligents sont des textiles ordinaires "augmentés" par des composants électriques ou mécaniques. Ils peuvent également intégrer des capteurs servant à mesurer les battements cardiaques, la température, etc. De nombreux prototypes de vêtements intelligents ont déjà été produits, par exemple dans le cadre de défilés de mode (voir Figure 1).



**Figure 1** – Figure 2 : Deux exemples de vêtements intelligents. (a) Vêtements intelligents utilisant des actionneurs leur permettant de modifier leur forme. Conception par Hussein Chalayan. Photo : AFP. (b) La structure portante d'un vêtement intelligent conçu pour l'environnement arctique [Rantanen et al., 2002].

Dans le cadre du projet Homo-Textilus l'objectif de cette thèse était d'intégrer une Interface Cerveau-Ordinateur (ICO) à des vêtements intelligents virtuels ou réels. L'objectif final était donc d'étudier la combinaison de systèmes d'ICO, de Réalité Virtuelle (RV) et Réalité Augmentée (RA) pour la conception de nouvelles générations de vêtements intelligents.

Les paragraphes suivants proposent de définir ces trois termes clés du présent manuscrit : les interfaces cerveau-ordinateur, la réalité virtuelle et la réalité augmentée.

**Interface cerveau-ordinateur :** Une interface cerveau-ordinateur a été définie par Wolpaw et al. comme un "système de communication ne dépendant pas des circuits de sortie classiques du cerveau, comme les muscles et nerfs périphériques". [Wolpaw et al., 2000]. Une ICO propose une voie alternative pour envoyer des commandes à des ordinateurs ou à d'autres appareils. L'ElectroEncephaloGraphie (EEG) est une des techniques les plus utilisées au sein de la communauté des ICOs pour accéder à l'activité cérébrale, et consiste à "enregistrer l'activité électrique autour de la tête due à l'activité neuronale au sein du cerveau" [Niedermeyer and da Silva, 2005]. Étant donné que les ICOs peuvent être utilisées pour envoyer des commandes, elles peuvent également être associées à la RV comme un nouveau périphérique d'entrée [Edlinger et al., 2011].

**Réalité virtuelle :** Les premières définitions de la RV étaient "basées sur la technologie". En effet, Greenbaum a proposé une définition de la RV comme étant "un monde alternatif rempli d'images générées par ordinateur qui répondent aux mouvements humains" [Greenbaum, 1992]. Des définitions ultérieures ont été basées sur le concept de "présence". Steuer décrit la présence comme étant le "sens d'être dans un environnement", la téléprésence comme étant "l'expérience de la présence

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dans un environnement via un moyen de communication” et finalement, la RV comme étant “un environnement réel ou simulé dans lequel le spectateur perçoit de la téléprésence” [Steuer, 1992].

**Réalité augmentée :** Milgram et al. ont proposé le concept de “continuum de réalité-virtualité”, et la “réalité mixte” [Milgram et al., 1995]. La réalité mixte est définie comme étant un environnement “dans lequel des objets du monde réel et du monde virtuel sont présentés simultanément avec un seul affichage”. Les environnements réels et virtuels sont placés de chaque côté de ce continuum. Selon ces chercheurs, la RA est un sous-élément de la réalité mixte, proche de l’environnement réel. La RA peut être définie comme une réalité “dans laquelle des objets virtuels 3D sont intégrés dans un environnement réel en 3D en temps réel” [Azuma et al., 1997]. La RA et la RV se partagent la présence d’objets virtuels avec lesquels les utilisateurs peuvent interagir.

### **Objectif principal de la thèse : contribution à l’association des interfaces cerveau-ordinateur à la réalité virtuelle et la réalité augmentée**

La dernière décennie a montré l’augmentation de l’intérêt porté à l’usage des ICO au sein d’environnements virtuels [Lotte et al., 2013], et plus particulièrement au sein des jeux vidéos [Lécuyer et al., 2008; Nijholt et al., 2009]. Auparavant, les ICO étaient principalement utilisées dans le milieu médical, par exemple comme un moyen de communication pour des personnes paralysées [McFarland and Wolpaw, 2011], mais de nouveaux cas d’utilisation pour des personnes valides apparaissent [Allison et al., 2007].

Lotte a proposé une vue d’ensemble des limitations et des perspectives sur l’usage des ICO au sein des jeux vidéos [Lotte, 2011]. Il a listé un certain nombre de limitations possibles lors de l’utilisation d’une ICO basée sur l’EEG : notamment la nécessité pour l’utilisateur de rester immobile afin d’éviter la génération de bruit au sein de l’EEG, le nombre limité de commandes qui peuvent être reconnues en utilisant uniquement une ICO et les performances limitées en termes de latence comparée aux périphériques d’entrées classiques. Ces limitations pourraient être levées en améliorant la technologie des ICOs, mais également en adaptant les techniques d’interaction. Une technique d’interaction est “la fusion des entrées et des sorties, consistant en tous les éléments logiciels et matériels, qui permettent à l’utilisateur d’accomplir une tâche” [Tucker, 2004]. Une de ces adaptations pourrait être l’utilisation d’une ICO hybride.

Une ICO hybride a été définie par Pfurtscheller comme étant “composée de deux ICOs, ou d’au moins une ICO et d’un autre système” [Pfurtscheller, 2010]. Une utilisation possible des ICOs hybrides peut être l’amélioration des performances d’un système par l’ajout d’un nouveau composant, ICO ou non. Un exemple classique d’une ICO hybride séquentielle est l’“interrupteur cérébral” [Pfurtscheller, 2010], où une ICO est utilisée comme un interrupteur pour l’activation (ou la désactivation) d’une autre ICO.

De plus en plus, plutôt que d’être considéré comme un substitut, les ICOs sont vues comme des compléments aux interfaces classiques [Lécuyer et al., 2008].

La Figure 2 montre l’architecture et les composants d’un système RV/RA utilisant une ICO comme un complément à un autre périphérique d’entrée manipulé via l’activité motrice et représenté par une main. Une technique d’interaction reçoit l’activité motrice/cognitive de l’utilisateur et envoie des commandes vers l’environnement virtuel. Le résultat peut être de la réalité virtuelle ou augmentée, en fonction de l’association de l’environnement virtuel avec l’environnement réel. Un affichage virtuel envoie des images qui sont recevables par les yeux et interprétées par le cerveau. La Figure 2 illustre les différentes combinaisons qui peuvent être obtenues entre différentes entrées (ICO ou non) et des affichages RV/RA.

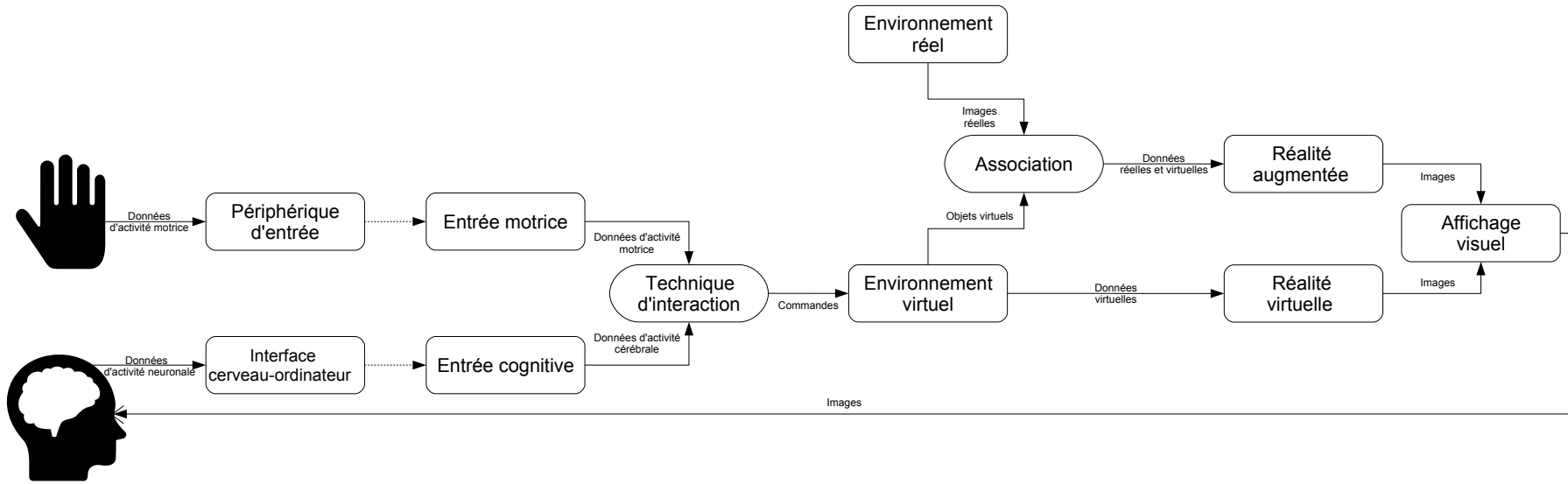


Figure 2 – Architecture générale des systèmes RV/RA intégrant une ICO.



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## Défis

Cette thèse se concentre sur plusieurs défis concernant la combinaison de systèmes basés sur les ICOs et la RV/RA :

- **Compatibilité des ICOs et des systèmes de RV/RA** : l'évaluation de la compatibilité entre les ICOs et la RV/RA peut être divisée en trois couches : matérielle, logicielle et utilisation. Au niveau du matériel, les composants du système sont-ils compatibles entre eux ? Qu'est-ce qui peut perturber l'association de deux composants matériels ? Au niveau du logiciel, quels composants logiciels peuvent être développés pour permettre et faciliter l'utilisation simultanée d'une ICO et de la RV/RA ? Pour finir, au niveau de l'utilisation, est-il possible pour les personnes d'utiliser à la fois une ICO et un système de RV/RA en même temps ?
- **Apprentissage de l'interaction basée sur les ICOs avec des environnements virtuels** : les utilisateurs peuvent-ils être entraînés à contrôler leur activité mentale tout en étant immergés dans un environnement virtuel ? De quelle manière peut-on exploiter leur activité cérébrale pour mieux interagir avec des systèmes de RV/RA ? Quels nouveaux types d'outils de visualisation utilisant la RV/RA peuvent être développés pour atteindre ces objectifs ?
- **Nouveaux usages des ICOs combinées avec la RV/RA** : quels nouveaux usages peuvent être trouvés pour des systèmes combinant des ICOs avec la RV/RA ? Comment ces usages peuvent-ils être évalués en terme de performance et d'utilisation ? Les vêtements intelligents peuvent-ils bénéficier des ICOs, éventuellement associés à la RV/RA ?

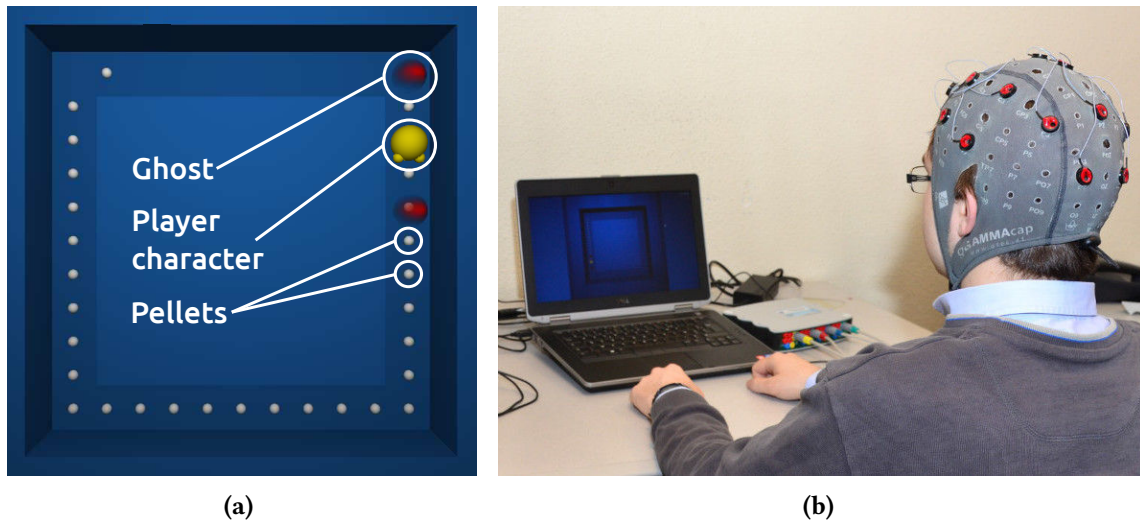
## Méthodologie

La méthodologie adoptée durant cette thèse suit les 4 étapes décrites ci-après :

1. **Étude de faisabilité sur la compatibilité entre les systèmes de réalité virtuelle et les interfaces cerveau-ordinateur** : nous avons conçu une évaluation de la performance d'une ICO lors de l'utilisation simultanée d'une ICO et d'un autre périphérique d'entrée. Une tâche musculaire nécessitant un engagement progressif a été utilisée. De plus, une tâche cognitive a également été exécutée afin de contrôler l'ICO. Le taux de succès des deux tâches a été mesuré.
2. **Outils pour l'apprentissage et la visualisation de l'activité cérébrale basé sur la RV/RA** : nous avons proposé de nouveaux outils permettant aux utilisateurs de visualiser leur activité cérébrale en temps réel. Ces outils pourraient permettre de faciliter l'apprentissage du contrôle de l'activité cérébrale. Plusieurs prototypes pour la visualisation 3D temps réel de l'activité cérébrale en RV/RA ont été conçus et évalués.
3. **Plateforme de test pour les vêtements intelligents** : nous avons conçu une plateforme de test basée sur la RV/RA afin d'évaluer des applications des vêtements intelligents avec un investissement minimal en temps et en ressources. Ce système permet aux utilisateurs portant des vêtements intelligents de les essayer et d'interagir avec plusieurs types de périphériques d'entrée.
4. **Nouveaux concepts de vêtements intelligents basés sur les ICOs** : nous avons étudié le design de nouveaux concepts de vêtements intelligents basés sur les ICOs. Notre plateforme de test RV/RA a été étendue afin d'intégrer une ICO, permettant d'adapter de multiples propriétés des vêtements virtuels. Nous avons conçu et évalué un prototype nommé la "Cape d'Invisibilité", permettant aux utilisateurs de se camoufler en RA en utilisant une ICO.

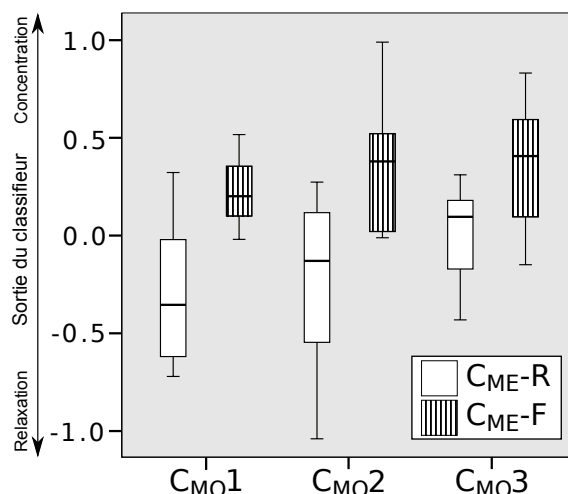
## Contribution 1 : Peut-on utiliser une interface cerveau-ordinateur et manipuler un autre périphérique d'entrée en même temps ?

L'objectif de cette contribution est d'étudier si une ICO peut-être utilisée avec un environnement virtuel en combinaison avec la manipulation d'un périphérique d'entrée fréquemment associé avec la RV. Nous avons décidé d'utiliser la souris dans le cadre de notre évaluation. Afin d'atteindre notre objectif, nous avons conçu un environnement virtuel utilisant une ICO basée sur l'EEG nous permettant d'estimer l'état mental lié à la concentration des utilisateurs. L'environnement virtuel consistait en une variante simplifiée du jeu vidéo Pac-Man (voir [Figure 3](#)). L'utilisateur contrôle un personnage jaune dans un labyrinthe et a pour objectif de manger des Pac-gommes pour gagner des points tout en évitant le contact avec deux fantômes (des entités rouges entourant le personnage). L'application est contrôlée à la fois avec une souris et une ICO. La souris (activité motrice) permet de contrôler la position du personnage alors que l'ICO permet de déclencher ou non la capacité de ce dernier à manger les Pac-gommes, suivant l'état mental demandé et celui qui est atteint par l'utilisateur.



**Figure 3** – Système expérimental. (a) Capture d'écran de notre version simplifiée du jeu vidéo Pac-Man. (b) Un participant portant un casque EEG devant un écran d'ordinateur.

Plusieurs niveaux d'activité motrice ont été testés : aucune activité ( $C_{MO1}$ ), une activité semi-automatique (effectuer des cercles avec la souris,  $C_{MO2}$ ) et une activité exigeante (déplacer la souris dans la même direction que celle du personnage,  $C_{MO3}$ ). Les résultats de l'étude utilisateur ont montrés que notre ICO peut être utilisée avec succès dans tous les cas, même dans le cas d'une activité motrice exigeante. La [Figure 4](#) présente la sortie de l'algorithme de classification de l'état mental ( $C_{ME-R}$  relaxation et  $C_{ME-C}$  concentration) pour chacun des niveaux d'activité motrice. Les participants ont également indiqué avoir l'impression de contrôler leur activité mentale dans tous les cas, et ont apprécié l'interaction hybride de la souris et l'ICO avec l'environnement virtuel.

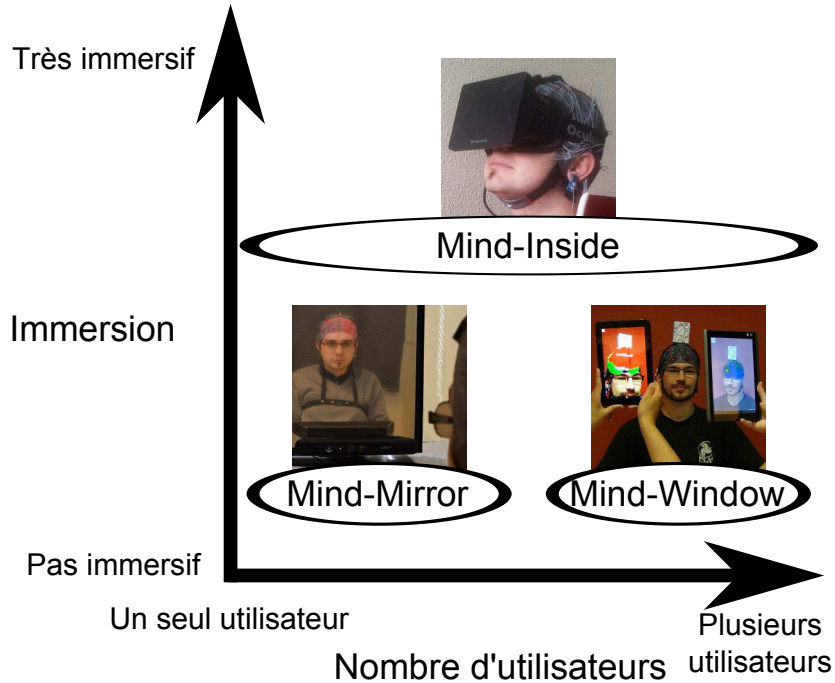


**Figure 4** – Diagramme en boîte montrant la sortie de l'algorithme de classification pour chacune des combinaisons d'activités motrices et mentales.  $C_{ME-R}$  : relaxation,  $C_{ME-C}$  : concentration,  $C_{MO1}$  –  $C_{MO3}$  : les trois niveaux d'activité motrice, du plus faible au plus élevé.

## Contribution 2 : Visualisation de l'activité cérébrale en temps réel en utilisant la réalité augmentée

Cette contribution consiste en trois systèmes pour la visualisation de l'activité cérébrale en temps réel basée sur l'électroencéphalographie et la réalité virtuelle/augmentée. Ces approches pourraient permettre aux utilisateurs de mieux apprendre à contrôler leur activité cérébrale. Notre premier système est le "Mind-Mirror", qui propose un outil permettant aux utilisateurs de visualiser leur propre activité cérébrale en temps réel comme s'ils se regardaient dans un miroir. Nous proposons ensuite dans un second système de faire intervenir plusieurs utilisateurs : le "Mind-Window" permet à plusieurs utilisateurs de voir leur propre activité cérébrale ou celle d'autres personnes. Cette visualisation utilise la RA et des tablettes. Notre troisième contribution est un système augmentant l'immersion : le "Mind-Inside". Ce système utilise la RV plutôt que la RA, ce qui augmente l'impression d'immersion. Le Mind-Inside utilise un visiocasque et propose à l'utilisateur d'être immergé à l'intérieur d'un cerveau avec un affichage volumétrique de l'activité cérébrale. La [Figure 5](#) présente une décomposition de nos trois systèmes. Notre objectif est ici d'étudier différents niveaux d'immersion et différents cas d'interaction (un seul ou plusieurs utilisateurs).

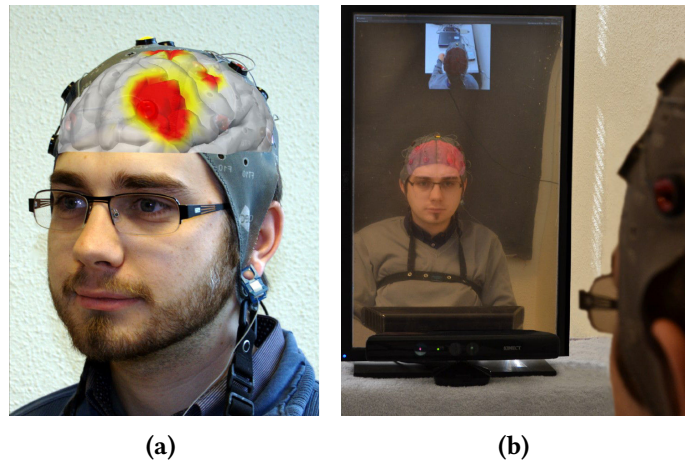
Nos trois systèmes pourraient être utilisés pour diverses applications dans le cadre de la médecine, l'éducation ou le divertissement. Ils pourraient représenter une alternative pour les médecins voulant visualiser l'activité cérébrale. Les systèmes qui autorisent cette visualisation ne le permettent souvent pas en temps réel [[Wolters et al., 2006](#)], contrairement à notre approche. Des enseignants voulant montrer comment certaines parties du cerveau fonctionnent pourraient utiliser ces systèmes comme une illustration en temps réel.



**Figure 5** – Décomposition de nos trois systèmes pour la visualisation de l’activité cérébrale en temps réel en terme d’immersion et d’interaction avec d’autres personnes.

**Mind-Mirror : visualisez votre cerveau en activité comme dans un miroir**

Notre premier système nommé “Mind-Mirror” permet la visualisation de l’activité cérébrale superposée à l’image d’un utilisateur dans un miroir (voir [Figure 6](#)). L’activité cérébrale est extraite en temps réel en utilisant une machine d’acquisition EEG et est affichée en utilisant un cerveau virtuel superposé à l’image de l’utilisateur.



**Figure 6** – Le prototype Mind-Mirror. (a) Un cerveau virtuel est superposé sur l’image réelle de l’utilisateur (photomontage). (b) Notre système utilise un miroir et de la RA.

Nous avons également conduit une étude utilisateur afin de comparer le retour visuel fourni par le Mind-Mirror à celui proposé par une jauge (classiquement utilisée en neurofeedback). Les résultats ont montré que les participants ont trouvé le Mind-Mirror comme étant plus innovant et plus engageant que la jauge mais également plus complexe à utiliser et à comprendre (voir [Table 1](#)). Cette complexité n'a toutefois pas entraîné une baisse significative de performance de l'ICO (voir [Table 2](#)).

**Table 1** – Résultats du questionnaire subjectif pour les 6 critères (de 1: pire à 7: meilleur). Les valeurs moyennes et l'écart type sont également fournies pour chaque représentation. \* : résultat significatif.

	Jauge		Mind-Mirror	
	Moyenne	Écart type	Moyenne	Écart type
Compréhensibilité	5.67	1.37	5.17	0.94
Motivation	4.75	1.05	4.67	1.37
Simplicité*	5.92	1.68	4.92	1.31
Clarté*	5.83	1.27	4.83	1.11
Innovation*	3.17	1.11	5.5	1.09
Originalité*	3.25	1.14	5.5	0.8

**Table 2** – Résultats de la performance de classification. Les valeurs moyennes de la sortie de la régression linéaire et l'écart type sont fournis pour chaque représentation (jauge; Mind-Mirror) et chaque état mental (concentration; relaxation), ainsi que la différence entre les deux états (Diff.). \* : résultat significatif.

	Jauge			Mind-Mirror		
	Con.	Relax.	Diff.	Con.	Relax.	Diff.
Moyenne	0.21	-0.25	0.46*	-0.004	-0.31	0.31*
Écart type	1.44	1.50	0.33*	1.1	1.22	0.39*

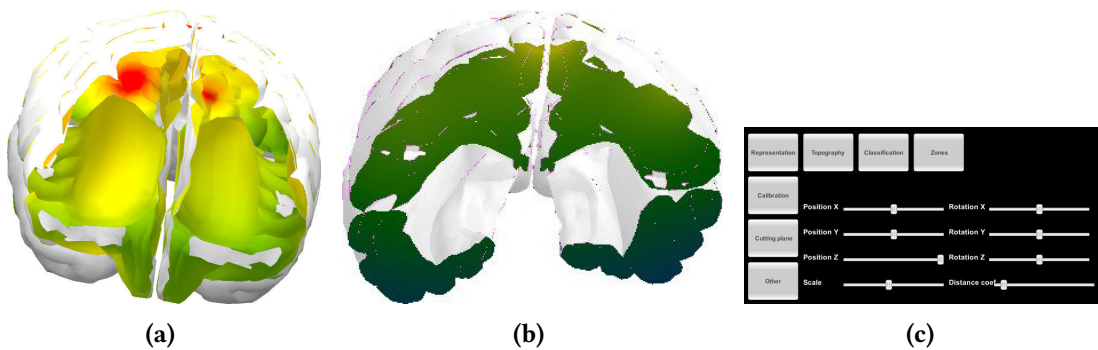
## Mind-Window : visualisation multi-utilisateurs de l'activité cérébrale

Nous proposons une nouvelle approche pour la visualisation en temps réel de l'activité cérébrale nommée le "Mind-Window". Notre approche permet à une seule ou à plusieurs personnes de voir directement l'activité cérébrale d'une personne "augmentée" grâce à de la RA basée sur une tablette. Les tablettes sont dirigées vers la tête de la personne portant un casque EEG. Ces tablettes sont utilisées comme des fenêtres, affichant un flux vidéo enregistré par leur caméra frontale. Un cerveau virtuel est affiché au dessus du flux vidéo à la position du cerveau qui est suivie grâce à un marqueur de RA (voir [Figure 7](#)). Un des objectifs du Mind-Window est d'afficher l'activité cérébrale en temps réel tout en étant simple à utiliser.

Nous avons conçu plusieurs techniques de visualisation et des outils tels qu'un plan de coupe en 3D qui peut être contrôlé en direct avec la tablette (voir [Figure 8](#), (a) et (b)). Un curseur permet de changer la position du plan de coupe le long de l'axe de la caméra alors que l'orientation de la tablette contrôle l'orientation du plan (voir [Figure 8](#), (c)). Un bouton permet à l'utilisateur de figer la rotation du plan de coupe.



**Figure 7** – L’approche “Mind-Window” permet à un seule ou à plusieurs personnes de voir l’activité cérébrale d’une autre personne in situ en utilisant des tablettes et de la RA. L’affichage du cerveau virtuel est mis à jour en temps réel par rapport à l’activité cérébrale de l’utilisateur portant un casque EEG.

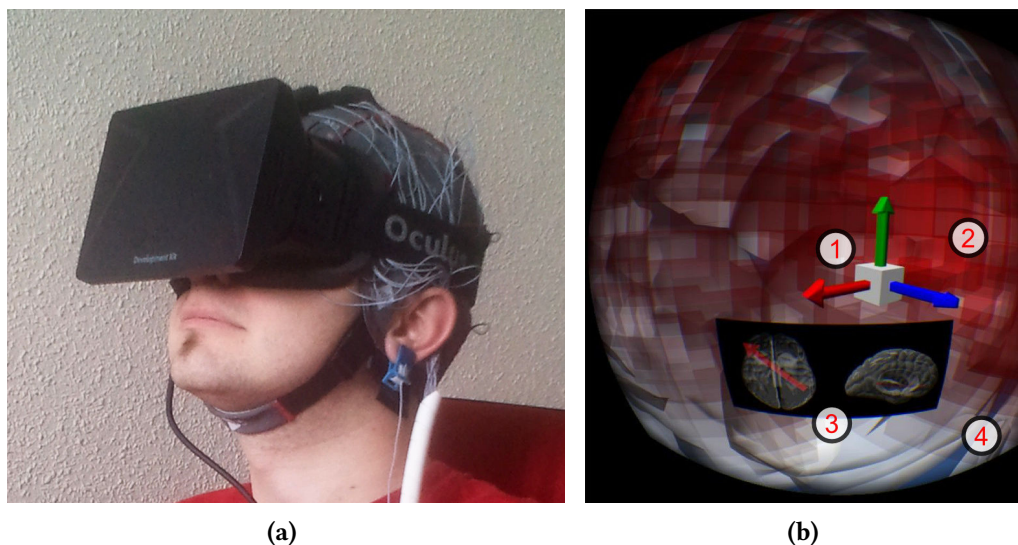


**Figure 8** – Un plan de coupe permet aux utilisateurs de voir l’intérieur du cerveau virtuel. (a) et (b) Deux cerveaux coupés. (c) Notre interface utilisateur permettant de modifier les paramètres de la coupe.

### Mind-Inside : téléprésence à l’intérieur d’un cerveau

Afin d’augmenter l’immersion des utilisateurs, nous proposons un troisième système pour la visualisation l’activité cérébrale utilisant la RV à la place de la RA. Ce système permet aux utilisateurs de visualiser de l’activité cérébrale en étant immergé dans un cerveau virtuel. Les utilisateurs doivent porter un casque EEG et un visiocasque qui sont utilisés pour enregistrer l’activité cérébrale et afficher l’activité cérébrale au sein d’un environnement virtuel (voir [Figure 9](#), (a)). Le système peut également être utilisé par plusieurs utilisateurs, l’un d’entre eux portant le casque EEG et un autre utilisateur portant le visiocasque. L’environnement virtuel affiche les zones les plus actives du cerveau afin que les utilisateurs puissent observer l’effet de plusieurs activités mentales. Ce dernier est composé de plusieurs éléments décrits sur la [Figure 9](#), (b).





**Figure 9** – Le prototype Mind-Inside. (a) Un utilisateur du Mind-Inside portant un visiocasque ainsi qu’un casque EEG. (b) Vue de l’utilisateur à partir du visiocasque. (1) L’origine du repère représenté ici par un cube et trois flèches aide les utilisateurs à s’orienter au sein de l’environnement virtuel. (2) Un affichage basé sur les voxels affiche les zones les plus actives en rouge clair. (3) Deux compas affichent l’orientation actuelle de la vue. (4) La structure du cerveau peut être visualisée en arrière plan.

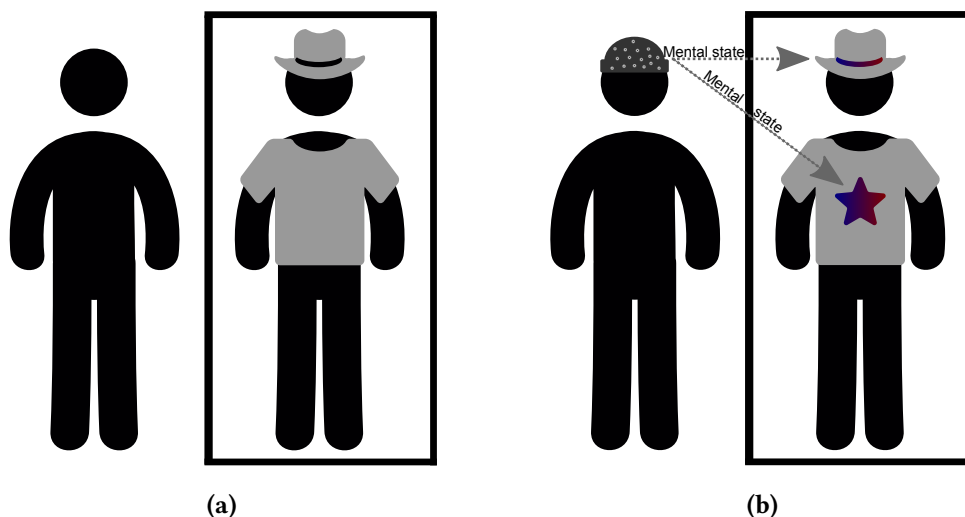
### **Contribution 3 : Vers des vêtements intelligents basés sur les interfaces cerveau-ordinateur et la réalité augmentée**

Cette partie présente notre plate-forme expérimentale pour l’intégration d’une ICO avec des vêtements intelligents. Nous présentons tout d’abord notre cabine d’essayage virtuelle où les utilisateurs peuvent expérimenter l’interaction avec des vêtements virtuels. Nous proposons l’utilisation de la RA afin de réduire les coûts de production des vêtements intelligents et de concevoir rapidement des prototypes intégrant des ICOs à ces derniers. Nous ajoutons ensuite une ICO basée sur l’EEG à la cabine d’essayage virtuelle afin que les utilisateurs puissent contrôler l’apparence des vêtements virtuels en utilisant leur état mental. Finalement, nous introduisons une Cape d’Invisibilité virtuelle inspirée de l’univers de Harry Potter. Les utilisateurs peuvent devenir invisibles en portant une vraie cape et en atteignant un état mental particulier.

#### **La cabine d’essayage virtuelle**

Nous présentons ici une plateforme de test basée sur la RA permettant aux utilisateurs de “porter virtuellement” des vêtements, comme s’ils étaient dans une cabine d’essayage. Cette cabine d’essayage virtuelle leur permet de se voir comme dans un miroir, leur donnant l’occasion d’essayer plusieurs vêtements et d’autres objets pouvant être portés (voir [Figure 10, \(a\)](#)).

Les objets virtuels suivent les utilisateurs alors qu’ils se déplacent devant le miroir, superposant leur image réfléchi. Un casque EEG porté par les utilisateurs peut être ajouté et leur permet de contrôler l’apparence des vêtements virtuels et/ou des objets portables selon leur état mental (voir [Figure 10, \(b\)](#)). Notre système utilise une caméra 3D afin de suivre les utilisateurs sans avoir à utiliser de marqueur de RA.

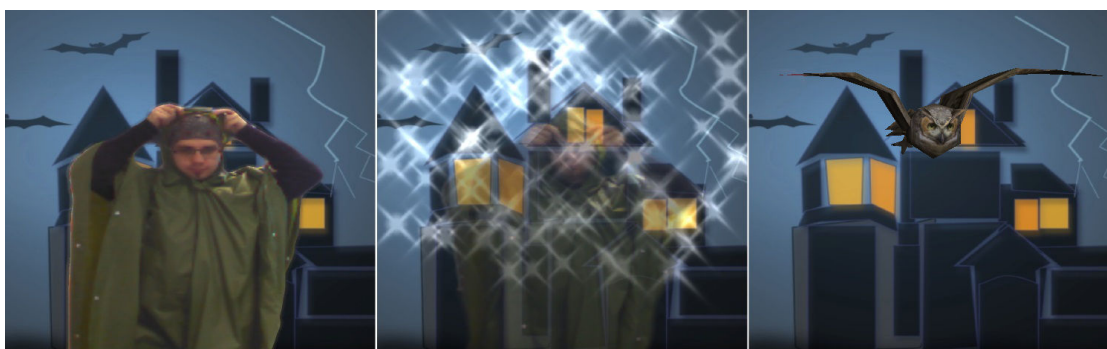


**Figure 10** – Principe de notre plateforme expérimentale permettant aux utilisateurs de porter des vêtements virtuels contrôlés par leur état mental. (a) cabine d’essayage basée sur la RA : l’utilisateur (à gauche) peut se voir portant des vêtements virtuels (à droite). (b) contrôle basé sur une ICO : l’utilisateur portant un casque EEG (gauche) peut modifier l’apparence des vêtements virtuels en changeant d’état mental (droite).

### La Cape d’Invisibilité et le B-C-Invisibility Power

L’objectif de cette partie est d’étudier plus en détail l’utilisation d’une ICO pour interagir et/ou contrôler des vêtements virtuels et intelligents. Nous voulons ici étudier et proposer de nouveaux concepts basés sur une ICO.

Nous proposons ici la “Cape d’Invisibilité” pilotée par EEG. Cette Cape d’Invisibilité est inspirée par l’univers de Harry Potter (voir [Figure 11](#)). Les utilisateurs doivent porter la capuche de la Cape d’Invisibilité et se concentrer pour devenir invisibles. Enlever la capuche les rend visible à nouveau indépendamment de leur niveau de concentration.



**Figure 11** – Une cape d’invisibilité illustre un concept divertissant de vêtements intelligents contrôlés par une ICO et est inspirée par l’univers de Harry Potter. Dans ce cas, l’utilisateur porte la capuche de la cape et se concentre afin de devenir invisible. L’enlever empêche tout niveau d’invisibilité. Un effet de particules apparaît à chaque fois que l’utilisateur met la capuche sur sa tête.

La Cape d’Invisibilité propose aux utilisateurs d’obtenir un pouvoir d’invisibilité (voir [Figure 12](#)). Dans le cas présent, ce pouvoir est dirigé par l’état mental de l’utilisateur en utilisant une ICO. C’est ce que nous proposons de nommer la “B-C-Invisibility Power”.

Nous avons conçu et réalisé une étude utilisateur évaluant si et comment une ICO peut être utilisée pour contrôler ce “super pouvoir”, et, par extension, des vêtements intelligents. Dans cette étude nous avons comparé l’utilisation de l’ICO avec celle d’un périphérique d’entrée classique :



**Figure 12** – Le B-C-Invisibility Power permet aux utilisateurs de devenir virtuellement invisibles en exécutant des tâches mentales. Les signaux cérébraux sont extraits en utilisant des électrodes EEG et analysés au sein de l'ICO.

le clavier. Les résultats ont suggéré que malgré le fait que l'ICO ait été plus difficile à contrôler qu'un clavier, les participants ont trouvé que l'ICO était plus innovante. Comparé au clavier, l'ICO a fourni aux participants une impression plus forte d'avoir un super pouvoir. Ces résultats indiquent que l'ICO pourrait être utilisée avec succès comme une alternative au clavier pour contrôler un pouvoir d'invisibilité ou des vêtements intelligents comme notre Cape d'Invisibilité.

## Conclusion

Dans ce manuscrit nous avons étudié l'utilisation d'ICOs au sein de la RV et de la RA. Nos objectifs étaient :

1. d'évaluer la compatibilité entre les systèmes basés sur une ICO et la RV/RA;
2. de proposer de nouveaux outils pour la visualisation de l'activité cérébrale basée sur la RV/RA;
3. de proposer de nouveaux usages pour les ICOs, et plus particulièrement en combinaison avec les vêtements intelligents.

Afin de réaliser ces objectifs, nous avons tout d'abord conçu et réalisé une étude de faisabilité concernant la combinaison entre une ICO avec la RV/RA. Plus particulièrement, notre objectif était d'étudier si une ICO peut être utilisée simultanément avec un autre périphérique d'entrée. Nous avons conçu un système similaire à un jeu vidéo, servant comme support pour une étude utilisateur mesurant les effets de l'activité musculaire sur les performances d'une ICO. Plusieurs niveaux d'activité musculaire ont été utilisés alors que les participants avaient à exécuter une tâche mentale : se concentrer ou se relaxer. Nos résultats ont montré que cette ICO peut être utilisée avec succès, même lorsque les participants exécutaient une activité musculaire exigeante. Les participants ont exprimé l'impression d'avoir eu la possibilité de garder le contrôle sur leur "super pouvoir" à travers l'ICO à tous les niveaux d'activité musculaire.

Nous avons également proposé des outils de visualisation de l'activité cérébrale basés sur la RV/RA et l'EEG. Notre premier système nommé le "Mind-Mirror" permettait aux utilisateurs de se voir eux-mêmes dans un miroir tout en visualisant leur activité cérébrale en temps réel au travers d'un cerveau virtuel. Ce cerveau virtuel était sur-imprimé au-dessus du reflet de la tête de l'utilisateur en utilisant la RA. Notre système proposait plusieurs outils de visualisation de l'activité cérébrale

dans un miroir. Nous avons réalisé une étude utilisateur comparant l’affichage basé sur le Mind-Mirror à un affichage classique du neurofeedback basé sur une jauge 2D. Notre étude a montré qu’aucune perte significative de la performance de l’ICO n’a été constatée même avec une complexité additionnelle due à l’affichage basé sur la RA. Les participants ont trouvé que le Mind-Mirror était plus innovant et plus engageant que l’affichage classique sous forme de jauge. Notre seconde contribution est nommée “Mind-Window”. Ce système étend le Mind-Mirror en permettant plusieurs points de vue sur un même enregistrement d’activité cérébrale. Nous proposons l’utilisation de tablettes comme des fenêtres virtuelles. Celles-ci permettent aux utilisateurs de se déplacer autour d’une personne portant un casque EEG et affichant toutes les parties de son activité cérébrale en temps réel. Nous avons conçu plusieurs systèmes d’affichage incluant une topographie montrant les parties les plus actives du cerveau, mais également la position et le nom des électrodes EEG, et un cerveau virtuel divisé en zones connues. Notre dernière contribution se nomme “Mind-Inside” et permet aux utilisateurs de voir leur activité cérébrale en temps réel en étant immergés dans un cerveau virtuel. Les utilisateurs portent un casque EEG permettant d’enregistrer leur activité cérébrale ainsi qu’un visiocasque affichant un environnement 3D. Ils sont entourés d’un cerveau virtuel rempli de voxels qui changent de couleur selon l’activité cérébrale reconstruite.

Pour finir, nous avons étudié comment les ICOs et la RV/RA peuvent être appliquées au domaine des vêtements intelligents. Notre objectif était de trouver de nouveaux usages des ICOs intégrés aux vêtements intelligents. Nous avons proposé l’utilisation de vêtements basés sur la RA afin de réduire les coûts de production de ces vêtements. Nous avons commencé par concevoir une plateforme d’expérimentation consistant en une cabine d’essayage virtuelle intégrant une ICO. Cette ICO, basée sur de l’EEG, a été utilisée pour enregistrer et évaluer l’état mental des utilisateurs. Nous avons ensuite conçu une “Cape d’Invisibilité” inspirée par l’univers de Harry Potter. Cette cape virtuelle permettait aux utilisateurs de se camoufler en RA en utilisant leur état mental. Une étude utilisateur comparant une ICO à un clavier pour contrôler l’effet d’invisibilité (appelé le “B-C-Invisibility Power”) a montré que les utilisateurs ont trouvé l’ICO comme étant plus innovante que le clavier, mais que ce dernier a été logiquement trouvé comme étant plus performant.

Nous pensons que le travail décrit dans ce document ouvre la voie à de futures recherches sur les ICOs utilisées pour interagir avec des vêtements intelligents réels en RA. De tels vêtements pourraient intégrer des électrodes EEG à l’intérieur d’une capuche et inclure des lunettes de RA. Un projecteur portable pourrait également être utilisé afin de modifier l’apparence des vêtements intelligents suivant l’état mental du porteur.

### **Ce travail a donné lieu aux publications et au brevet suivants :**

#### **Articles publiés dans des conférences avec comité de lecture**

Mercier-Ganady, J., Loup-Escande, E., George, L., Busson, C., Marchal, M., and Lécuyer, A. (2013). Can we use a brain-computer interface and manipulate a mouse at the same time? In *Proceedings of the 19th ACM Symposium on Virtual Reality Software and Technology*, pages 69–72.

Mercier-Ganady, J., Lotte, F., Loup-Escande, E., Marchal, M., and Lécuyer, A. (2014). The Mind-Mirror: See your brain in action in your head using EEG and augmented reality. In *Proceedings of the IEEE Virtual Reality*, pages 33–38.

Mercier-Ganady, J., Marchal, M., and Lécuyer, A. (2015). B-C-Invisibility Power: Introducing optical camouflage based on mental activity in augmented reality. In *Proceedings of the 6th ACM Augmented Human International Conference*, pages 97–100.

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## **Poster publié dans une conférence avec comité de lecture**

Mercier-Ganady, J., Marchal, M., and Lécuyer, A. (2015). The Mind-Window: Brain activity visualization using tablet-based AR and EEG for multiple users. In *Proceedings of the 6th ACM Augmented Human International Conference*, pages 197–198.

## **Brevet**

Lécuyer, A., Mercier-Ganady, J., Lotte, F., and Marchal, M. (2013). Système d’affichage de données caractérisant l’activité cérébrale d’un individu, procédé et programme d’ordinateur associé. Patent FR3015710A1.

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## Peer-reviewed conference poster

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## Résumé

L'objectif de cette thèse est d'étudier l'utilisation d'Interfaces Cerveau-Ordinateur (ICOs) au sein de la Réalité Virtuelle (RV) et de la Réalité Augmentée (RA). Notre but est d'évaluer la compatibilité entre les systèmes basés sur une ICO et la RV/RA, de concevoir de nouveaux outils pour la visualisation de l'activité cérébrale basée sur la RV/RA, et finalement de proposer de nouveaux usages pour les ICOs, plus particulièrement en combinaison avec des vêtements intelligents.

Afin de réaliser ces objectifs, nous avons tout d'abord réalisé une étude de faisabilité concernant l'association entre une ICO et la RV. Notre objectif était d'étudier l'influence de l'activité motrice sur une ICO. Nous avons conçu un système similaire à un jeu vidéo, servant comme support à une étude utilisateur montrant que l'ICO peut être utilisée avec succès, même lorsque les participants exécutent une activité musculaire exigeante.

Dans un second temps, nous avons également proposé des outils de visualisation de l'activité cérébrale basés sur la RV/RA. Notre premier système nommé "Mind-Mirror" superpose un cerveau virtuel représentant l'activité cérébrale d'un utilisateur à l'image de celui-ci dans un miroir. Une étude utilisateur a montré qu'aucune perte significative de performance de l'ICO n'a été constatée, même avec une complexité additionnelle due à l'affichage basé sur la RA. Notre seconde contribution se nomme "Mind-Window" et étend les possibilités du Mind-Mirror en permettant plusieurs points de vue sur un même enregistrement d'activité cérébrale en utilisant des tablettes. Notre dernière contribution se nomme "Mind-Inside" et permet aux utilisateurs de visualiser en RV leur activité cérébrale en temps réel tout en étant immergés dans un cerveau virtuel.

Enfin, nous avons étudié comment les ICOs et la RV/RA peuvent être appliquées au domaine des vêtements intelligents. Nous avons mis en place une plateforme d'expérimentation consistant en une cabine d'essayage virtuelle intégrant une ICO et permettant aux utilisateurs de porter des vêtements intelligents virtuels en RA. Poursuivant ces travaux, nous avons également conçu une "cape d'invisibilité" inspirée par l'univers de Harry Potter. Cette cape virtuelle permet aux utilisateurs de se camoufler en RA en utilisant leur état mental. Une étude utilisateur sur le contrôle de l'effet a mis en avant l'amélioration de l'expérience utilisateur et "l'impression d'avoir un super-pouvoir".

## Abstract

The objective of this PhD thesis is to study the use of Brain-Computer Interfaces (BCIs) within Virtual Reality (VR) and Augmented Reality (AR). Our goal is to evaluate the compatibility between systems based on a BCI and VR/AR, to design new tools for the visualization of the brain activity based on VR/AR, and finally to propose new uses for the BCIs, and especially in combination with smart clothes.

In order to fulfil these objectives, we have first designed and performed a feasibility study concerning the combination of a BCI and VR. Our objective was to study the influence of motor activity on a BCI. We have designed a system similar to a video game, serving as a base for a user study showing that this BCI can be successfully used, even when participants are performing a demanding muscular activity.

We have also proposed three visualization tools for the brain activity based on VR/AR. Our first system called the "Mind-Mirror" which enables the visualization of our own brain activity "inside our own head" by superimposition. A user study has shown that no significant drop in BCI performance occurred, even with the additional complexity due to our AR-based display. Our second contribution is called "Mind-Window" and extends the Mind-Mirror's possibilities by enabling one or multiple users to visualize the brain activity of another person as if her skull was transparent. Our last contribution is called "Mind-Inside" and allows users to visualize their brain activity in real-time while being immersed in a virtual brain.

Finally, we have studied how BCIs and the VR/AR can be applied to smart clothes. We have designed an experimental platform comprising a dressing room integrating a BCI. Following this work, we proposed an "invisibility cloak" inspired by the Harry Potter universe. This virtual cloak allows users to camouflage themselves in AR using their mental state. Results from a preliminary study based on a simple video-game inspired by the Harry Potter universe could notably show that, compared to a standard control made with a keyboard, controlling the optical camouflage directly with the BCI could enhance the user experience and the feeling of "having a super-power".



## DOCTORAT

### DE L'INSTITUT NATIONAL DES SCIENCES APPLIQUÉES DE RENNES

Discipline :

Spécialité : Informatique

Loi n° 85-52 du 26 janvier 1984 sur l'Enseignement Supérieur et décret n° 84-573 du 5 juillet 1984, relatif aux diplômes nationaux de l'Enseignement Supérieur, modifié par le décret n° 2002-603 du 25 avril 2002.

Arrêté du 7 août 2006 relatif aux études doctorales

### PROCES-VERBAL DE SOUTENANCE DE THESE

**Monsieur MERCIER JONATHAN**

**Né le 28 Août 1986 à AMIENS - SOMME**

**N° INSEE : 186088002138660**

justifiant des diplômes, titres ou travaux suivants :  
**INGÉNIEUR EN INFORMATIQUE**

a présenté en soutenance

Une thèse

~~Un ensemble de travaux~~

**Intitulé de la thèse :**

**Contribution to the Study of the Use of Brain-Computer Interfaces in Virtual and Augmented Reality**

Recherches effectuées dans les établissements suivants : *INSA de RENNES*  
*IRISA*

Codification du doctorat : préciser les sections et sous-sections du C.N.U. et du Comité National du CNRS dont relève la thèse

*CNU 27*  
*Section 07 CNRS*

Autorisation de soutenance accordée le : 25 septembre 2015

Rapporteurs :

Monsieur HACHET Martin, Chargé de Recherche HDR, INRIA Bordeaux  
Madame THOUVENIN Indira, Professeur Université Technologique Compiègne

Après délibération, les membres du jury, soussignés ont prononcé


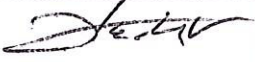


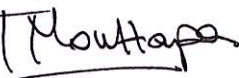

L'ajournement (Decision du jury manuscrite)	L'admission (*) (devra être portée dans la case ci dessous en toutes lettres)	Mention
	ADMISS	Très Honorable

(\*) L'admission donne lieu à l'attribution d'une mention : Honorable, très honorable

de **MERCIER JONATHAN**

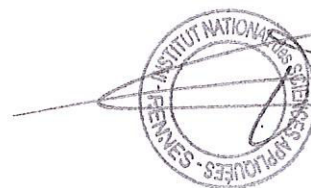
Fait à Rennes, le 12 Octobre 2015

### JURY DE SOUTENANCE

Fonction	Noms	Titres	Signatures
Directeur de thèse	Monsieur LECUYER Anatole	Directeur de Recherche INRIA Rennes - Bretagne Atlantique	
Rapporteur	Monsieur HACHET Martin	Chargé de Recherche HDR, INRIA Bordeaux	
Examineur	Monsieur ARNALDI BRUNO	Professeur INSA Rennes	
Examineur	Monsieur MOREAU Guillaume	Professeur Ecole Centrale de Nantes	
Rapporteur	Madame THOUVENIN Indira	Professeur Université Technologique Compiègne	
Co-Encadrant de thèse	Madame MARCHAL Maud	Maitre de conférences HDR INSA Rennes	

Le jury a été présidé par *ARNALDI Bruno*

Le directeur,



M'hamed DRISSI

## RAPPORT DE SOUTENANCE DE THESE DE DOCTORAT

Nom Prénom du doctorant : MERCIER JONATHAN

Spécialité de la thèse : Informatique Date de soutenance 12 Octobre 2015

Intitulé de la thèse:

Contribution to the Study of the Use of Brain-Computer Interfaces in Virtual and Augmented Reality

Membres du jury :

- Monsieur LECUYER Anatole
- Monsieur HACHET Martin
- Monsieur ARNALDI BRUNO
- Monsieur MOREAU Guillaume
- Madame THOUVENIN Indira
- Madame MARCHAL Maud

Jonathan Mercier-Ganady a présenté ses contributions lors d'un exposé synthétique, clair et bien illustré!

Le jury a particulièrement apprécié la contribution, dans le domaine de la réalité virtuelle, présentée par Jonathan Mercier-Ganady concernant la réalisation des activités cérébrales, en mettant à profit l'expertise et le travail de son équipe d'accueil. En effet, cette contribution exploratoire ouvre de nombreux champs de recherche potentiels.

Lors des échanges avec le jury, Jonathan Mercier-Ganady a proposé des réponses rapides et précises, montrant sa connaissance du domaine.

En conclusion, le jury est unanime pour que soit décerné à Jonathan Mercier-Ganady, le grade de Docteur de l'Université de Rennes, spécialité Informatique, avec la mention Très Honorable.

ARNALDI Bruno

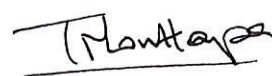
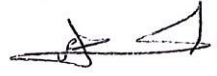
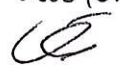
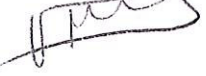
MOREAU G.

M. HACHET

A. LECUYER

M. MARCHAL

I. THOUVENIN





## AVIS DU JURY SUR LA REPRODUCTION DE LA THESE SOUTENUE

**Titre de la thèse:**

Contribution to the Study of the Use of Brain-Computer Interfaces in Virtual and Augmented Reality

**Nom Prénom de l'auteur : MERCIER JONATHAN**

Membres du jury :

- Monsieur LECUYER Anatole
- Monsieur HACHET Martin
- Monsieur ARNALDI BRUNO
- Monsieur MOREAU Guillaume
- Madame THOUVENIN Indira
- Madame MARCHAL Maud

Président du jury : *ARNALDI Bruno*

Date de la soutenance : 12 Octobre 2015

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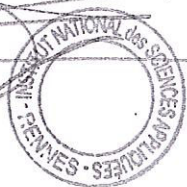
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Fait à Rennes, le 12 Octobre 2015

Signature du président de jury

Le Directeur,

M'hamed DRISSI





## Résumé

## Abstract

L'objectif de cette thèse est d'étudier l'utilisation d'Interfaces Cerveau-Ordinateur (ICOs) au sein de la Réalité Virtuelle (RV) et de la Réalité Augmentée (RA). Notre but est d'évaluer la compatibilité entre les systèmes basés sur une ICO et la RV/RA, de concevoir de nouveaux outils pour la visualisation de l'activité cérébrale basée sur la RV/RA, et finalement de proposer de nouveaux usages pour les ICOs, plus particulièrement en combinaison avec des vêtements intelligents.

Afin de réaliser ces objectifs, nous avons tout d'abord réalisé une étude de faisabilité concernant l'association entre une ICO et la RV. Notre objectif était d'étudier l'influence de l'activité motrice sur une ICO. Nous avons conçu un système similaire à un jeu vidéo, servant comme support à une étude utilisateur montrant que l'ICO peut être utilisée avec succès, même lorsque les participants exécutent une activité musculaire exigeante.

Dans un second temps, nous avons également proposé des outils de visualisation de l'activité cérébrale basés sur la RV/RA. Notre premier système nommé «Mind-Mirror» superpose un cerveau virtuel représentant l'activité cérébrale d'un utilisateur à l'image de celui-ci dans un miroir. Une étude utilisateur a montré qu'aucune perte significative de performance de l'ICO n'a été constatée, même avec une complexité additionnelle due à l'affichage basé sur la RA. Notre seconde contribution se nomme «Mind-Window» et étend les possibilités du Mind-Mirror en permettant plusieurs points de vue sur un même enregistrement d'activité cérébrale en utilisant des tablettes. Notre dernière contribution se nomme «Mind-Inside» et permet aux utilisateurs de visualiser en RV leur activité cérébrale en temps réel tout en étant immergés dans un cerveau virtuel.

Enfin, nous avons étudié comment les ICOs et la RV/RA peuvent être appliquées au domaine des vêtements intelligents. Nous avons mis en place une plateforme d'expérimentation consistant en une cabine d'essayage virtuelle intégrant une ICO et permettant aux utilisateurs de porter des vêtements intelligents virtuels en RA. Poursuivant ces travaux, nous avons également conçu une «cape d'invisibilité» inspirée par l'univers de Harry Potter. Cette cape virtuelle permet aux utilisateurs de se camoufler en RA en utilisant leur état mental. Une étude utilisateur sur le contrôle de l'effet a mis en avant l'amélioration de l'expérience utilisateur et «l'impression d'avoir un superpouvoir».

The objective of this PhD thesis is to study the use of Brain- Computer Interfaces (BCIs) within Virtual Reality (VR) and Augmented Reality (AR). Our goal is to evaluate the compatibility between systems based on a BCI and VR/AR, to design new tools for the visualization of the brain activity based on VR/AR, and finally to propose new uses for the BCIs, and especially in combination with smart clothes.

In order to fulfil these objectives, we have first designed and performed a feasibility study concerning the combination of a BCI and VR. Our objective was to study the influence of motor activity on a BCI. We have designed a system similar to a video game, serving as a base for a user study showing that this BCI can be successfully used, even when participants are performing a demanding muscular activity.

We have also proposed three visualization tools for the brain activity based on VR/AR. Our first system called the «Mind- Mirror» which enables the visualization of our own brain activity «inside our own head» by superimposition. A user study has shown that no significant drop in BCI performance occurred, even with the additional complexity due to our AR-based display. Our second contribution is called «Mind-Window» and extends the Mind-Mirror's possibilities by enabling one or multiple users to visualize the brain activity of another person as if her skull was transparent. Our last contribution is called «Mind-Inside» and allows users to visualize their brain activity in real-time while being immersed in a virtual brain.

Finally, we have studied how BCIs and the VR/AR can be applied to smart clothes. We have designed an experimental platform comprising a dressing room integrating a BCI. Following this work, we proposed an «invisibility cloak» inspired by the Harry Potter universe. This virtual cloak allows users to camouflage themselves in AR using their mental state. Results from a preliminary study based on a simple video-game inspired by the Harry Potter universe could notably show that, compared to a standard control made with a keyboard, controlling the optical camouflage directly with the BCI could enhance the user experience and the feeling of «having a super-power».