Research in Neuroscience and Virtual Reality

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1. Introduction

Virtual reality is one of the most challenging applications of computer graphics and is currently being used in many fields. Participants of immersive virtual environments have unique experiences which were never before possible. Although they know from a cognitive point of view that the virtual environment is not a real place, they act and think as if the virtual environment were real. Virtual environments take advantage of the imaginative ability of people to psychologically transport them to other places.

In this chapter, we are going to analyze the two-way relationship between virtual reality and neuroscience.

First, it will be described how virtual reality can be a useful tool in neuroscience research, as long as it can be used to create controlled environments where participants can perform tasks while their responses are monitored in order to achieve a more detailed understanding of the associated brain processes. Previous work and research in this field will be detailed and discussed.

Secondly, the applications of neuroscience in the virtual reality field will be analyzed. There are aspects of the virtual reality experience such as presence that can be an object of study for neuroscientists (Sanchez-Vives & Slater, 2005). Results from neuroscience studies can help virtual reality researchers to improve their knowledge about the processes that occur in the brain during the exposure to virtual environments and generate more compelling and effective versions of the virtual environments that they develop.

At the end of the chapter, some general conclusions and implications that the research in virtual reality and neuroscience may have for future work will be described.

The different kinds of studies that will be described in this chapter are listed in Table 1.

2. Virtual reality for neuroscience

Virtual reality can be a perfect tool to generate controlled environments that can be used to observe human behaviour. Different aspects can be analyzed from a neuroscience perspective, including perception, control of movement, learning, memory, and emotional aspects.

Usually, in order to analyze human responses to different kinds of events or tasks, the participant behaviour has to be monitored in a real situation or during the execution of experimental tasks designed to analyze the influence of specific variables on human behaviour.

Virtual reality for neuroscience	Study of human navigation with highly immersive virtual environments	(Warren et al., 2001; Tarr & Warren, 2002; Kearns et al., 2002; Foo et al., 2004; Foo et al., 2005; Waller et al., 2007; Richardson & Waller, 2007)
	Virtual versions of classical neuroscience tests to study navigation and spatial memory	(Astur et al., 1998; Jacobs et al., 1997; Jacobs et al., 1998 ; Driscoll et al., 2003; Astur et al., 2004; Astur et al., 2005; Duncko et al., 2007; Cornwell et al., 2008)
	Animal navigation	(Astur et al., 2003; Hölscher et al., 2005; Harvey et al., 2009)
	Human social interaction	(Bailenson et al., 2001; Schilbach et al., 2006; Slater et al., 2006)
Neuroscience for virtual reality	Presence research – Electroencephalogram	(Schlögl et al., 2002; Baumgartner et al., 2006; Kober, 2010)
	Presence research – functional magnetic resonance	(Hoffman et al., 2003; Baumgartner et al., 2008; Jäncke et al., 2009)
	Presence research – Transcranial Doppler	(Alcañiz et al., 2009; Rey et al., 2010)
	Virtual representation of the body	(Slater et al., 2008)

Table 1. Classification of previous studies combining virtual reality and neuroscience

Those previous approaches have both positive and negative points that have to be taken into account when applying them to study human behaviour.

Laboratory experimental tasks allow the controlled study of any of the variables that may be having an influence on the participant's responses. However, the situation presented to the user is not realistic, and usually the participant has to execute the task in a laboratory setting and isolated from other contextual factors that are also associated with the situations or tasks that are being analyzed.

On the other hand, the analysis of human responses in real situations is complicated because the stimuli that are intervening in the experience cannot be controlled (or, at least, not completely controlled) by the experimenter.

However, with virtual reality, it is possible to design a virtual environment and situation with key elements analogous to those of a similar situation in the real world, but, in this case, the presentation of stimuli to the participant can be controlled in a precise way. Furthermore, virtual reality can also be used to create virtual versions of classical neuroscience tests that had only been applied to animals because of their characteristics. Virtual reality allows that the virtual version of the test can be conveniently applied to human participants.

In the following subsections, different kinds of studies about human behaviour that have been conducted up to now with the help of virtual reality settings will be described:

1. Study of human navigation with highly immersive virtual environments. Behavioural neuroscientists have been interested in analyzing how humans learn routes to get from one place to another. Highly immersive virtual environments provide a virtual laboratory where this kind of studies can be conducted and easily controlled.

2. Virtual versions of classical neuroscience tests to study navigation and spatial memory.
3. Animal navigation. In these cases, neural circuits underlying navigation have been studied in animals such as mice using specifically designed virtual environments.
4. Human social interaction. There are other aspects, apart from navigation and spatial memory, that have been analyzed with virtual reality settings. Studies that have analyzed the neural correlates of social interaction will be described.

2.1 Study of human navigation with highly immersive virtual environments

Human navigation is one of the issues that have been analyzed using virtual environments. Users can navigate in a virtual reality system with specific goals, while their behaviour is analyzed to obtain conclusions about how humans learn routes to get from one place to another.

Tarr & Warren (2002) considered that three sources of information were available for this learning process: visual information in the form of optic flow (the pattern of visual motion at the moving), visual information about objects distributed in the environment (which can be used as landmarks) and body senses including vestibular and proprioceptive information. In order to analyze the influence of each of those factors, it is necessary that the subject moves through an environment where the experimenter can manipulate aspects such as the optic flow and the objects that appear in the environment. Virtual reality can be used to generate this controlled environment where the participant can navigate freely.

Fig. 1. Subject of a virtual reality experiment wearing a head mounted display

Tarr & Warren (2002) created a highly immersive virtual reality system, which they called VENLab, in which users visualized the environment using a stereo head mounted display. A photograph of a subject wearing a head mounted display is shown in Figure 1. Participants navigated in the VENLab using real walking (a wide-area head tracker was attached to the head tracker)

In different studies conducted with the VENLab, they analyzed the role of each of these sources of information while participants navigated in a virtual world where optic flow and landmarks could be controlled by the experimenter.

In one of the studies, Warren et al. (2001) analyzed if optic flow information is actually used when users have to walk towards a goal. Two different hypotheses had been proposed in the literature. The optic flow hypothesis indicated that the observer would walk to cancel the error between the heading perceived from optic flow and the goal navigation. On the other hand, the egocentric direction hypothesis considered that the observer just walks in the perceived visual direction of the goal with respect to the body. As the two hypotheses usually predict the same behaviour, it was fundamental the use of a virtual environment to be able to dissociate them. The virtual environment that was designed made it possible to displace the heading direction specified by the optic flow by an angle from the actual direction of walking. Different experimental conditions with growing levels of optic flow were analyzed, including an initial condition where no surrounding flow was available. It was found that subjects walked in the visual direction of a target, but increasingly relied on optic flow as it was added to the display.

In another study, Kearns et al. (2002) analyzed the role of visual information and body senses during a homing task. In this kind of tasks, the participant must be able to return to a home location after following a trajectory in the environment. Path integration is defined in this context as a navigation strategy in which information about one's velocity or acceleration is integrated on-line to estimate the distance travelled and the angles turned from an initial point (Loomis et al., 1999). Both optic flow information and body senses information (such as vestibular information and proprioception from receptors in muscles, tendons and joints) can provide information about distances and rotations. In order to analyze the role of the different variables, three experiments were proposed in the study. The task was a triangle completion task, in which participants walk two specified legs of a triangle and then they have to return to the starting position. In the first two experiments, only optic flow was analyzed, by making users navigate in a virtual environment using a joystick during the homing task. In the third experiment, the combined influence of visual and body senses was analyzed, by making the user navigate in the virtual environment with real walking. Results from the first two experiments showed that optic flow can be used for path integration in a homing task. Results from the third experiment showed a different pattern of results. Participants were more consistent, exhibited a pattern of overturning instead of underturning, and had similar responses independently of the presence of optic flow. These results seemed to indicate that, even if participants can perform path integration from optic flow if it is required, they usually rely more on body senses if this information is available.

Later, Foo et al. (2004) analyzed the influence of landmarks in navigation when compared with path integration. The task was also a triangle completion one. Four repetitions of the task with different triangles were conducted. In the first and last repetition, no landmarks were available. In the intermediate ones, a red post was placed near the starting position, but slightly displaced, with viewing angles from the final point ranging from 0 to 28 degrees. The participants did not notice the displacement, and followed the direction of the landmark. In a second experience, they were told that the landmark was unreliable, and in this case, they used path integration instead. It seems that, even if both systems provide information for homing tasks, landmarks are the factor that usually dominates navigation.

In a more recent study, Foo et al. (2005) continued the comparison of landmarks with path integration. In this case, they analyzed if the participant was able to find shortcuts in different environments during a triangle completion task. The subjects were trained on the

two legs of the triangle and the angle between them in the context of a specific environment. After training, they had to find a shortcut between the endpoints of the two legs of a triangle. The first virtual environment that was used was a virtual desert world, which contained minimal optical aids. Optic flow and body senses information provided information for path integration, but no other sources of information were present. It was compared with a forest environment that contained multicoloured posts, to provide the user with a landmark strategy that could be used for navigation. Participants could not find successful shortcuts in the desert environment, but they could find them in the forest with multicoloured posts. These results seem to support that subjects rely on the potential landmarks when they are available and use them as a reference to guide navigation.

Apart from the VENLab, other special virtual reality systems have been developed to study spatial cognition. One of them is the HIVE - Huge Immersive Virtual Environment (Waller et al., 2007). This system consists of a large tracking area that lets users move through virtual worlds as they would in the real world, thus allowing the analysis of mental processes that require extensive movements through an environment. The system makes it possible to include in the experiments body-based sources of sensory information (such as vestibular and proprioceptive data), as happened also with the VENLab. Technically, the HIVE is based on an eight-camera optical tracking system that monitors user's position data, which are sent wirelessly to a rendering computer worn by the user. The environment is shown to the participant using a head-mounted display. The system is completed with an orientation tracking device. The HIVE has been used, for example, to analyze the influence of a user's physical environment on distance underestimation in immersive virtual environments. Previous research has found that egocentric distances are underestimated in immersive virtual environments (i.e., Lampton et al., 1995; Witmer & Kline, 1998). Using systems like the HIVE, it is possible to analyze if this underestimation occurs also when navigation is controlled by real physical walking. Richardson & Waller (2007) conducted an experiment which showed that the execution of an interaction task in the immersive virtual environment significantly corrected the underestimation that has been observed in previous studies.

All the studies described in this section have in common two main factors:

- The user can navigate using real walking in a wide area. Tracking systems designed to monitor the user position in large areas are used.
- The appearance and responses (such as optical flow) of the virtual environment can be controlled and changed between the different experimental conditions.

These are issues that should be taken into account when designing a virtual environment for the study of human navigation.

2.2 Virtual versions of classical neuroscience tests to study navigation and spatial memory

Virtual reality has also been used by other researchers to create virtual versions of classical neuroscience tests to study navigation.

In previous non-human research, the gold standard for analyzing place learning ability in rodents is the Morris water task (Morris, 1981). In this task, the rat has to swim to a fixed hidden platform (that cannot be seen, heard or smelt) in a circular pool, making use of distal spatial cues outside the pool. The apparatus used when this task was first applied was a circular pool with dimensions of 1.30 m diameter by 0.60 m high (Morris, 1981). The platform

used in the experiment was put at a specific location in the pool, either visible or invisible (under water). Research has found that the ability to learn to navigate in this task is highly influenced by the integrity and plasticity in the hippocampus (Sutherland et al., 1982).

In order to apply the Morris water task in human research about navigation and spatial learning, practical difficulties appear. One requisite would be that humans and non-human animals should be tested in comparable spatial domains. A big pool would be required, and the manipulation of the platforms and monitoring of the experiment in this real pool would be more difficult than in the small circular container used in the experiments with rats. Furthermore, participants would probably find the task uncomfortable.

However, with virtual reality, virtual versions of the Morris water task can be prepared and applied in experiments about the analysis of place learning and spatial memory in humans. The advantages that virtual reality can provide are the following:

- A virtual pool environment with adequate dimensions for human participants can be generated and applied in the experiments.
- Subjects can navigate using virtual reality hardware for navigation. There is no necessity to physically swim.
- As the navigation occurs in a controlled computer system, it is possible to program it to easily control experimental variables such as the initial position of the participant, the position of the platforms inside the pool and the position of any visual cues in the environment.
- Furthermore, as the instantaneous position of the subject at each moment is known by the system, it is possible to store the exact trajectories that the participant has followed until arriving to the platform, allowing posterior analyses about different aspects such as the required time to find the platform or the length of the followed trajectory.

Astur et al. (1998) developed a computerized version of the test to analyze if the observed results in experiments with rats would generalize into the human domain. In their experiment, the virtual environment consisted of a circular pool in a room where several distal cues were present. No local cues were used. Participants had to swim in the pool navigating with a joystick. They had to find a platform hidden under the surface of the water from different initial locations. The fact of starting from different locations requires that a cognitive map is formed using the distal cues on the surrounding walls. Performance can be established using objective values that can be calculated, such as the path length or the required time to reach the platform. Different studies with a virtual version of the Morris water task have been developed and have shown the feasibility of applying it in human research (Astur et al., 1998; Jacobs et al., 1997; Jacobs et al., 1998; Driscoll et al., 2003; Duncko et al., 2007). These studies have shown that it is possible to apply a computerized Morris water task in human research. Each of them has focused on a different aspect of the experience. Differences in the performance of the Morris water task have been found associated to different factors such as sex, age or stress.

Posterior studies have combined the virtual Morris water maze with a virtual analogue of another task that has been used classically to analyze spatial memory in animals: an eight-arm radial maze. Radial arm mazes are composed of a central area with a number of identical arms radiating outwards (Olton & Samuelson, 1974). A schema of the eight arm radial maze has been represented in Figure 2.

In the eight-arm radial maze, four of the arms have food at the end, but the other four arms do not have anything. In the first experimental trial, the rat should be able to find the food that is placed in four of the arms. Afterwards, the animal is removed from the maze. In the
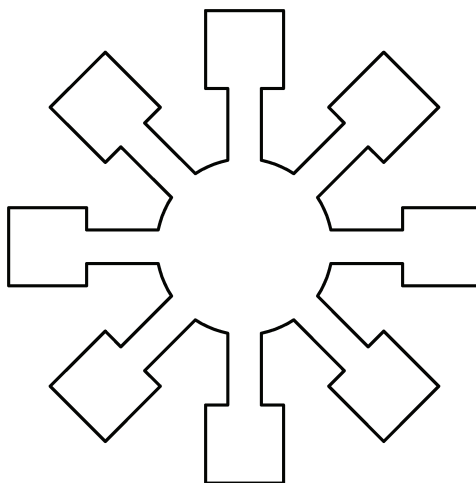
Fig. 2. Distribution of the eight arm radial maze

following experimental trials, the location of the food is maintained. With training, the rodents learn to find the food without entering in the empty arms.

Astur et al. (2004) combined the virtual Morris water maze with an eight-arm radial maze. The virtual eight-arm radial maze consisted of a virtual room that had eight runways extending out of a round middle area. Participants knew that in four of the runways there was an award at the end, and that in the other four runways there was not. They had to retrieve all the awards as soon as possible. Results of the study showed that men performed significantly better than women when trying to find the hidden platform in the virtual Morris water task. However, there are no sex differences in working memory errors, reference memory errors or distance to find the rewards in the virtual radial maze. These results seemed to indicate that the virtual Morris water task and the virtual eight-arm radial maze assess spatial memory in different ways.

Other studies with the virtual Morris water task and the radial mazes have monitored brain activation associated with these tests, specially analyzing the activity in the hippocampus.

Cornwell et al. (2008) recorded neuromagnetic activity using magnetoencephalography (MEG), which is a technique that records magnetic fields produced by electrical activity in the brain and that can be used for mapping brain activity. Participants had to navigate to the hidden platform in a virtual Morris water task. The objective was to determine if hippocampal / parahippocampal theta activity was related to behavioural performance on the virtual Morris task. Source analysis of the MEG data captured during the study showed an increase in the power in the theta band of the spectrum (4-8 Hz) in hippocampus and parahippocampal structures during goal-directed navigation. It was also found a linear relationship between these theta responses and navigation performance on the virtual Morris task.

Astur et al. (2005) conducted an experiment with a radial arm maze to assess the function of the hippocampus and to see if the results from non-human research could be extrapolated to humans. Participants of the study had to perform a virtual radial arm task during functional magnetic resonance imaging (fMRI). An image of an fMRI machine can be visualized in Figure 3.

Fig. 3. 4T fMRI, part of the Brain Imaging Center, in: Helen Wills Neuroscience Institute at the University of California, Berkeley

fMRI is used for the study of metabolic and vascular changes that accompany changes in neural activity. The technique is based on the Blood Oxygen Level Dependent method (BOLD), which measures the ratio of oxygenated to deoxygenated haemoglobin in the blood across regions of the brain. As oxygen is extracted from the blood, increases in deoxyhaemoglobin can lead to an initial decrease in BOLD signal. However, this is followed by an increase, due to overcompensation in blood flow that tips the balance towards oxygenated haemoglobin. It is this that leads to a higher BOLD signal during neural activity. fMRI is not a tool that can be easily combined with virtual reality environments. First of all, a test platform has to be developed to allow the exposition to the virtual environment while capturing the fMRI images without altering in a significant way any of both technologies. Moreover, the user has to be inside the magnetic resonance machine in supine position and with minimum head movement, and devices used to navigate and interact in the virtual environment have to work inside high magnetic fields with minimum electromagnetic interference.

Astur et al. (2005) used an fMRI-adapted joystick to allow participants to navigate in the virtual environment. As happened with other previous studies, significant changes were found in the activity of the hippocampus during the performance of the task. However, a decrease in activity occurred during the spatial memory component of the task. On the other hand, frontal cortex activity was also found, which could indicate activity associated to working memory circuits.

2.3 Animal navigation

Virtual reality has also been used in neuroscience experiments with non-human animals. There have been some studies that have shown that primates, similarly to humans, can also interpret interactive two-dimensional projections as a virtual environment in which they can move (Leighty & Fragaszy, 2003; Nishijo et al., 2003; Towers et al., 2003). Astur et al. (2003), for example, examined if rhesus monkeys could learn to explore virtual mazes. In their experiment, four male macaques were trained to locate a target in a virtual environment. The monkeys controlled the navigation by moving a joystick. They completed successfully

the task, and were able to locate the target. The search pattern that the animals followed within the maze was similar to the navigation pattern observed on more traditional two-dimensional computerized mazes and was in accordance with predictions made from actual patterns in physical space.

But not only primates have been immersed in virtual reality experiences to analyze navigation patterns and spatial memory. Recently, it has been proven that rats are also able to navigate in virtual environments. Hölscher et al. (2005) built a virtual reality set-up and tested it with rats. It was shown that rodents could learn spatial tasks in this virtual reality system. One important point that had to be taken into account in the design of the virtual reality setting was to consider the wide-angle visual system of rats into account. That is why, while immersed in the virtual environment, the rat was surrounded by a toroidal screen of 140 cm diameter and 80 cm height. This screen covers a large part of the rat's visual field (360° azimuth, -20° to +60° of elevation).

Recently, Harvey et al. (2009) used this kind of virtual reality system to study the neural circuits underlying navigation in mice. The purpose was to measure the intracellular dynamics of place cells during the navigation in a virtual environment. However, intracellular recording methods require a mechanical stability which cannot be obtained when the animals can move freely in the real world. In this study, the mouse was allowed to run on top a spherical treadmill while its head was maintained stable using a head plate. Regarding the projection of the virtual environment, similarly to the previous study, the environment was projected on a toroidal screen that surrounded the rodent and that was designed to cover a wide area according to the large field of view of the animal. The movements of the mouse were measured as rotations of the spherical treadmill using an optical computer mouse. The mice were trained to run along a virtual linear track (180 cm long) with local and distal cues in the walls. Small water rewards were given to the animal when it has run between opposite ends of the track. The intracellular dynamics of hippocampal place cells were measured during the navigation with precision, because the mouse's head was stationary. The observed dynamics in the hippocampal place-cells had similar properties to those recorded in real environments.

2.4 Human social interaction

Virtual reality can also be a technology that can help to analyze other aspects of human behaviour. In this subsection, some studies that have been made in the social cognitive neuroscience field will be summarized.

There are several factors that contribute to make virtual reality a useful technology to address questions related to human behaviour in social situations. Participants of virtual reality experiences can feel that they are present in the virtual environment. This means that they have the sense of being in the virtual environment instead of being in their physical location, for example, the experimental room (Held & Durlach, 1992; Schumie et al., 2001). Presence is a multi-dimensional concept, and one of the dimensions that are analyzed when studying this complex experience is social presence, which occurs when part or all of a person's perception fails to accurately acknowledge the role of the technology that makes it appear that s/he is communicating with other people or entities. Virtual characters convey social information to human participants of virtual reality experiences. Furthermore, they are perceived by the participants as social agents, who exert social influence on human subjects that participate in the virtual reality experience (Bailenson et al., 2003).

Consequently, virtual reality has started to be applied in social psychological research (de Kort et al., 2003). In the following paragraphs, different studies that have analyzed several aspects of human interaction using virtual reality will be described.

Bailenson et al. (2001) analyzed the equilibrium theory specification (Argyle & Dean, 1965), which specified an inverse relationship between mutual gaze and interpersonal distance. In order to analyze this theory, participants were exposed to a virtual environment in which a male virtual character stood. The users were told to remember certain features about the agent's shirt. The participants' positions were tracked by the system, so the distance between participants and the virtual agent were continuously monitored. The results showed that the space between the participant and the virtual character was higher than the distance between the participants and objects with similar size and shape, but without human appearance. On the other hand, the interpersonal distance was higher in the case of women interacting with agents who did engage them in eye contact than with agents who did not. This effect was not observed in men. Results seem to indicate that factors such as non-verbal expressions of intimacy are in the origin of changes in the personal space.

Schilbach et al. (2006) studied the differences between being personally involved in a social interaction or being just a passive observer of a social interaction between other people, using virtual characters to generate the social situations. The virtual characters that were used in the study would gaze directly to the human observer, or look away towards a third person situated at an angle of approximately 30º (and not visible by the human participant). The virtual characters would show changing facial expressions similar to the ones that they would have in real-life social interaction situations or they would show arbitrary and socially irrelevant movements. fMRI was used to monitor brain activity while the participants of the study observed the virtual characters. The sequences were projected onto a screen inside the fMRI scanner. After each repetition of the task, the participant had to answer two questions about how s/he has interpreted the behaviour of the virtual character. In order to allow this interaction inside an fMRI scanner, compatible keypads were used. Eye movements during conditions were also monitored using an infrared video-based eye-tracking system. The results showed that higher neural activity was found in the anterior medial cortex when the virtual character was looking at the participant. Furthermore, if facial expressions were perceived as socially relevant, increased neural activity was observed in the ventral medial prefrontal cortex. Finally, the perception of arbitrary facial movements activated the middle temporal gyrus. Globally, the results showed that different regions of the medial prefrontal cortex contributed differentially to social cognition.

The interaction with a virtual character in an extreme social situation such as the conflict created within Milgram's paradigm (Milgram, 1963) has also been studied. This paradigm creates a social dilemma in which participants try to follow the experimenter's commands to administer pain to another person, but at the same time they feel that they have to avoid causing any harm to that person. This paradigm has been partially replicated within an immersive virtual environment (Slater et al., 2006). The participants of the virtual reality experience showed discomfort and increased arousal over the course of the conflict, and some of them stopped administering pain to the avatar, or expressed that they did not want to continue with the experience.

3. Neuroscience for virtual reality

In the previous section, a review of studies in which virtual reality has been applied as a tool for neuroscience has been presented. However, as has already been stated, neuroscience

tools can also be used in virtual reality studies and can provide useful information for researchers in this field.

Some of the studies in which neuroscience has been a tool for virtual reality research are going to be described. They have been grouped in two different fields of application:

1. Presence studies. Neuroscience research can provide useful information to better understand the concept of presence in virtual environments. Different techniques and their combinations have been proposed and used to measure presence in virtual environments (Insko, 2003). These techniques have been classified in two main groups: subjective tools and objective tools. Subjective techniques have been mainly based on the application of psychological measurement instruments like rating scales and subjective reports. On the other hand, objective techniques include behavioural measures and physiological measures. These measures are usually obtained during the virtual reality experience rather than following it, so they can be used for real-time monitoring during the exposure. However, although they are called objective, they do not generate a direct measure of presence. Instead, presence is assumed to be related in some way with the degree of change in parameters that can be obtained from physiological measures or from behavioural observation. It has been only in recent years that it has been studied applying neuroscience tools. Different neurological measures have been applied to analyze brain activity during the exposure to virtual environments in order to look for brain correlates of the presence experience. Three main neurological measures have been applied:

   a. Electroencephalogram (EEG).
   b. Functional magnetic resonance imaging (fMRI).
   c. Transcranial Doppler (TCD).

   In the following subsections, the advances in the presence research field that have been obtained in recent years using these three different techniques will be described.

2. Virtual representation of the body. Other works have applied neuroscience tools to analyze the interpretation of participants of virtual reality experiences about the virtual representation of their own body. For virtual reality researchers, it is necessary to know the interpretation that the participants of the experience attribute to the virtual representation of their bodies. The studies in this area will also be summarized in the following points.

3.1 Presence research: Electroencephalogram

Electroencephalogram (EEG) reflects the brain's electrical activity, and in particular postsynaptic potentials in the cerebral cortex. Scalp-recorded EEG signals are thought to be generated by the addition of excitatory and inhibitory post-synaptic potentials in the cortical pyramidal neurons (Speckman et al., 1993). EEG signals always represent the potential difference between two electrodes, an active electrode and the reference electrode. This technique has a high temporal resolution, which makes it possible to analyze both fluctuations of EEG dependant of task demand, and differentiate between functional inhibitory and excitatory tasks.

EEG was proposed as a possible tool for obtaining objective indicators of presence, to detect brain states and transitions in the user, who can feel present in the virtual world and then change to feel present in the real world (Schlögl et al., 2002).

Baumgartner et al. (2006) were the first to use EEG to analyze neural correlates of spatial presence in arousing virtual environments without interaction. The virtual environment

used was a virtual roller coaster scenario. Twelve children and eleven adolescents participated in the study. There was a control session, with a horizontal roundabout track, and several realistic rides (with ups, downs and loops). EEG and skin conductance were captured during the experience. It was found in both groups that spatial presence was higher in the realistic rides (when compared with the control condition). Furthermore, this was accompanied by increased electrodermal reactions and activations in parietal brain areas known to be involved in spatial navigation. Parietal processing centres in turn stimulated the insula as the core region for generating body sensations and the posterior cingulated which is strongly involved in emotion processing. On the other hand, children showed higher spatial presence, but less activity in some prefrontal areas than adolescents. These prefrontal areas are involved in the control of executive functions. The higher increase in spatial presence observed in children can have its origin on the fact that their frontal cortex function is not fully developed.

Recently, preliminary results from a study to analyze the parietal activity in interactive virtual reality were presented (Kober, 2010). The goal of the study was to analyze if the parietal activity that was found in the study from Baumgartner et al. (2006) would also appear during a free navigation in a virtual environment. The environment was a virtual maze in which the participant performed a wayfinding task while EEG activity was monitored. Results showed that parietal activation also occurred in this interactive virtual reality.

3.2 Presence research: functional magnetic resonance imaging

In the first fMRI study related to virtual reality and presence (Hoffman et al, 2003), subjects reported experiencing an illusion of presence in virtual reality via a magnet-friendly image delivery system despite the constraint of lying down with their head immobilized in an enclosed environment. fMRI results were not reported in the study.

Recent works (Baumgartner et al., 2008; Jäncke et al., 2009) have complemented the previously described study that used the roller coaster scenario as stimulus and EEG to monitor brain activity. These recent works have analyzed fMRI data captured during the exposure to the same virtual environment. Each ride lasted 102 s in total, whereas the different phases where divided into the following time scheme: anticipation phase 30 s, dynamic phase 60 s and end phase 12 s. In total, eight different roller coaster rides were presented, four High Presence and four Low Presence roller coaster rides. Results from the fMRI analysis show that the presence experience evoked by the virtual roller coaster scenario is associated with an increase in activation in a distributed network, which comprises extrastriate areas, the dorsal visual stream, the superior parietal cortex (SPL) and inferior parietal cortex (IPL), parts of the ventral visual stream, the premotor cortex (PMC), and the brain structures located in the basal and mesiotemporal parts of the brain. The network is modulated by the dorso lateral prefrontal cortex (DLPFC). The DLPFC activation strongly correlates with the subjective presence experience (the right DLPFC controlled the sense of presence by down-regulating the activation in the egocentric dorsal visual processing stream, the left DLPFC up-regulated widespread areas of the medial prefrontal cortex known to be involved in self-reflective and stimulus-independent thoughts). In contrast, there was no evidence of these two strategies in children. This difference is most likely attributable to the prefrontal cortex that is not fully matured in children.

3.3 Presence research: Transcranial Doppler

Transcranial Doppler monitoring (TCD) has also been applied recently to analyze cognitive states related with presence during the exposure to virtual environments in different immersion and navigation conditions. TCD is a secure and non-invasive ultrasound diagnosis technique with high temporal resolution which is used to analyze hemodynamic variations in the brain. It monitors blood flow velocity in the main vessels of the brain: the left and right Middle Cerebral Arteries (MCA-L and MCA-R), the left and right Anterior Cerebral Arteries (ACA-L and ACA-R) and the left and right Posterior Cerebral Arteries (PCA-L and PCA-R). These velocity variations constitute a reliable source of information about brain activity. When the neurovascular coupling is adequate (Iadecola, 1993), the velocity variations that are detected by TCD reflect changes in regional cerebral blood flow due to brain activation in the brain areas supplied by the monitored vessel (Daffertshofer, 2001). Consequently, the spatial resolution of the technique is delimited by the size of the cortical areas supplied by the vessels selected for a particular study. In order to apply the measurement, two probes (transducers) are required, one for each cerebral hemisphere. In functional studies, each probe is placed in its correct location by attaching it to a headpiece that the user has to wear during the whole experiment.

Alcañiz et al. (2009) used the TCD technique to compare two different navigation conditions (user-controlled vs. system-controlled navigation) potentially associated with different levels of presence in the participants of the study. The study was carried out in a CAVE-like environment with four sides (three walls and the floor), using a wireless joystick and an optical tracking system to navigate in the environment. The virtual environment that was used in the study was a maze composed of several rooms and corridors. The virtual maze was designed specifically for this task. An image of one of the rooms of the virtual environment can be visualized in Figure 4.

Results from the study showed that it was possible to use TCD to monitor brain activity during virtual reality studies. The percentage variations between mean blood flow velocity in the user-controlled navigation and its preceding baseline (repose period), and between the mean blood flow velocity in the system-controlled navigation and its preceding baseline, were positive in all the arteries under study (MCA-L, MCA-R, ACA-L and ACA-R). Significant differences between the percentage variations in the two navigation conditions were observed in the case of the left arteries: MCA-L and ACA-L. Motor tasks to control the joystick with the right hand might be the origin of the observed variations in MCA-L blood flow velocity. However, the variations in ACA-L are not directly related to this issue, and can only be explained by other factors related to the virtual reality experience, such as decision making and emotional aspects. In fact, it is expected that the user may be more emotionally involved in the free navigation condition. Furthermore, during this experimental condition, more decisions have to be made, specially associated to navigation factors. All these issues are related with the level of presence that the user is experiencing during exposure to the different navigation conditions. Presence questionnaires confirmed that the level of presence was significantly higher during the free navigation condition.

Rey et al. (2010) compared the same navigation conditions (user-controlled vs. system-controlled), but in two different immersion configurations (corresponding to two different virtual reality settings: the CAVE-like system and a single projection screen). In this case, only MCA-L and MCA-R were considered. The navigation factor had a significant influence on the observed blood flow velocity variations in both monitored vessels. Higher percentage

Fig. 4. Image of one of the rooms of the virtual maze that was used in the studies that analyzed presence in virtual environments using TCD

variations were observed in the free navigation condition than in the automatic navigation condition. As in the previous study, the observed differences in MCA-L can have their origin in the motor tasks differences between navigation conditions. On the other hand, a possible explanation of the differences in MCA-R percentage variations between navigation conditions could be found in the higher degree of involvement of the user in the creation of a motor plan in the free navigation condition. Results from questionnaires also found higher values of presence during the free navigation condition.

3.4 2 Virtual representation of the body

Other works have applied neuroscience tools to analyze the interpretation of participants of virtual reality experiences about the virtual representation of their own body. Virtual reality can be used to replace a person's real body by a virtual representation. For example, a virtual limb can be made to feel part of the participant's body if appropriate multisensory information is provided. Slater et al. (2008) created this illusion on participants of a virtual reality experience using a tactile stimulation on a person's hidden real right hand while, simultaneously, a 3D virtual arm was projected out of their shoulder. Questionnaire responses and behavioural analyses showed that participants were experiencing the virtual arm as part of themselves. These results open up the possibility that the whole virtual body could be interpreted by participants as part of themselves in the future.

4. Conclusion

This chapter has summarized the contributions and implications that advances on the virtual reality field may have for behavioural neuroscience studies. Virtual reality can provide a virtual laboratory where experiments can be conducted in a controlled way and with the desired conditions. Applications in neuroscience studies related to spatial navigation and social interaction have been described. Based on the results of these studies,

it can be foreseen that virtual reality may be the basis to develop further studies about human behaviour in the following years.

On the other hand, neuroscience tools have provided the virtual reality research field with new techniques that may contribute to the understanding of human factors and human responses during the virtual reality experience. Although neurological correlates of virtual reality experiences have still to be further analyzed, advances in this area may help virtual reality researchers to design more compelling and effective versions of the virtual environments that they develop.

The two-way cooperation between virtual reality and neuroscience can be the basis of many advances in these research areas in the following years. Both fields of research can take advantage of the results from the studies that combine the use of virtual environments with neuroscience techniques that study aspects of human behaviour inside these environments.

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