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Breaks in Presence in Virtual Environments: An Analysis of Blood Flow Velocity Responses

Abstract

One of the techniques used to monitor variations in presence during a virtual reality experience is the analysis of breaks in presence (BIPs). Previous studies have monitored peripheral physiological responses during BIPs in order to find a characteristic physiological response. In this work, blood flow velocity (BFV) in middle cerebral arteries (MCAs) has been monitored using transcranial Doppler ultrasound during the exposure to a virtual environment. Two BIPs of different intensity were forced during the virtual reality experience. Variations in BFV during each BIP and during the recovery periods that followed them have been analyzed. A decreasing trend was observed in BFV signal during the most intense BIP in most subjects. However, during the less intense BIP an oscillating behavior was observed. Significant differences have been found between the maximum percentage variations observed in each BIP. During the recovery periods, an increasing trend was observed. The mean response times (time elapsed since the beginning of the period until the maximum percentage variation in the period occured) ranged between 10.116 s and 12.774 s during the BIPs, and between 11.025 s and 13.345 during the recovery periods, depending on the vessel and on the kind of BIP.

1 Introduction

Presence is one of the concepts most widely analyzed in the field of virtual reality (VR) and different definitions of it have been proposed. One approach considers it as the subjective experience of being in one place, even when you are physically located in another (Baños et al., 2005; Sadowski & Stanney, 2002; Sheridan, 1992; Slater & Wilbur, 1997; Witmer & Singer, 1998). Focused on virtual environments (VE), it can be described as the sense of being in a VE instead of being in the room where the VR experience is taking place.

However, this is not the only approach to this complex concept, and other definitions have been proposed. One of them relates presence to functionality. Being there in an environment is based on the ability to do things there (Zahorik & Jenison, 1998). This perspective has generated body-centered definitions which look at several components to determine presence, such as the plausibility of the VE and the sensorimotor contingencies (Slater, Steed, McCarthy, & Maringelli, 1998). Recently, a process model of presence has been proposed (Wirth et al., 2007) which evaluates the experience of presence in

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relation with concepts of psychology and communication, including attention or involvement. The model distinguishes two steps that are necessary to achieve presence, and that may be influenced both by media factors and user characteristics: the construction of a spatial situation model (users evaluate if the stimuli are a space and which are the characteristics of this space) and the perception of the virtual environment as the primary egocentric reference frame (users actually evaluate if they are feeling located in the virtual space).

Different techniques and their combinations have been proposed and used to measure presence in VE (Insko, 2003; Friedman et al., 2006). However, no measure of presence has been universally accepted.

1.1 Subjective Measures

One of the methods most commonly applied to measure presence has been the use of subjective measures, specifically, questionnaires. Different questionnaires have been developed to analyze presence and its components as a result of the exposure to a VE (Usoh, Catena, Arman, & Slater, 2000; Witmer & Singer, 1998; Schubert, Friedmann, & Regenbrecht, 1999; Kim & Biocca, 1997; Lessiter, Freeman, Keogh, & Davidoff, 2001; Lombard et al., 2000; Baños et al., 2000). Questionnaires have also been proposed to predict a person's tendency to experience the cognitive state of presence (Thornson, Goldiez, & Le, 2009). However, the use of questionnaires has received some criticism. Freeman, Avons, Pearson, & IJsselsteijn (1999) showed their inherent instability. Furthermore, Slater (2004) discussed the possibility that the concept of presence was brought to mind by the fact of asking questions about it.

1.2 Objective Measures

In order to avoid the problems inherent to subjective measurements, objective techniques have been proposed. Most of these techniques study the extent to which users react as they would in a similar situation in the real world.

One of the approaches is based on behavioral measures: postural responses (Freeman, Avons, Meddis, Pearson, & IJsselsteijn, 2000), conflicts between real and virtual cues (Slater, Usoh, & Chrysanthou, 1995), reflex responses (Nichols, Haldane, & Wilson, 2000) and facial analysis (Huang & Alessi, 1999). These measures are closely related to the contents of the VE and are usually not generalizable for any kind of VE.

The other approach is based on the use of physiological measurements such as cardiovascular parameters (Dillon, Keogh, Freeman, & Davidoff, 2000), skin conductance changes (Meehan, Insko, Whitton, & Brooks, 2002), ocular movements (Laarni, Ravaja, & Saari, 2003), and facial electromyography (Ravaja, 2002). If the user is present in the VE, the physiological responses observed during the exposure will be similar to those observed during a similar situation in the real world. This analysis has usually been related to stressful situations (Meehan et al., 2002; Slater et al., 2006). However, recent works have also applied it to non-stressful environments (Antley & Slater, 2009).

Other possible indicators of presence that have been proposed are neuroscientific measures of brain activity (Sánchez-Vives & Slater, 2005). Use of an electroencephalogram (EEG) was proposed by Schlögl, Slater, and Pfurtscheller (2002) and later used to analyze neural correlates of spatial presence in an arousing VE without interaction (Baumgartner, Valko, Esslen, & Jäncke, 2006). Activations were found in parietal brain areas known to be involved in spatial navigation. Posterior studies have analyzed the use of functional magnetic resonance imaging (fMRI). Hoffman, Richards, Coda, Richards, and Sharar (2003) verified that subjects felt subjectively present when they were exposed to a VE during an fMRI scan. In a posterior study using fMRI, Baumgartner et al. (2008) found that presence was associated with an increase in activation in a distributed network in the brain which included the dorsal and ventral visual stream, the parietal cortex, the premotor cortex, mesial temporal areas, the brainstem, and the thalamus. This network was modulated by the dorsolateral prefrontal cortex (DLPFC), which was strongly correlated with the subjective presence experience. The left DLPFC up-regulated areas of the medial prefrontal cortex involved in self-reflective and stimulus-independent thoughts and the right DLPFC down-regulated the activation in the dorsal visual processing stream (Jäncke, Cheetham, & Baumgartner, 2009).

More recently, transcranial Doppler sonography (TCD) has also been proposed as an alternative technique to evaluate presence (Alcañiz, Rey, Tembl, & Parkhutik, 2009; Rey, Alcañiz, Tembl, & Parkhutik, 2010). Increments in blood flow velocity (BFV) measured with this technique are associated with brain activity in the cortical areas supplied by the arteries under study. It has been widely applied to the study of brain activation during the performance of cognitive tasks (Duschek & Schandry, 2003; Kelley et al., 1992; Knecht et al., 2000; Matteis et al., 2006; Stroobant & Vingerhoets, 2000; Vingerhoets & Stroobant, 1999; Vingerhoets, Berckmoes, & Stroobant, 2003). The maximum increment in BFV has been found to be 4 s (Knecht et al., 1996) to 20 s (Schnittger, Johannes, Arnavaz, & Münte, 1997) after the initiation of a cognitive task, with an average peak after 6–9 s (Harders, Laborde, Droste, & Rastogi, 1989; Orlandi & Murri, 1996; Rihs et al., 1995).

BFV differences have been found in previous studies about presence (Alcañiz et al., 2009; Rey et al., 2010) associated with different immersive conditions that generated different presence levels measured by questionnaires. These works have proven that TCD is a tool that is worthy of use to analyze brain activity during VR experiences, especially due to its noninvasiveness and high spatial resolution.

1.3 BIPs

The concept of BIP has been proposed to contribute to the analysis of presence during the VR experience. The BIPs approach is based on the idea of analyzing presence during the VR experience itself, instead of only using a postexperience questionnaire.

The use of BIPs to analyze presence was first proposed by Slater and Steed (2000). A BIP occurs when the participant stops responding to the virtual stream and instead responds to the real sensory stream (Slater, Brogni, & Steed, 2003). At different times during a VR experience, the participant would switch between interpreting the sensory inputs as coming from the VE or as coming from the real world. Several studies have tried to evaluate global presence during exposure to a VE depending on the number of reported BIPs during the experience, observing that more BIPs were associated with a reduced global presence (Slater & Steed, 2000; Brogni, Slater, & Steed, 2003).

Other studies have discussed that finding a common pattern of physiological responses to a BIP would help to automatically identify when these events occur without requiring that the user report them (Slater, 2002; Slater et al., 2003). In later studies (Garau et al., 2008; Slater et al., 2006), these aspects were analyzed with forced BIPs during the experience: the projections were forced to go white, generating identifiable anomalies in the audiovisual experience. Garau et al. (2008) focused on a qualitative analysis of interviews from this experiment. They found that the anomalies were subjectively experienced by subjects as breaks in presence. The interviews also revealed that BIPs experienced by subjects had different causes (not only the whiteouts, but also environmental factors and the interaction with virtual characters). These different types of BIPs could range in intensity, resulting in varying recovery times as indicated by subjects in these interviews. In general, participants experienced a longer recovery after whiteouts than after character-related BIPs. Slater et al. (2006) made an analysis of physiological responses to BIPs captured during the same experiment. Physiological measures including electrocardiogram (ECG) and galvanic skin response (GSR) were recorded during the whole experiment. The GSR waveform was extracted for ±10 s around each BIP point, and averaged over all BIPs over all participants to find a characteristic GSR response to the induced BIPs. Regarding heart rate, a decrease was observed in the forced BIPs.

1.4 Objectives

Previous works with neuroscience techniques have analyzed brain activation associated with the exposure to a VE that generated presence in the subjects (Baumgartner et al., 2006; Baumgartner et al., 2008; Alcañiz et al., 2009; Rey et al., 2010). However, brain activation during BIPs has not been analyzed in any of these previous studies.

In one of our previous works with TCD (Alcañiz et al., 2009), we analyzed the BFV associated with the exposure to a VE in a CAVE-like system. In that study, participants navigated in the virtual environment for 3 min 30 sec, but only BFV data from the first 1 min 20 sec was included in the analysis. The goal of that study was to evaluate the brain activation during a normal exposure to a VE (without any abrupt rupture that could generate a BIP in the participants).

In the present paper, the goal is completely different. Our main interest is to evaluate which are the patterns of BFV that can be observed during the occurrence of a BIP. We analyze BFV data from the same subjects of the previous study (Alcañiz et al., 2009), but corresponding to BIPs that occurred after the period of free navigation that was analyzed there.

The present study intends to contribute to the research line that is evaluating the physiological responses to BIPs with the objective of finding a common pattern, but using a neuroscience tool to evaluate brain activation: TCD. The purpose of the study is twofold. Firstly, one goal is to analyze the BFV signal during a BIP (when a transition from the virtual world to the real world occurs), studying its temporal evolution and its magnitude variation, and evaluating possible hemispheric differences. Secondly, another goal is to analyze the evolution of the BFV signal when the BIP finishes and the normal state of the VE is recovered (when a transition from the real world to the virtual world occurs), also evaluating the possible differences in BFV in each hemisphere.

Furthermore, an additional objective of the work is to analyze whether the intensity of the BIP has any influence on the temporal and magnitude features of the BFV signal during the BIP and during the recovery from the BIP. BIPs of different intensity have been included in the experimental design in order to study this aspect.

2 Methods

2.1 Participants

Thirty-two right-handed volunteers (24 men, 8 women) aged between 17 and 51 years (mean age 29.93 years; *SD* 6.35) participated in the study. All the participants gave their informed consent prior to their inclusion in the study. Handedness was established during the previous interview by a neurologist. Only right-handed subjects were included in the study in order to have a homogeneous group, because qualitative BFV differences in response to cognitive tasks have been observed between right- and left-handed users (Stroobant & Vingerhoets, 2000)

2.2 Apparatus

The TCD unit that was used in the study was the Doppler-Box (DWL Compumedics Germany GmbH, Singer, Germany). It was connected to a PC in which DWL Doppler software was installed to store the BFV signals on the PC hard disk for later analyses. Two 2-MHz probes were used to monitor both brain hemispheres simultaneously. The sampling frequency of this device is 100 Hz. Mean BFV (in cm/s) in the registered vessels was recalculated by the software every 1.3 s.

2.3 Virtual Reality Setting

The experiment was conducted in a CAVE-like environment (the Reality Center). The selection of this kind of environment was made to maximize participants' presence, because previous studies (Sutcliffe, Gault, & Shin, 2005) have shown that CAVE-like systems have better usability and provide a better sense of presence to their users. The system had four sides: three walls and the floor, and the dimensions were 2.5 × 2.5 × 2.35 m. Four Barco 909 (Barco, Kortrijk, Belgium) projectors were used to deliver the images, which were generated in an SGI Prism (SGI, Sunnyvale, CA). Liquid crystal shutter glasses, CrystalEyes3 (Real D, StereoGraphics, Beverly Hills, CA), were required for the visualization. A wireless joystick (Flystick, Advance Realtime Tracking GmbH, Weilheim, Germany) was used to navigate combined with a tracking system, ARTtrack1 (Advance Realtime Tracking GmbH, Weilheim, Germany).

2.4 Software

A virtual maze with several rooms and corridors was used as the stimulus. The contents of this VE were carefully reviewed in order to avoid inconsistencies or problems that could generate spontaneous BIPs (not controlled by the experimental design) in the users. The environment was programmed using Brainstorm eStudio software (Brainstorm Multimedia, Madrid, Spain). The participants could not make any interaction with the VE, apart from navigation.

2.5 Procedure

When users arrived in the experimental room, they read a short description of the experiment. Once in the Reality Center, the probe holder with the two ultrasound probes was adjusted to capture BFV values from left and right middle cerebral arteries (MCA-L and MCA-R) and left and right anterior cerebral arteries (ACA-L and ACA-R). However, only middle cerebral arteries (MCA) were analyzed in the present study because each of them carries 80% of the blood flow within its cerebral hemisphere (Toole, 1999) and our goal was to analyze global interhemispheric differences during the BIPs. Details about the insonation technique can be found in different studies (e.g., Ringelstein, Kahlscheuer, Niggemeyer, & Otis, 1990). The neurosonologist validated the registries for the different vessels. Some measurements were discarded because a clear enough signal could not be obtained, or because the signal was unstable during the procedure due to brusque head movements.

After a training stage, the user navigated freely through the environment for 3 min 30 sec. Following a similar approach to Slater et al. (2006) and Garau et al. (2008), two interruptions or anomalies were forced in the VR experience at two times at approximately evenly spaced intervals during the navigation period. In one of the interruptions, the four projection walls became completely black. In the other interruption, the lateral and floor walls also became completely black, but the frontal wall remained active, so the VE could be visualized in the frontal wall. However, navigation was blocked, so the user could not advance or go backward in the VE for the duration of this interruption. Each of these anomalies lasted 20 s, and after this period, the normal navigation and visualization conditions were restored.

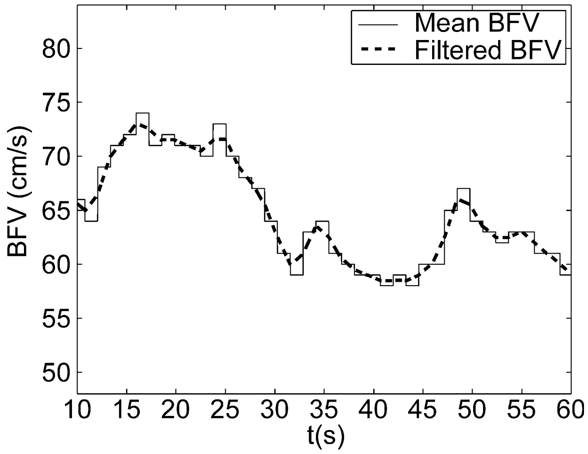

Figure 1. *MCA-L mean BFV of one of the participants: original signal and filtered signal.*

In the remainder of this paper, the term *Total BIP* will be used to refer to the most intense BIP caused by the interruption in which the four projection walls became black, and *Partial BIP* will be used to refer to the less intense BIP caused by the interruption in which only the lateral walls and floor became black and navigation was blocked. *Total Recovery* will be used to refer to the period of 20 s that follows the end of *Total BIP*, and *Partial Recovery* to refer to the period of 20 s that follows the end of *Partial BIP*. In the recovery period, the normal state of the VE has been recovered, so users can visualize the VE normally and navigate again.

2.6 Data Filtering and Normalization

As we are interested in the analysis of the transient behavior of the BFV signal during BIPs and recoveries, the BFV analyses that will be applied are different from those of our previous study about global presence during a period of normal navigation (Alcañiz et al., 2009). Before calculating temporal parameters of the BFV signal, it is necessary to adapt the BFV supplied by the Doppler box for those later analyses. First, the BFV signal is low-pass filtered to smooth it using a moving average FIR filter of 250 coefficients. A sample of the original BFV signal and the filtered signal from one of the subjects can be observed in Figure 1.

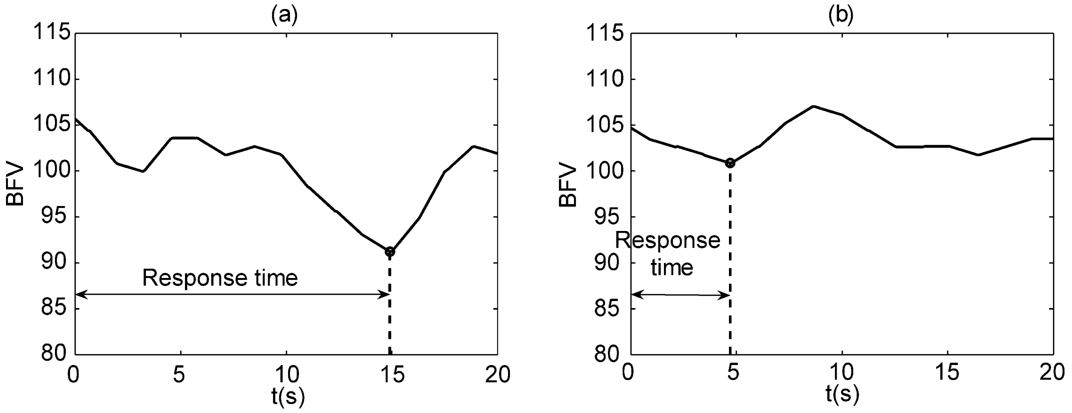

Figure 2. *Filtered and normalized BFV in a sample subject during (a)* Total BIP *and (b)* Partial BIP. *The maximum variation is marked in the graphs with a black dot. In this case, a decreasing trend can be observed for the* Total BIP *and an oscillating trend for the* Partial BIP. *The response time is indicated graphically.*

After filtering, the signal is transformed to normalized units simply by dividing BFV by the mean BFV measured during the whole examination time and multiplying by 100 (Sitzer, Diehl, & Hennerici, 1992), as indicated by the following formula:

$$X[n] = 100 \cdot \frac{x[n]}{\frac{1}{N} \cdot \sum_{n=0}^{N-1} x[n]} \qquad (1)$$

where n is the sample, $X[n]$ is the normalized signal, $x[n]$ is the original BFV signal, and N is the length of the data captured during the whole examination time.

2.7 Response Time and Maximum Percentage Variation Calculation

Two parameters have been obtained from the filtered BFV signal in order to characterize its temporal evolution during the BIPs and during the recovery periods: the maximum BFV percentage variation and the response time.

The maximum BFV percentage variation is calculated as the percentage difference between the peak value of the BFV signal during the period (which can be a maximum or a minimum) and its initial value. The response time is calculated as the time that has elapsed between the beginning of the period and the moment in which the peak value is achieved.

2.8 Statistical Analysis

A statistical analysis has been applied to check if the response time and the maximum BFV percentage variation show significant differences between both BIPs and between both vessels considered in the study (MCA-L and MCA-R). Prior to the analysis, the variables were checked for normality using the Kolmogorov-Smirnov test.

Two-way ANOVAs with repeated measures were applied to analyze the effects on the response time and on the percentage variation (dependent variables) of the within-subjects factors (hemisphere and kind of BIP/recovery).

3 Results

Only those cases in which measurements from both MCA-L and MCA-R are available (17 subjects) have been included in the analysis to allow comparisons between hemispheres.

During the *Total BIP*, it can be observed how the BFV signal from most subjects has a decreasing trend. The maximum variation that is observed in the period when compared with the initial value corresponds to a minimum. However, the instantaneous temporal evolution during the *Partial BIP* has important interindividual differences. Usually, there are oscillations inside the period without a clear decreasing or increasing trend. In Figure 2, the filtered MCA-L BFV signals corresponding

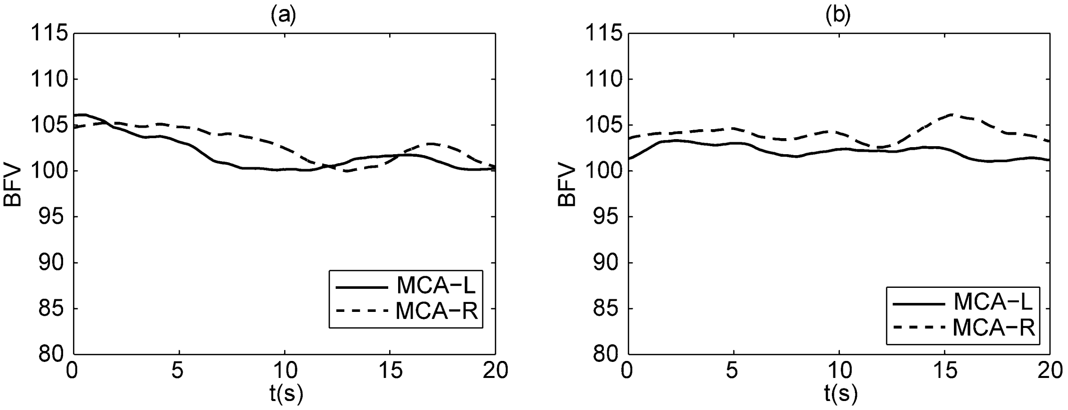

Figure 3. *(a) Grand average of the 17 subjects' MCA-L and MCA-R BFV signals during the* Total BIP. *(b) Grand average of the 17 subjects' MCA-L and MCA-R BFV signals during the* Partial BIP.

to both BIPs (*Total BIP* and *Partial BIP*) of one of the subjects are shown.

As in previous studies (Knecht et al., 1996; Schnittger et al., 1997; Sitzer et al., 1992), the grand average curves for each BIP have been calculated and are shown in Figure 3. These grand average curves show a decreasing trend during the *Total BIP* and oscillations during the *Partial BIP*.

On the other hand, the temporal evolution of BFV during recovery periods also presents important interindividual differences. However, in this case, for most of the subjects, the maximum variation that is observed is positive in the recovery periods from both BIPs. The evolution depends on the subject and can have a continuous growing trend or oscillations. In Figure 4, the filtered MCA-L BFV signals corresponding to both recovery periods (*Total Recovery* and *Partial Recovery*) of one of the subjects are shown.

The grand average curves corresponding to the recovery periods have been calculated and are shown in Figure 5.

3.1 BFV Parameters During BIPs

In Figure 6, mean values of the maximum percentage variations and response times in the different BIPs for both vessels are shown, with their standard error of the mean (*SEM*).

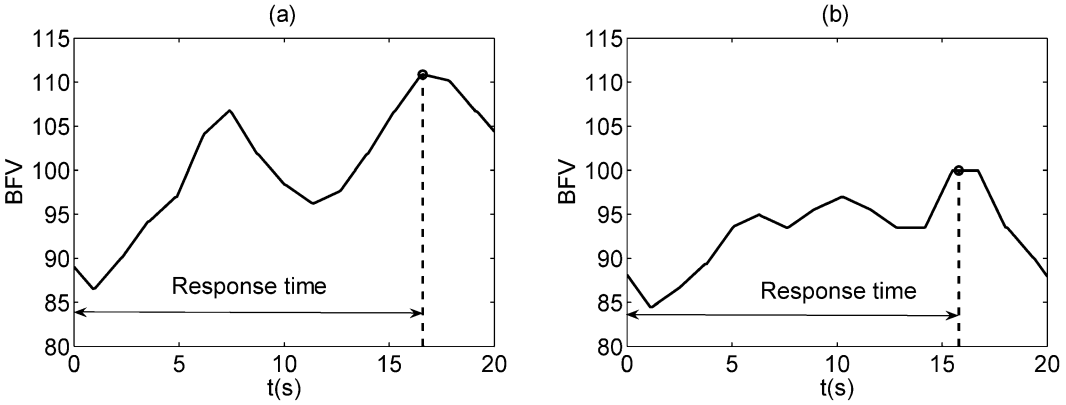

Figure 4. *Filtered and normalized BFV in a sample subject during (a)* Total Recovery *and (b)* Partial Recovery. *The maximum variation is marked in the graphs with a black dot. In this case, a growing trend is observed in both cases. The response time is indicated graphically.*

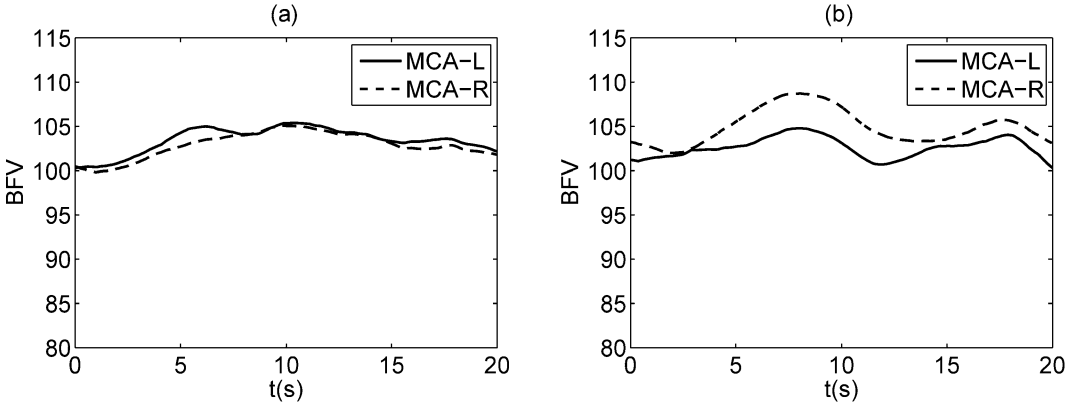

Figure 5. *(a) Grand average of MCA-L and MCA-R BFV signals during the* Total Recovery. *(b) Grand average of MCA-L and MCA-R BFV signals during the* Partial Recovery.

Results from the ANOVA applied to the maximum percentage variation show a significant effect for the type of BIP, $F(1, 16) = 6.986$; $p = .018$. No significant effect was found for the hemisphere factor. Pairwise comparisons using the Bonferroni correction show that there are significant differences between BIPs in MCA-L BFV ($p = .027$), but not in MCA-R BFV.

Results from the ANOVA applied to the response time show no significant effect either for the kind of BIP or for the hemisphere.

3.2 BFV Parameters During Recovery Periods

Figure 7 shows mean values and *SEM* of the maximum BFV percentage variations and response times in the recovery periods for both vessels. No significant effect has been found for any of the analyzed factors (hemisphere and kind of BIP that precedes the recovery).

4 Discussion

The present work has analyzed the blood flow velocity responses of participants in a VR experience during BIPs.

The objective was to contribute to the analysis of physiological responses during BIPs that have been described in previous studies (Slater et al., 2006), but focusing on a neuroscientific measure closely related to the processes that occur in the brain during these rup-

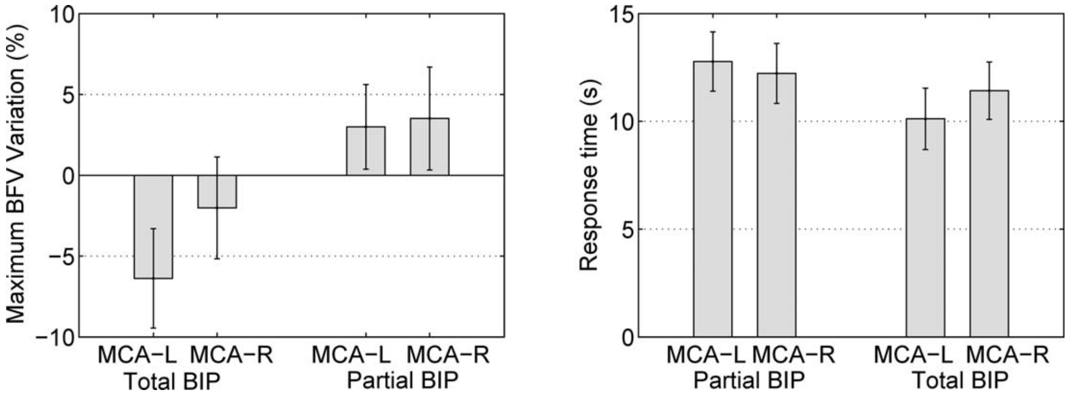

Figure 6. *(a) Mean percentage variation in MCA-L and MCA-R BFV during the* Total BIP *and the* Partial BIP. *(b) Mean response time in MCA-L and MCA-R BFV during the* Total BIP *and the* Partial BIP. *Error bars represent* SEM.

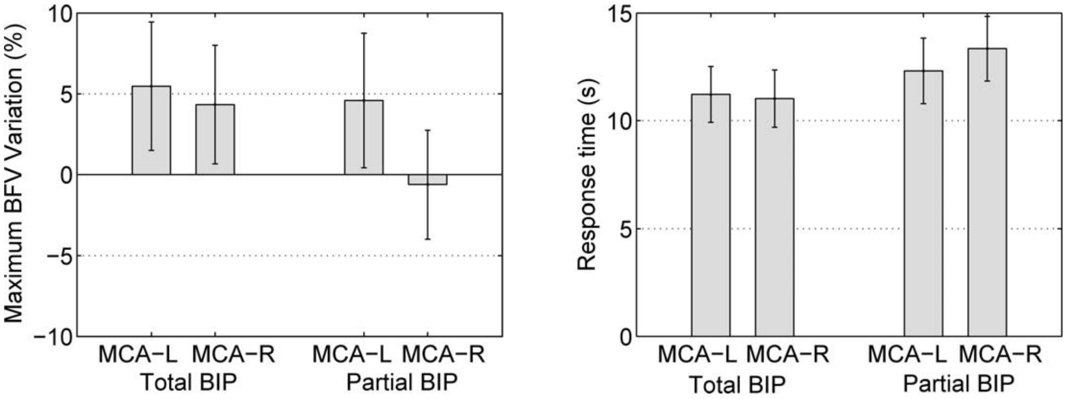

Figure 7. *(a) Mean percentage variation in MCA-L and MCA-R BFV during the* Total Recovery *and the* Partial Recovery. *(b) Mean response time in MCA-L and MCA-R BFV during the* Total Recovery *and the* Partial Recovery. *Error bars represent* SEM.

tures in the VR experience. In order to analyze brain activation, TCD monitoring was used. This technique has been used combined with VR in previous studies (Alcañiz et al., 2009; Rey et al., 2010), which have analyzed BFV during a normal navigation in a VE and have shown that TCD is a tool that can be easily integrated in VR settings to monitor brain activity during the VR experience, its main advantages being its high temporal resolution and its noninvasiveness.

The election of the vessels is of great importance during TCD studies, as they determine the brain area that will be analyzed. In this case, the objective was to analyze global responses of the brain in each hemisphere, so MCAs were selected, because these vessels supply blood to the greater part of the brain. Their perfusion territory includes subcortical areas, large fractions of the frontal and parietal lobes, and the temporal lobes (Angevine & Cotman, 1981).

Posterior cerebral arteries (PCAs) have not been included in this experience. They are the vessels that supply the primary visual cortex as well as the lateral geniculated body and some of the visual association regions in the occipital cortex, so it is assumed that variations in PCAs BFV will occur when users are exposed to variations in visual stimulation (Panczel, Daffertshofer, Ries, Spiegel, & Hennerici, 1999).

One of the first steps of the BFV signal processing was the normalization process. There are several reasons for performing this transformation. First of all, BFV values have important interindividual variations if described using absolute units (Ringelstein et al., 1990). In addition, absolute values are sensitive to the insonation angle α between the ultrasound beam and the course of the insonated artery (Aaslid, Markwalder, & Nornes, 1982). These problems are solved by using normalized signals. When signals are normalized, it is possible to make comparisons between vessels in both hemispheres without any influence from the angles of the two probes (Deppe, Knecht, Henningsen, & Ringelstein, 1997).

4.1 Responses During BIPs

The first general conclusion that has been obtained from this study is about the kind of response that can be expected in MCAs BFV during BIPs.

Mean response times ranged between 10.116 s and 12.774 s depending on the vessel and on the kind of BIP, in accordance with BFV response times observed in previous studies that analyzed other kinds of cognitive activity (Harders et al., 1989; Orlandi & Murri, 1996; Rihs et al., 1995).

As already pointed out by Slater et al. (2006), there are several factors that may be having an influence in the responses observed during a BIP. During the normal navigation in a VE environment, there is a complex interaction between visuospatial interaction tasks, attention tasks, and the creation and execution of a motor plan (Alcañiz et al., 2009). Users are actively participating in the creation of the motor plan, focusing their attention on this task. However, this active role is suddenly interrupted when a BIP occurs, which could justify a decrease in BFV, as can be observed during the *Total BIP*.

When this happens, users become suddenly aware that they are in a laboratory participating in an experiment and not in the VE. The interruption of the visuospatial interaction tasks, attention tasks, and the creation and execution of a motor plan that were happening during navigation can generate a sudden decrease in presence or a BIP, associated with the observed changes in BFV.

Recent studies with TCD (Matthews et al., 2010) discuss that there is a decline in BFV in both hemispheres during sustained attention vigilance tasks. They propose that this decline is related to a decrease in the alertness and vigilance of the participants during the task. Thus, BFV in MCAs is associated, among other factors, with vigilance and alertness. During navigation in a VE, the user is alert to all the events that are occurring in the environment. Users are focused on the VE and ignoring the real world. However, when a BIP occurs, the level of alertness may decrease, which could explain the decrease in BFV that is observed during the BIP. These results are also consistent with the previous study from Baumgartner et al. (2008), in which it was found that, when the user is present and alert, there is a widespread activation in brain areas known to be involved in spatial processing (dorsal visual stream, including superior and inferior parietal lobule and precuneus), object-based visual analysis and recognition (ventral visual stream, including fusiform gyrus, inferior and middle temporal gyrus, and premotor cortex), acoustic processing (auditory cortex), and emotion processing including insula. Consequently, if presence or alertness decrease (which occurs, e.g., during a BIP), the activation of those brain areas should be reduced. Some of these areas are irrigated by MCAs, so the reduced BFV that has been found in the current study could reflect a decrease in the activity of those zones.

Another factor that has to be discussed is that, during the VR experience, users have to make movements with their right arms and hands to control the joystick to navigate (as stated in the methods, subjects were all right-handed). The interruption of hand movements during the BIPs can also contribute to the observed decrement in MCA-L BFV. However, MCA-R BFV is not influenced by the interruption of hand movements, as no movements are made in any case with the left arm (either during the navigation or during the BIP).

The oscillating behavior observed during the *Partial BIP* can have its origin in the kind of BIP (the *Partial BIP* is less traumatic than the *Total BIP*). Although subjects cannot navigate during the BIP, they can visualize in the front wall a projection of the VE, which constitutes a connection with the VR experience in which they were participating before the BIP occurred. Furthermore, as the VE is visible in the front wall of the Reality Center, they keep on trying to advance by pressing the front button of the Flystick. The movements with the right arm and hand to control the joystick do not completely stop. That could justify the significant difference that appears between BIPs in MCA-L BFV. In fact, subjects may become more involved in the task of pressing the button, as long as the expected reaction (a movement in the VE) is not achieved. This greater involvement may justify that an oscillating trend (instead of a clear decrease) is observed during the *Partial BIP* both in MCA-L and MCA-R BFV. The order of occurrence of the BIPs could also be having an influence on the observed behavior during the *Partial BIP*.

4.2 Responses During Recovery Periods

The second general conclusion that has been obtained from this study is that, in general, when the interruption that causes the BIP finishes, an increase in BFV signal is observed (as a result of the return to the normal navigation and visualization conditions during the VR experience). The recovery time after a BIP has only been analyzed previously in a qualitative way using interviews (Garau et al., 2008). In this work, a quantifiable and objective way to analyze the recovery period has been provided based on obtaining the response time and the maximum percentage variation in the BFV signal.

Maximum percentage variations were predominantly positive for all the vessels and conditions. The same aspects that can be having an influence on BFV during BIPs could also be the origin of the changes in BFV that are observed in the recovery from each BIP. When the recovery starts, the visuospatial interaction tasks begin again, and subjects recover their active role in the creation and execution of the motor plan. The BIP has finished, so subjects feel present again in the VE and focus their attention on the events that may occur in this space. There is an increase in brain activation, in accordance with previous fMRI studies about presence (Baumgartner et al., 2008) and TCD studies about attention (Matthews et al., 2010). Furthermore, the hand movements recover their normal pattern during navigation in the VE. All these aspects can justify an increment in BFV during the recovery periods.

Mean response times ranged between 11.025 s and 13.345 s depending on the vessel and recovery period studied. As happened with response times observed during the BIPs, these values are in accordance with the results of previous cognitive studies (Harders et al., 1989; Orlandi & Murri, 1996; Rihs et al., 1995). Although the previous study by Garau et al. (2008) stated that users reported in the interviews to have experienced different recovery times, depending on the kind of BIP, in the case of the current experience, objective parameters obtained analyzing the BFV signal show that there is not a significant difference between both BIPs (neither in the response time nor in the percentage variation). Maybe the users subjectively experience a different recovery time, although the response time measured from BFV is similar in all cases. Or perhaps the differences between kinds of BIP considered in this experience are not enough to generate different response times. Further research will help to clarify the causes.

4.3 Final Comments

Summarizing the main conclusions of this study, BFV responses have been analyzed during BIPs that were forced during the exposure to a VE. Two different kinds of BIPs have been compared, where one of them was more traumatic than the other. It has been observed that the maximum BFV percentage variation that was observed during the most intense BIP was negative in most of the subjects. The behavior was oscillating in the less intense BIP. Response times were similar in both BIPs. On the other hand, during the recovery periods, maximum BFV percentage variations were predominantly positive, and no differences in maximum percentage variations and response times in the different recovery periods have been found. No hemispheric differences have been observed in the BFV responses to the different kinds of BIPs and recoveries.

Several causes have been analyzed as the origin of the variations in BFV observed in the different periods, associated with the changes of presence that are provoked during the experience. Future studies can be conducted to analyze the effects on BFV of other kinds of BIPs, so a deeper understanding can be achieved about the nature of the BFV variations that are observed after different kinds of BIPs and about the factors that could be having an influence on these variations.

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