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Brain Activity and Presence: a Preliminary Study in Different Immersive Conditions Using Transcranial Doppler Monitoring

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Abstract

Transcranial Doppler (TCD) sonography is a brain activity measurement technique that monitors the hemodynamic characteristics of the major cerebral arteries in normal and pathological conditions. As it is not invasive, it can be easily used in combination with virtual environments (VE). In the present study, TCD has been used to analyze brain activity variations in different presence conditions during the exposure to a VE. Forty-two subjects have taken part in the experience grouped in two different visualization conditions: a CAVE-like and a single screen projection configuration. In each session, two different navigation conditions were used: a free navigation (controlled by the subject) and an automatic navigation (controlled by the system). Results show that these immersion and navigation modifications in VE generate generalized changes in brain activity that can be detected using TCD techniques. Variations are greater in the configurations that generate higher levels of presence in subjects. Nevertheless, further research must be conducted in order to analyze the relationship of these changes with presence modifications.

Keywords--- **Presence, Brain Activity, Transcranial Doppler, Virtual Reality, Immersion, Navigation**

1. Introduction

Virtual reality is one of the most challenging applications of computer graphics and is currently being applied in many fields [1]. In order to study the usefulness of these virtual environments (VE) in their applications, different measures can be used, presence being one of them. A commonly accepted definition of this concept indicates that presence is the subjective experience of being in one place, even when you are physically located in another [2-5].

Up to now, different techniques and combinations of them have been used to measure and analyze presence in VEs [6, 7]. These techniques are typically classified into subjective and objective measures.

Using subjective measures is the most common method. Questionnaires are used to obtain indicators of presence. The main advantage of this method is that it is very easy to apply and it gives quick information about the experiences of the user. One disadvantage can be found in the great variability between subjects in the answers to questionnaires. Besides, users can be influenced by many different factors when answering, even in an unconscious way.

Presence questionnaires that have been commonly used as a measure of presence in VEs are the SUS questionnaire [8], the Presence Questionnaire – PQ [9], the Igroup Presence Questionnaire – IPQ [10], Kim and Biocca’s Questionnaire [11], the ITC Sense Of Presence Inventory – ITC-SOPI [12], Lombard and Ditton’s Questionnaire [13] and the Presence and Reality Judgement Questionnaire [14].

Other kinds of subjective measures have also been used. For example, Ijsselstein and de Ridder [15] used a continuous registration of measures during the exposure to the VE; a control was shown in the screen and users could move it in real time to indicate their level of presence. Slater and Steed [16] used a virtual counter that measured the transitions from the VE to the real one. And other qualitative measures, such as thinking aloud, interviews and group discussions have already been proposed.

In order to avoid the inherent problems to subjective measures, objective techniques have also been proposed. A group of objective measures are based on behavioral measures, such as postural responses [17], conflicts between real and virtual cues [18], reflex responses [19] and facial analysis [20]. Other group of measures estimate the quality of actions made in the VE, such as the completion time and the error rate [21], the number or actions required to finish a task [22] and the transfer of abilities to the real world [23]. However, the most commonly used are physiological measures. Skin conductivity and heart rate are related with the anxiety level of users and could constitute an indicator of the presence that the user is feeling in environments that generate this kind of responses. Examples of measures that have been analyzed include cardiovascular measures [24], skin measures [25], ocular measures [26] and facial electromyography [27]. However, although these measurements can be closely related to presence, results from the experiments are frequently unreliable [2] to reflect the subtle construct of presence.

Other possible indicators of presence that have been proposed are measures of neurological activity. It has been stated recently that VR is not only a tool for neuroscience, but that presence is also an object of study [28]. These techniques will share with physiological recordings the advantage of being more objective than questionnaires. Neural correlates of presence appear to be a promising measure because they potentially provide data that is not influenced by the participant’s interpretation. However, the analysis of these measures can be difficult since very little is known about the neural processes that are involved in the complex experience of presence.

The brain activity measures that have been proposed for presence measurement are the electroencephalogram (EEG) and the functional magnetic resonance (fMRI). EEG has been described by Schlögl as a possible tool for obtaining objective indicators of presence, to detect brain states and detect transitions in the user, who can feel present in the virtual world and then change to feel present in the real world [29]. However, the description does not include data about studies that have been made analyzing presence with this technique. Some studies have been made investigating EEG responses to VE experiences, but without relating them to the concept of presence [30-31]

Regarding fMRI, it 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 VE while capturing the fMRI images without altering in a significant way any of both technologies. 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 VE have to work inside high magnetic fields with minimum electromagnetic interference.

In the first paper to propose the use of fMRI to measure presence [32], only a description of the system was included, and no fMRI results related to presence were presented because the authors feared misinterpretation. Other related studies only present preliminary results [33].

In the present study, transcranial Doppler sonography (TCD) is used as an alternative brain activity measurement technique. This is a technique of diagnosis by ultrasound with a high temporal resolution which was first used in 1982 [34]. It controls the hemodynamic characteristics of the major cerebral arteries in normal and pathological conditions. These measures are not invasive, and can monitor the signals in a continuous way through the skull, without making any kind of lesion.

In order to take the measurements, two probes are placed on the head of the subject using a headband or similar object. The most common location to place the probes that register the ultrasound signal is the transtemporal window. This window allows us to register directly the information about the Middle Cerebral Artery (MCA), Anterior Cerebral Artery (ACA) and Posterior Cerebral Artery (PCA). The probe direction, the reference volume depth and the flow direction identify each cerebral artery. A signal is obtained that represents the maximum velocity of the cardiac cycle in the vessel under study.

The most common value that is analyzed in TCD studies is the mean velocity or mean blood flow velocity (BFV), also known as the mean of the maximum velocities. It is described as a time-averaged, area-averaged mean velocity value that results when a line is placed on the horizontal axis of the maximum velocity signal achieving that the area above the line is the same as the area below it [35].

Previous research has shown that regional cerebral blood flow (CBF) increases during mental activities [36]. The neurovascular coupling is the mechanism that adapts CBF to the metabolic demands and the activity of the brain cortex [37]. When the neurovascular coupling is adequate, the velocity variations that are detected by TCD reflect changes in regional CBF due to brain activation [38]. It has been shown in many studies that mean BFV obtained from TCD data changes when users are doing a cognitive activity when compared to baseline periods [39-43].

One of the main disadvantages of TCD is its low spatial resolution, which is defined by the size of the cortical areas under study. Velocity increments in small vessels could not generate a noticeable increment in the bigger artery, so activations of small groups of neurons in areas of the brain that can be visualized with fMRI cannot be detected using TCD. However, its main advantage when compared with fMRI is that TCD does not require special adaptations in the virtual devices used to navigate and interact in the VE and it avoids that the user has to expose to the VE in an uncomfortable way (supine position and restricted head movements). Doppler technique is minimally invasive (it only requires to place two probes in the outer part of the temporal windows of the skull) and imposes fewer limitations to the user.

The analysis of changes in BFV is one of the applications of TCD and has been widely used to monitor the hemodynamic activity of the brain [44]. Some of the studies have analyzed the response of the user when playing computer games [40-41], and this kind of studies can be easily adapted to design new tests with virtual reality environments.

In this study, the main goal has been to analyze if the BFV variations that are observed when subjects are exposed to a VE are different in environments with different levels of immersion, understanding this concept as the degree to which a virtual environment submerges the perceptual system of the user [45] (in a stereoscopic CAVE-like environment and in a monoscopic single projection screen), and with different navigation possibilities (self-guided vs. automatic navigation). A high sense of presence is expected in the stereoscopic CAVE-like environment as supported by previous studies [46-47; 17] and in the self-controlled navigation condition [48].

Another objective has been to check if there is any correlation between accepted measures of presence and BFV when subjects are exposed to those different immersive and navigation conditions of the VE.

2. Methods

A between-subjects design (factorial design) using repeated measures was used.

Forty-two right-handed volunteers (29 men and 13 women) aged between 17 and 55 years (mean age, 30.92 years; standard deviation, 1.10) participated in the study. All the participants gave their informed consent prior to their inclusion in the study. Thirty-two participants were randomly allocated to the first experimental condition: the CAVE-like environment. The other ten subjects were assigned to the second experimental condition: the single projection screen.

Only right-handed subjects were included in the study to obtain a homogeneous group, as long as BFV differences in the response to cognitive tasks have been observed in right- and left- handed users in previous studies [44].

2.2. Apparatus

A commercially available 2-MHz pulsed-wave TCD unit (Doppler-BoxTM Compumedics Germany GmbH) was used to monitor BFV during the experiment. This device was chosen mainly due to its portability.

The apparatus was connected to a PC in which QL software was installed. This software was used to receive the data from the Doppler Box and save the selected variables on the PC hard disk for off-line analysis. Two dual 2-MHz transducers were connected to the Doppler Box. Probes were attached to the user’s head using the probe holder provided with the device. Details about the insonation technique can be found in different studies [49]. Both sides were simultaneously monitored through the temporal window using probes capable of simultaneous explorations at two different depths. First gate was located between 50-55 mm depth in order to register MCA flow.

The captured signal was sampled at a frequency of 100 Hz. The mean of the maximum velocities (in centimeters per second) was recalculated by the software every 1.3 s. An example of a captured signal with the calculated mean can be visualized in Figure 1.

Other physiological measurements such as blood pressure, CO_2 and respiratory rate were not controlled during the experiments. Firstly, because including these kinds of measures would have a negative influence on the ecological validity of the experiment. Secondly, because several studies have proven that these variables do not significantly change while doing cognitive tasks in TCD studies [41; 50-51].

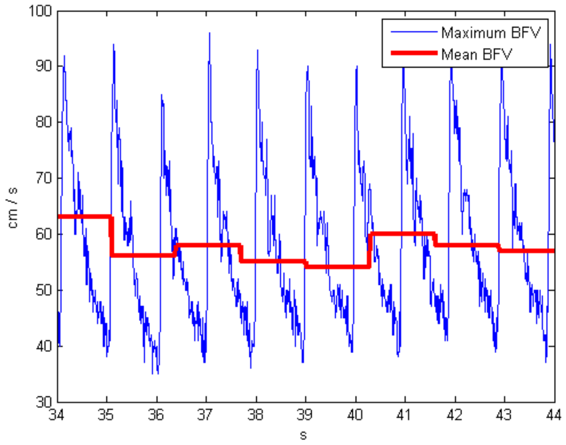

Figure 16 Maximum Blood Flow Velocity in the left middle cerebral artery in a sample subject and mean BFV calculated by QL software

2.3. Virtual reality settings

In the first experimental condition, the study was carried out in a CAVE-like environment with four sides (three walls and the floor). The dimensions of the floor were 2.5 x 2.5 m, and the height of the walls was 2.35 m. In order to deliver the images to the different screens, four Barco 909 (Barco, Kortrijk, Belgium) projectors were used. The machine which was used to generate the images was a SGI Prism (SGI, Sunnyvale, USA), which includes 16 Itanium2 1500MHz 4MB L3 CPUs, 16 GB of main memory (NUMA) and 8 graphic pipes.

The system used active stereoscopy so liquid crystal shutter glasses, CrystalEyes3 (Real D, StereoGraphics, Beverly Hills, USA) were required for the visualization. The device used to navigate was the Flystick (Advance Realtime Tracking GmbH, Weilheim, Germany), which is a wireless joystick with 8 buttons.

An optical tracking system, ARTtrack1 (Advance Realtime Tracking GmbH, Weilheim, Germany) was also used. Reflective targets were attached to the CrystalEyes3 and to the Flystick in order to detect their position and orientation.

In the second experimental condition, the environment was retro-projected in a 2 x 1.5 m metacrilate screen. Monoscopic vision was used in this case. A single Sony VPL – CX5 (Sony, Minato, Tokyo, Japan) projector was used to project the image in this case. The device that was used to navigate inside the VE was an Attack^{TM} 3 Joystick from Logitech (Logitech, Fremont, CA, USA).

2.4 Virtual environment

The VE displayed in both experimental conditions was a maze composed of several rooms and corridors. The environment was programmed using Brainstorm eStudio software (Brainstorm Multimedia, Madrid, Spain), which allows the creation of interactive real-time 3D graphic solutions.

In the case of the CAVE-like environment, the front button of the Flystick was used to advance in the direction in which it was pointing, and the rear button was used to move in the opposite direction (backwards).

In the case of the retro-projected condition, the user could advance and go back in the VE just by moving the joystick forwards and backwards.

2.5. Procedure

In both experimental conditions, users had to follow the same protocol during the experiment. When they arrived to the experimental room, they had to read basic instructions about the experiment. The only personal data collected were age and sex.

Users walked into the room where the environment was going to be projected: the CAVE-like configuration or the single screen configuration. Once there, the probe holder with the two ultrasound probes was adjusted to capture BFV values from the left and right Middle Cerebral Arteries (MCA-L and MCA-R).

In the case of the CAVE-like configuration condition, the user remained standing up in the middle of the screens for the entire duration of the experiment. In the case of the single screen configuration, users remained sitting in front of the screen, with the joystick placed on a small table in front on the chair. Although most of the experiments using TCD have focused on simple and controlled tests with seated patients, recently it has been published that in healthy subjects with intact cerebral autoregulation, the neurovascular coupling works in an independent way to adapt flow demand to the activity in the different orthostatic situations [52].

There was a training stage, during which it was confirmed that the user felt comfortable and the cardiac frequency was stable prior to the beginning of the experiment.

Subjects had to move in the same VE in two different navigation conditions.

The first one was identified as the “Free Navigation Environment” or the FNE. It consisted in a free navigation in the VE using the Flystick or the Logitech Joystick, for 3:30 minutes. Only data from the first 1:20 minutes were included in the analysis. Before this condition, there was a baseline period used to obtain reference values. Only data from the last 20 s (and at least 15 cardiac cycles) of the baseline period were included in the analysis in order to guarantee that the signal was stable and that the obtained value was representative of the situation. Similar approaches have been used to calculate the baseline value in other studies [43; 53]. Figure 2 shows an image from a real session with one of the subjects that participated in the experiment.

Figure 17 Image of one user navigating in the CAVE-like experimental condition during the FNE period

The other navigation condition, named the “Automatic Navigation Environment” or the ANE, consisted in watching an automatic navigation through the same VE. Users were completely passive. They only had to watch the automatic navigation that was presented to them. The display lasted 3:30 minutes, but only data from the first 1:45 minutes were included in the analysis. The ANE condition was also preceded by a baseline period, and data from the last 20 s of this baseline period were included in the analysis.

The different experimental conditions are summarized in Table 1.

A neurologist validated the registries for the different vessels during the experiment. Some measurements were discarded because the recorded signals were not reliable (their values were not included in the typical range of BFV in the vessels) or because in the moment of measurement it was impossible to detect a good quality signal corresponding to this vessel.

		NAVIGATION	
		MOMENT 1: *FNE* *(Free Navigation Environment)*	***MOMENT 2:*** *ANE* *(Automatic Navigation Environment)*
IMMERSION	***GROUP 1:*** *CAVE-like configuration*	Baseline (20 s) + VE exposure (1:20)	Baseline (20 s) + VE exposure (1:45)
	GROUP 2: *Single screen projection configuration*	Baseline (20 s) + VE exposure (1:20)	Baseline (20 s) + VE exposure (1:45)

Table 4 Summary of the different experimental conditions

The number of valid measurements in the CAVE-like experimental condition was 24 for MCA-L and 22 for MCA-R. The number of valid measurements in the single screen experimental condition was 8 for MCA-L and 9 for MCA-R.

Simulation sickness was not observed in the subjects of the different experimental conditions.

Their level of presence was measured using a sufficiently validated method: subjective reports, more specifically, SUS questionnaire [8]. Once the experiment finished, users had to answer this questionnaire, which includes six 7-point Likert-like questions that were adapted to the contents of the VE including references to the maze. The user had to answer the questionnaire twice, once for the FNE, and the other for the ANE.

2.6. Analysis of SUS questionnaires responses

Data from SUS questionnaires were analyzed. Apart from the individual responses to the six questions associated with each of the periods (FNE and ANE), two additional measures were calculated following a similar analysis to previous studies [8]: SUS Count and SUS Mean. SUS Count indicates the number of the SUS responses with “6” or “7” scores amongst the 6 questions. SUS Mean is the mean score across the 6 questions.

The effects of the immersion variable were analyzed using two-way ANOVAs, being the dependent factors the answers to each of the six SUS questions, as well as and the SUS Count and SUS Mean values. Navigation (FNE vs ANE) was the within-subjects factor and immersion (CAVE-like vs. single screen environments) was the between-subjects factor.

2.7. Analysis of BFV measurements

As described before, each activation period is preceded by a baseline period, and the BFV of each activation period is compared with the BFV of the preceding baseline [44, 50, 54]. In order to compare between the different experimental conditions, the percentage variation in BFV between the baseline and the activation moments was used, as reported in previous studies [39-40; 42; 55-56]:

$$BFV(\%) = \frac{BFV_{activation} - BFV_{baseline}}{BFV_{baseline}} \cdot 100,$$

where $BFV_{activation}$ is the mean BFV during the activation period and $BFV_{baseline}$ is the mean BFV during the baseline.

This procedure eliminates any variability associated with changes in the insonation angle or the vessel diameter [57-58]. In the present study, these values have been calculated just to allow the comparison of the magnitude of the variation that occurs in the mean BFV between the different experimental conditions.

The percentage variations in the BFV for the different vessels were compared using a two-way ANOVA (dependent factor: percentage of BFV change) with navigation (FNE vs. ANE) as within-subjects factor. Immersion (CAVE-like vs. single screen configuration) was evaluated by adding it as between-subjects factor to the ANOVA.

3. Results

In the following points, the results obtained with the SUS questionnaire and the BFV registered in the different experimental conditions will be described.

3.1. Presence measurements

The descriptive statistics for the different answers to the questionnaire and for SUS Count and SUS Mean are shown in Table 2. A greater mean value in presence measurements can be observed in the FNE navigation condition when compared with the ANE, both in the CAVE-like environment and in the single screen environment. This trend also appears in the CAVE-like environment when compared with the single screen environment, both for the FNE and the ANE.

Results from the ANOVA applied to SUS-Mean value show that navigation has a significant effect (F(1,39)=31.803; p=0.000). However, no other significant effects were found in SUS-Mean, neither for the immersion factor, nor for the navigation x immersion. Similar results are obtained for SUS-Count value, and for the responses to most of the individual SUS questions.

Immersion	Navigation	SUS-Mean	SUS-Count	Q1	Q2	Q3	Q4	Q5	Q6
CAVE-like	FNE	4.83 (0.23)	2.48 (0.38)	5.25 (0.24)	4.87 (0.31)	4.51 (0.33)	5.16 (0.29)	4.58 (0.27)	4.61 (0.26)
	ANE	3.89 (0.28)	1.19 (0.30)	4.19 (0.26)	4.06 (0.28)	3.80 (0.33)	3.80 (0.32)	4.00 (0.28)	3.67 (0.31)
Single screen	FNE	4.10 (0.41)	1.50 (0.66)	4.20 (0.42)	4.10 (0.54)	4.10 (0.58)	4.70 (0.52)	3.30 (0.47)	4.20 (0.46)
	ANE	3.00 (0.49)	0.60 (0.54)	3.00 (0.47)	3.00 (0.50)	3.30 (0.59)	3.20 (0.57)	2.70 (0.50)	2.80 (0.55)

Table 5 SUS responses in the different experimental conditions. The mean value and the standard error of the mean (s.e.m.) are shown

Nevertheless, results from questions 1 and 5 analysis add information to complete this analysis. Results of the ANOVA for question 1 (*I had a sense of "being there" in the maze*) show a significant effect both for the navigation factor (F(1,39)=24.599; p<0.001) and for the immersion factor (F(1,39)=5.856; p=0.020). In question 5 (*I think of the maze space as a place in a way similar to other similar places where I have been*), results of the ANOVA also show a significant effect both for the navigation factor (F(1,39)=8.572; p=0.006) and for the immersion factor (F(1,39)=5.923; p=0.020). No significant effect was found for the interaction factor.

Taking into account these results, it can be concluded that both the navigation and the immersion variables have significant effects in presence measures obtained from questionnaires.

3.2. BFV values

The percentage variations between mean BFV in the FNE and its preceding baseline, and between mean BFV in the ANE and its preceding baseline have been calculated for the different vessels and the different immersive conditions. Their values have been indicated in Table 3.

The percentage variations are always positive, indicating an increase in BFV when changing from baseline to the FNE or to the ANE. This increase in BFV is associated with neural activity in the cortical areas irrigated by the vessel under study.

BFV percentage variations have been represented graphically in Figure 3 (for MCA-L) and Figure 4 (for MCA-R).

Results from the ANOVA applied to MCA-L show an effect for navigation factor which is close to significance (F(1,30)=3.965; p=0.056). However, analyses for the other factors clearly show that there is no significant effect for the immersion and for the navigation x immersion factor in this vessel. Results from the ANOVA applied to MCA-R show a significant effect for the navigation factor (F(1,29)=6,311; p=0.018) with no significant effect for the other factors.

Immersion	Navigation	MCA-L	MCA-R
CAVE-like	FNE	9,77 (1,38)	9,99 (1,28)
	ANE	6,47 (1,43)	8,25 (1,30)
Single screen	FNE	8,27 (2,39)	9,04 (2,00)
	ANE	5,18 (2,47)	3,54 (2,04)

Table 6 BFV Percentage Variations (%) in the different experimental conditions in MCA-L and MCA-R

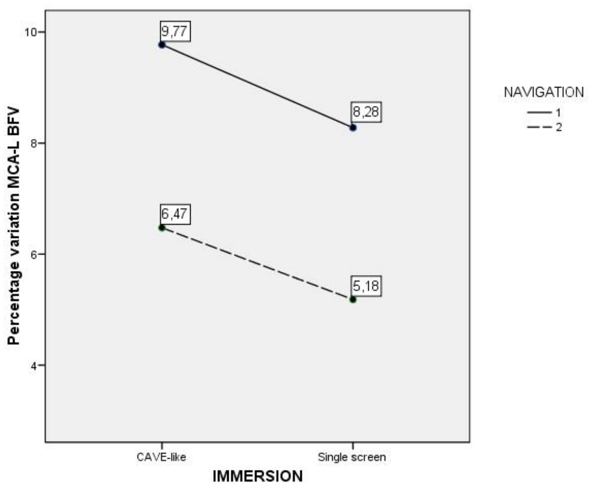

Figure 18 Percentage variations in MCA-L for different immersion and navigation (1- FNE; 2- ANE) conditions

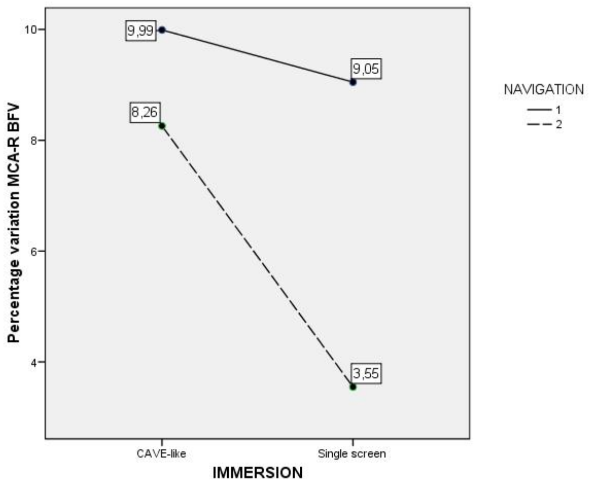

Figure 19 Percentage variations in MCA-R for different immersion and navigation (1- FNE; 2- ANE) conditions

Nevertheless, if Fig. 3 and Fig. 4 are compared, it can be seen that the means do not follow the same trend in the case of the MCA-L and in the case of the MCA-R.

In MCA-L, the highest variations are observed in the FNE condition. The greatest percentage variation occurs in the CAVE-like environment and there is a smaller variation in the single screen environment. In the ANE condition, the variations are smaller, but the same trend is observed. The greatest variation occurs in the CAVE-like environment and the lowest in the single screen environment.

In MCA-R, these general considerations that have been described for MCA-L are also true. The highest percentage variations occur in the FNE condition, and there is also a decrease in the single screen environment when compared with the CAVE-like environment.

However, as it can be observed in the Fig. 4, this decrease is much greater in the case of the ANE condition. In fact, the difference in the percentage variation between FNE and ANE conditions in the CAVE-like environment is smaller than in the single screen environment. The navigation x immersion factor seems to be having an influence in the measurements in the case of MCA-R. Nevertheless, these are no conclusive results as no statistical significance has been obtained.

4. Discussion and conclusions

The first observation that can be made in this study is that the percentage variations between baseline and FNE or ANE are always positive both in the CAVE-like and the single-screen environment. This increment in the BFV that is observed in the different conditions in both vessels can be explained by several factors.

First of all, during a VE exposure there is a complex interaction between visuospatial interaction and attention tasks, and the creation and execution of a motor plan [59] that cannot be observed during the baseline. Besides, any variation in the user's emotions that may happen when the VR experience starts may also be having an influence in BFV measurements [55, 60], because the middle cerebral arteries also supply areas of the parietal and frontal lobe involved in the processing of emotion [61]. Finally, the presence that the user is feeling during the FNE and the ANE could be an additional factor that is having an influence in the observed increase.

The second observation that can be made in this study is that there are measurable differences in BFV percentage variations observed in different immersive and navigation conditions in VE. In the following paragraphs, the effects of the different conditions are discussed.

4.1. Effects of navigation

SUS questionnaires have been used both in the FNE and ANE periods. Results from the analysis show that users feel present in both situations, when they navigate freely through the environment (FNE) and when they are just passive spectators (ANE). However, the level of presence during the ANE is significantly lower than the level of presence during the FNE.

Regarding MCA-L BFV percentage variations, results show a difference in the percentage variation between the ANE and the FNE which is close to achieving significance. Regarding MCA-R BFV percentage variations, results show a clearly significant difference between the ANE and the FNE.

Given that the user had to navigate and control a joystick in the environment, differences observed in MCA-L could be mainly due to these motor tasks. Users that took part in the experiments were right-handed, and variations in BFV in right-handed users have been observed in the left hemisphere during motor tasks [42, 56, 62].

However, differences in MCA-R cannot be explained by this issue. A first factor that can explain them is the difference in the degree of involvement of the users in the creation of a motor plan in the FNE and in the ANE, which can generate a change in the BFV variations. Presence is another factor which is different between the FNE and the ANE (greater scores in SUS results have been observed during the FNE), so it may also be having an influence in BFV variations.

4.2. Effects of immersion

Results from the ANOVA applied to SUS questionnaires show a significant effect for the immersion factor just in questions 1 and 5. Interestingly, question 1 asks users about their sense of being in a place during the virtual experience, so it is one of the questions most closely related to the definition of presence. Question 5 asks users to what degree they think about the maze in a way similar to other similar places where they have been. Also in this case, results of the ANOVA show a significant effect. Taking this into account, it can be concluded that the level of presence in the CAVE-like configuration is significantly greater than the level of presence in the single screen configuration.

Regarding MCA-L and MCA-R BFV variations, no significant differences are found between both immersive conditions. There is only a trend to a higher variation in the case of the most immersive system. Further investigations with a higher number of users (especially in the single screen condition), will help to clarify if this factor has a significant effect in BFV variations.

In any case, there are several possible explanations for this trend. It can be influenced by the degree of involvement of the user in visuospatial tasks of the VE, which can be greater in the case of the CAVE-like system. Furthermore, another factor that can potentially explain the observed trend would be the higher level of presence that has been measured using questionnaires in users of the CAVE-like configuration when compared with the single screen configuration.

4.3. Effects of navigation x immersion

Finally, the possible influence of the interaction effect (navigation x immersion) in SUS measurements and in BFV percentage variations is going to be reviewed.

Taking into account results from the ANOVAs, it has to be concluded that the level of presence (measured by SUS questionnaires) is not influenced by the interaction between navigation and immersion effects.

The same conclusion can be achieved when analyzing BFV percentage variations in both MCA-L and MCA-R: no significant effect is found for the interaction factor.

However, in the case of MCA-R, a trend has been found for a possible influence of the interaction factor in BFV variations: the BFV percentage variation difference between FNE and ANE is greater in the case of the single screen configuration than in the case of the CAVE-like configuration. It is also observed that the BFV percentage variation difference between CAVE-like and single screen configurations is greater in the case of the ANE than in the case of the FNE. Conclusive results can not be obtained taking into account only data from this experiment and future studies may help to confirm and understand the origin of this pattern.

A possible explanation can come from the different experimental conditions that are being considered. In the CAVE-like configuration, the immersion is so high that the brain activity changes that occur when starting the virtual reality experience are mainly influenced by this factor. The influence of navigation may be masked by the effect of immersion. That can explain why in the case of the CAVE-like configuration there is almost no difference in MCA-R BFV variations in the FNE and in the ANE.

On the other hand, in the single screen configuration, the immersion is not so high, so this effect is not so powerful to mask the effect of navigation. Brain activity variations may be more influenced in this case by the effect of navigation. Greater differences are observed in MCA-R BFV variations between FNE and ANE in the single screen configuration.

An analogous explanation may be applied to the differences in brain activity between CAVE-like and single screen configurations in the case of the ANE and in the FNE. In the FNE condition, the navigation requires that the user is actively involved in the task. This requirement may imply a higher brain activity that can mask of the influence of the immersion factor, so the observed difference between both immersive conditions is low. On the other hand, in the ANE the navigation effect has less influence, so it does not mask the effect of immersion that can have in this case a greater influence in brain activity. Greater differences are observed in MCA-R BFV variations between CAVE-like and single screen conditions in the ANE.

In any case, what are the processes that are generating these differences in brain activity? As it has been described in previous sections, visuospatial and attention tasks (that can require more user involvement in the CAVE-like configuration and in the FNE) may be the origin of the BFV percentage variation. Presence (that is also higher in the case of the CAVE-like configuration and in the FNE) may be another factor that is influencing this BFV percentage variation. If it could be proven that presence is the main factor that generates the brain activity changes, some interesting conclusions regarding the causes of presence could be extracted. Both immersion and navigation are factors that have been studied as causes of presence [46-48, 17]. The observed trend may show that environments with high immersion or a self-controlled navigation can mask the influence of other factors. The CAVE-like configuration may mask the influence of the navigation factor, so the differences between FNE and ANE are low. Furthermore, the FNE may mask the influence of the immersion factor, so the differences between CAVE-like and single screen conditions are also low. Nevertheless, future works may contribute to achieve conclusive results.

General conclusions

This study has proven that TCD is a valid technique for measuring blood flow changes secondary to brain activity under different immersive and navigation conditions in VEs. Results show that immersion and navigation modifications in VE generate generalized changes in brain activity that can be detected using TCD techniques. Variations are greater in the configurations that generate higher levels of presence in subjects, so these changes could be related to the sense of presence. However, further research must be conducted in order to deepen in this analysis.

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