Annual Review of Cybertherapy and Telemedicine
Volume 7 Year 2009 ISSN: 1554-8716

Advanced Technologies in the Behavioral Social and Neurosciences

Editors:
Brenda K. Wiederhold, PhD, MBA, BCIA
Giuseppe Riva, PhD, MS, MA
Transcranial Doppler: a Non-Invasive Tool for Monitoring Brain Activity in Virtual Reality Therapy

Beatriz REY\textsuperscript{a,1}, Vera PARKHUTIK\textsuperscript{b}, Mario ALCAÑIZ\textsuperscript{a}, Jose TEMBL\textsuperscript{b} and Valery NARANJO\textsuperscript{a}

\textsuperscript{a}Instituto en Bioingeniería y Tecnología Orientada al Ser Humano, Universidad Politécnica de Valencia, Camino Vera s/n, 46022 Valencia, Spain
\textsuperscript{b}Neurology Service, Hospital Universitari La Fe, Av. Campanar 21, 46009 Valencia, Spain

Abstract. In this work, we propose the use of Transcranial Doppler Monitoring (TCD) as a tool to measure brain activity during the exposure to Virtual Environments (VE) used in clinical therapy sessions. The technique is non-invasive, and can be easily integrated with Virtual Reality (VR) settings. Moreover, it provides a high temporal resolution, which grants the possibility to analyze changes in brain activity during the evolution of a clinical session and to correlate them with specific events that may occur in the VE. We have performed two studies combining TCD with VR. Results of these studies show that it is feasible to use this technique in combination with VR settings designed for virtual therapy. It was observed that immersion and navigation modifications in the VE generated changes in brain activity that can be detected using TCD.

Keywords. Transcranial Doppler, Cerebral blood flow, Virtual Reality Therapy

Introduction

Clinical Therapy is one of the most challenging applications of Virtual Reality (VR). During the exposure to Virtual Environments (VE) in clinical therapy sessions, it is beneficial to monitor as much information from the patient as possible. Some information can be collected using questionnaires that analyze different factors of the VR experience, such as presence, immersion, or emotions \cite{1-3}. However, the use of questionnaires has limitations. Most of them can only be used after the exposure to the VE, and therefore is not possible to have data pertaining to the temporal evolution of the patient during the session. In order to avoid this limitation, some studies have tried to adapt questionnaires in order to monitor different variables during the virtual experience. For example, a handheld slider was proposed as a new form of direct subjective presence evaluation \cite{4}. Other studies used short questions, which were included in the VE during the VR experience to collect information on the level of anxiety \cite{5}. These approaches can be useful to have information directly related with specific events. However, they can hardly interfere with the VR experience itself. This is why, in many cases, physiological measurements, such as electrocardiogram (EKG)

\textsuperscript{1}Corresponding Author: E-mail: brey@labhuman.i3bh.es.
or skin conductance (SC) [6], and neurological measurements such as electroencephalogram (EEG) [7] have been proposed as tools to monitor the evolution of the patient during the exposure to VE in clinical therapy applications.

In this study, we proposed an alternative neurological measurement tool that can be used to monitor brain activity during the exposure to VE. This technique is called Transcranial Doppler (TCD), a non-invasive measurement with high temporal resolution that can be easily integrated in the VR settings used in clinical therapy sessions.

1. Transcranial Doppler (TCD)

TCD was first used in 1982 [8]. It is an ultrasound diagnosis technique to control the hemodynamic characteristics of major cerebral arteries in normal and pathological conditions with high temporal resolution. Based on the Doppler Effect, this technique can obtain the instantaneous blood flow velocity (BFV) in the main cerebral arteries of the brain: middle cerebral arteries (MCAs), anterior cerebral arteries (ACAs) and posterior cerebral arteries (PCAs). Each of these vessels supplies different cerebral regions. Previous research has shown that Cerebral Blood Flow (CBF) increases when users are performing mental tasks [9]. When the neurovascular coupling [10] is adequate, BFV variations detected using TCD reflect changes in regional CBF due to brain activation in the areas supplied by the vessels under study.

TCD has important advantages when compared to other techniques. First of all, it has a high temporal resolution, which allows instantaneous monitoring of cerebral responses to specific events. Furthermore, it is non-invasive, so it is possible to use it in an ecological way in a great variety of environments. That constitutes its main advantage when compared with other techniques such as fMRI, which imposes serious restrictions to the experiments in which it is used, as long as the subject has to remain in supine position inside the magnetic resonance machine with minimum head movements while hearing annoying noises. The main disadvantage of TCD is its spatial resolution, which is limited by the size of the cortical areas supplied by the arteries under study.

1.1. TCD adjustment procedure

This technique requires that two probes be placed on the skull of the subject using a headband or a probe holder. The adjustment of the probes to their correct location is a process that can be easily performed by a neurophysiologist in a short period of time without requiring any previous preparation from the patient and without generating any inconvenience. Once the probes are located, the patient can be stood up or sitting during the VR session, as the system is compatible with both positions [11]. The location of the probes in the head has to be maintained during all the experiences, so the only restriction is that the patients cannot make abrupt movements during the session.

1.2. Cortical areas supplied by TCD monitored arteries

MCAs supply blood to the greater part of the brain. Their perfusion territory includes subcortical areas, large fractions of the frontal and parietal lobes, as well as the
temporal lobes [12]. Modifications in their BFV can be produced by brain activity associated with different kinds of tasks (such as motor tasks, memory tasks or even emotional states). Usually, BFV variations are used to analyze hemispheric dominance during these tasks. In any case, some parts of the MCAs perfusion territory are closely related with the processing of emotions (mainly parts of the parietal and frontal lobe, as well as areas of the temporal lobe with the limbic systems [13]), so their analysis would be interesting during clinical therapy sessions.

The other vessels that can be monitored with TCD have a smaller perfusion territory, thus we can obtain from them more detailed information about the brain areas that are activated. ACAs can be especially important in clinical therapy sessions, as long as they supply most of the medial areas of the brain, including the medial frontal cortex and most parts of the limbic system [12]. Such BFV variations are closely related with the emotional state of the patient.

1.3. TCD in psychophysiological studies

TCD has been used to analyze cognitive states of subjects in psychophysiological research [14-15]. These studies have shown that mean BFV obtained from TCD signals increases when users are performing cognitive tasks (such as reading, arithmetic operations, visual stimulation, attention, verbal tasks, motor tasks, visuospatial tasks and memory) when compared to baseline periods. Some of the previous studies have analyzed emotion-related changes in BFV and have found an emotion-related cerebral asymmetry [16-17]. A significantly higher increase is observed in the right than in the left MCA during emotional processing.

2. Results of TCD in Virtual Reality experiences

Although there have been many previous studies using TCD in neurophysiologic research, the first studies that analyze brain activity during a VR exposure have been developed by our group. The complete description of the experiences has already been published [18, 19], but a short summary is included in this section.

In order to monitor BFV signals during the exposure to this VE, a commercially available 2-MHz pulsed-wave TCD unit (Doppler-Box™ Compumedics Germany GmbH) was used. The apparatus was connected to a PC in which DWL® Doppler software (QL) was installed. This software was used to receive the data from the Doppler Box and to save the selected variables on the PC hard disk for off-line analysis. Two dual 2-MHz transducers were connected to the Doppler Box. Both hemispheres were simultaneously monitored through the temporal window using two probes capable of simultaneous explorations at two different depths. In the first study [18], both MCAs and ACAs were monitored. In the second study, [19] only MCAs were monitored.

Thirty-two volunteers participated in the first study [18]. The VE used was a maze composed of several rooms and corridors. A joystick was used to navigate inside a CAVE-like system. TCD was used to monitor brain activity during the different navigation conditions (self-guided with joystick vs. automatic navigation). Fig. 1 shows an image of a user during the automatic navigation condition in this study.

Results show that the variations in BFV in left hemisphere arteries that occurred in the self-guided navigation condition when compared with baseline were significantly higher than in the automatic navigation. The variations in left MCA (MCA-L) could be
due to the motor tasks with the right hand to control the joystick. However, the variations in left ACA (ACA-L) are not directly related to this issue, and can only be explained by other factors such as differences in the emotional state or the level of presence that the user is experiencing during the VE exposure in the different navigation conditions. Presence questionnaires confirmed that the level of presence was different between experimental conditions.

![Figure 1. User during the automatic navigation in the first study [18].](image)

In the second study [19], forty-two subjects were exposed to different immersion (CAVE-like vs. single screen projection) and navigation conditions (self-guided with joystick vs. automatic navigation). The same VE was used. Only the navigation factor had significant influence in BFV variations in right MCA (MCA-R) and MCA-L. Differences in MCA-R BFV variations cannot be explained by motor tasks, as subjects used the right hand to control the joystick. A possible explanation of these differences could be found in the different degree of involvement of the users to create the motor plan in both conditions. The level of presence at each condition (which is different as measured by questionnaires) could also be having an influence.

3. Conclusions and discussion

TCD is a tool that can be easily used to monitor brain activity during the VR experience in clinical therapy. Its main advantage is that it provides a high temporal resolution that allows the monitoring of fast changes in BFV values caused by neural activity. The works in our group [18, 19] are the first to use TCD in combination with VR. These works show that it is possible to obtain robust BFV signals even during the exposure to a VR experience. Besides, the use of TCD does not interfere with the capability of the subjects to focus their attention on the VE. These conclusions show the feasibility of using TCD in combination with VR during virtual therapy. The use of TCD may help therapists to have reliable information on the brain activity of their patients and correlate its changes with specific events in the VR session.

The studies also show the feasibility of simultaneously monitoring BFV in different cerebral vessels during the exposure to VE. Two probes are used, so it is
possible to monitor both hemispheres. As different vessels supply different brain areas, an important issue in TCD studies is to identify the brain area most directly related with the task under study in order to select the more adequate vessel. MCAs are the vessels most commonly used, as they have the largest perfusion territory. ACAs have smaller perfusion territories, including most parts of the limbic system, thus can be especially useful in studies where emotional aspects have to be considered.

Taking all these aspects into account, we conclude that TCD is a significant measure to be studied that monitors aspects such as emotions and presence during exposure of patients to VE in clinical therapy sessions.

References

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