International Journal of Psychophysiology 95 (2015) 254–260

Contents lists available at ScienceDirect

International Journal of Psychophysiology

journal homepage: www.elsevier.com/locate/ijpsycho

Modulation of cortical activity in 2D versus 3D virtual reality environments: An EEG study

Semyon M. Slobounov [a,*], William Ray [b], Brian Johnson [a], Elena Slobounov [a], Karl M. Newell [a]

[a] Department of Kinesiology, The Pennsylvania State University, 276 Recreation Building, University Park, PA 16802, USA
[b] Department of Psychology, The Pennsylvania State University, 356 Moore Building, University Park, PA 16802, USA

ARTICLE INFO

Article history:
Received 11 August 2014
Received in revised form 2 November 2014
Accepted 4 November 2014
Available online 8 November 2014

Keywords:
Virtual reality
2D versus 3D immersion
EEG theta power

ABSTRACT

There is a growing empirical evidence that virtual reality (VR) is valuable for education, training, entertaining and medical rehabilitation due to its capacity to represent real-life events and situations. However, the neural mechanisms underlying behavioral confounds in VR environments are still poorly understood. In two experiments, we examined the effect of fully immersive 3D stereoscopic presentations and less immersive 2D VR environments on brain functions and behavioral outcomes. In Experiment 1 we examined behavioral and neural underpinnings of spatial navigation tasks using electroencephalography (EEG). In Experiment 2, we examined EEG correlates of postural stability and balance. Our major findings showed that fully immersive 3D VR induced a higher subjective *sense of presence* along with enhanced success rate of spatial navigation compared to 2D. In Experiment 1 power of frontal midline EEG (FM-theta) was significantly higher during the *encoding phase* of route presentation in the 3D VR. In Experiment 2, the 3D VR resulted in greater postural instability and modulation of EEG patterns as a function of 3D versus 2D environments. The findings support the inference that the fully immersive 3D enriched-environment requires allocation of more brain and sensory resources for cognitive/motor control during both tasks than 2D presentations. This is further evidence that 3D VR tasks using EEG may be a promising approach for performance enhancement and potential applications in clinical/rehabilitation settings.

1. Introduction

The success of virtual reality (VR) applications used in education, entertainment and medical assessment/rehabilitation applications depends highly on the subjects' *sense of presence* (Jancke et al., 2009). *Sense of presence* is the experience of feeling that the VR environment represents a real world situation and not just a viewed video experience. This sense of presence is associated with stronger behavioral reactions in the VR situations influencing task performance. While several studies have used VR to examine spatial navigation in humans (Iaria et al., 2008; Kober and Neuper, 2011; Kober et al., 2012), the effects of 2D versus 3D immersive environment on behavioral parameters (e.g., subjective *sense of presence* and success rate of task performance) and associated neural underpinnings are still poorly understood. Here we examined 2D versus 3D environments in 2 experiments that recorded EEG as participants performed spatial navigation and whole body postural tasks in a VR environment that was toggled between 2D and 3D scenarios.

EEG offers a real-time measure of task requirements and the VR applications allow one to develop the virtual world in which an individual can perform numerous motor and cognitive tasks along with the sense of self-motion while retaining the head fixation requirement of the EEG environment (Haibach et al., 2008; Slobounov et al., 2011). We implemented our previous VR-based spatial navigation paradigm in order to: (a) manipulate the various degrees of subjects' immersion via 3D versus 2D VR scenarios; (b) examine the subjective *sense of presence* during both encoding and retrieval phases along with the success rate of navigation performance; and (c) track the modulation of brain activation patterns via EEG. In our analysis, we focused primarily on EEG FM-theta power because previous research has documented that modulation of frontal–central theta power is related to route learning (Shelton and Gabrieli, 2002), error monitoring during motor performance (Adkin et al., 2006), and successful performance of perceptual-motor tasks (Slobounov et al., 2000).

Postural stability and balance reflect the body's ability to maintain equilibrium in response to external perturbations (Peterka, 2002; Mergner et al., 2002). In everyday life, this includes moving over uneven terrain, playing sports, and climbing stairs. Postural stability is reduced with aging and various pathologies such as Parkinson's disease, stroke, and brain injuries including concussion (Slobounov et al., 2005, 2006, 2011). The monitoring of postural stability is often an important variable in determining improvement or degeneration associated with these pathologies.

Traditionally, postural stability is measured via a force plate technology that reflects changes in distribution of pressure of the feet on the

* Corresponding author at: Department of Kinesiology, The Pennsylvania State University, 19 Recreation Building, University Park, PA 16802, USA. Fax: +1 814 863 7360.
E-mail address: sms18@psu.edu (S.M. Slobounov).

http://dx.doi.org/10.1016/j.ijpsycho.2014.11.003
0167-8760/

floor. In terms of force platform measures, there is a high correlation between several of the standard force platform measures (Slobounov and Newell, 1994). The area of center of pressure (COP) is used as a traditional measure to characterize postural stability. Specifically, there is an inverse relationship between the area of COP and postural stability index (Slobounov et al., 2008). Also, the percent change of COP motion significantly changes as a function of postural challenge indicating an increased risk of falling (Slobounov et al., 2011). Thus, increased area of COP as a function of VR manipulation can indicate the degree of its destabilizing effects in postural control.

The destabilizing effect of VR environment on postural stability inducing the manipulation of optic flow has been documented in numerous previous studies (Keshner and Kenyon, 2000; Slobounov et al., 2011; Wright, 2013, 2014). Together these reports suggest that VR can be used to induce motor responses to a non-veridical virtual input. This is the case even without destabilizing physical stimuli that require an appropriate postural response to prevent actual loss of balance. Thus, VR can cause an unexpected and task irrelevant postural response leading to instability and potential falls (Haibach et al., 2008).

In the present paper, we report 2 experiments examining the differential effect of 3D versus 2D VR environment on cognitive/motor task parameters and associated EEG responses. This parametric research is needed to fully document the potentially differential effects of 2D versus 3D VR on the cortical and sensory system that in turn influence postural stability and/or spatial navigation skills. This is a novel and needed approach to further investigate the feasibility of advances in the 3D VR enriched environment in research and potential clinical settings.

2. Experiment 1

2.1. Methods

2.1.1. Participants

Twelve subjects with no history of neurological disorders aged 18 +/− 2.3 years old (6 males and 6 females), participated in this study. All subjects signed an informed consent form and the Institutional Review Board of the Pennsylvania State University approved this protocol.

2.1.2. Procedures

The experimental paradigm used in this study consisted of a *virtual corridor* (Fig. 1) in which participants: (a) were shown the navigation route to encode (*encoding phase*); and (b) navigated purposefully with the goal of reaching specific target room location (*retrieval phase*) using a wireless remote Wii joystick. The subjects “moved” around using their right thumb to freely navigate in forward, backward, and side-to-side directions. The virtual corridor was generated by a VTC Open GL developing kit (InnovativeVR, Inc., USA, see Slobounov et al., 2010 for details).

The subjects stood 2.5 ft away from a 65″ 3D television (Samsung, Model # UN65F8000, resolution = 1080 p (1920 × 1080), Quad core internal processor, 240 Hz refresh rate) screen that was positioned 60 from the floor with the visual stimuli projected in 2D or 3D modes. Surrounding the screen were two black curtains to each side. A remote wireless Wii controller was used for navigation and initiation of the trial was coordinated with the stimuli presentation in synchrony with EEG system. *CrystalEyes* stereo glasses were worn by subjects and fit to the head with a connective head strap for 3D condition. Each subject participated in two sessions (2D versus 3D condition) in the same day with time interval about 2 h. It should be noted that the routes for both conditions were randomized between sessions. The success rate of navigation performance was assessed based on the number of errors (erroneous turns during retrieval phase and time (s) for reaching the target location) (see Slobounov et al., 2010 for details).

2.1.3. Behavioral responses

Subjects' behavioral responses are summarized as follows. First, *sense of presence* was measured by subjective reports after the completion of each experimental condition, similar to Jancke et al. (2009). Sense of presence refers to the subjective feeling of absorption in the virtual environment while unaware of one's real location and surrounding. This includes a lack of awareness that technology is delivering a stream of virtual input to the senses. Specifically, subjects were instructed to rate the strength of *presence* on the scale ranging from 0 (no presence) to 10 (very strong presence).

The task performance success rate was assessed combining three variables: (1) accuracy of the task performance (ability to find correct route presented during *encoding* phase); (2) number of trials needed to successfully complete the test (total allowed, n = 3); and (3) time needed to complete the test (30 s maximal allowed). These three data sets were used as an input for normalized reports of success rate ranging from 10 to 0 for each subject under study (n = 12).

2.1.4. EEG recording

EEG recording was conducted using Ag/AgCl electrodes mounted in a 62-channel Electro-cap (NeuroScan Inc., Eaton, OH). The ground electrode was located 10% anterior to FZ, with linked earlobes serving as references. EEG signals were recorded using a programmable DC coupled broadband SynAmps amplifier (NeuroScan, Inc., El Paso, TX). The EEG signals were amplified (gain 2500, accuracy 0.033/bit) with a recording range set to ± 55 mV in the DC to a 70-Hz frequency range. The EEG signals were digitized at 250 Hz using 16-bit analog-to-digital converters. Impedance was measured at all sites and was kept below 5 kΩ.

From the 62-channel array, EEG recording was filtered in the 2–30 Hz frequency range. The data were checked and corrected for

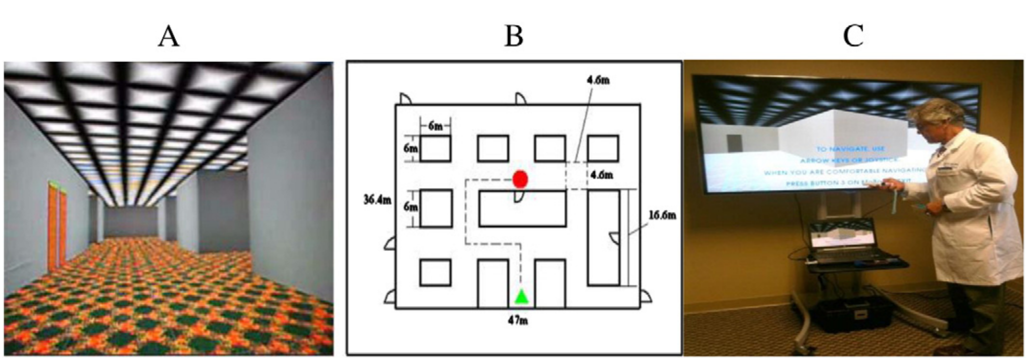

Fig. 1. (a): View of the virtual corridor used for navigation tasks under study; and (b) floor plan, and a sample of the route for one of the runs; (c) 3D/2D TV and associated hardware used for this study. The subjects were instructed to reproduce (e.g., *retrieval phase*) the previously shown routes (e.g., *encoding phase*) via navigating through virtual corridor by a joystick and to find the target location. It should be noted that starting position was the same for all runs. However, floor maps were randomized between subjects during presentation of 2D and 3D conditions.