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BRAIN ACTIVITY ON NAVIGATION IN VIRTUAL ENVIRONMENTS

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ABSTRACT

This article reports a first attempt to assess the cognitive processing that takes place in virtual environments, by measuring subjects' electrical brain activity using Fast Fourier Transform analysis. The aim of the study was the evaluation of virtual learning environments using the above methodology in addition to the standard methodology of social sciences and educational research, namely quantitative and qualitative empirical research. Twelve university students, undergraduates and postgraduates, were asked to perform the same task in a real and a virtual environment. During the two processes, their brain signals were recorded and analyzed. Eye-movement measurements showed that all the subjects were more attentive when navigating in the virtual world. The difference between alpha and beta rhythms for the virtual task indicated that students placed more attention in the virtual environment and were more responsive to the cognitive stimulation. Lower theta activity in the virtual task demonstrated that all the subjects placed less mental effort in the virtual task signifying that virtual reality provides environments suitable for knowledge transfer. These results show that virtual reality may provide educational environments for students to concentrate, perceive, and judge, and give us indications that there is a need of training of the users of virtual worlds.

Virtual Reality (VR) is a multi-sensory highly interactive computer based environment where the user becomes an active participant in a virtually real world. First person's point of view, freedom in navigation, and interaction are essential for a computer environment to be characterized as a VR environment (virtual environment, VE). A virtual environment designed to educate the user is called a virtual learning environment. It should have an educational objective and provide users with experiences they would otherwise not be able to experience in the physical world.

VR proposes the adaptation of technology to people and not the opposite as other technology-based learning environments do. However, VR has introduced new technologies and theoretical approaches which users need to get used to. Immersive or non-immersive systems, caves and cyberspace, and augmented and artificial realities introduce users into completely new worlds not necessarily representing the real one, giving them experiences other than the usual ones. Avatars, first person point of view, and freedom of navigation in three-dimensional (3D) spaces make users experience a different kind of environment. Moreover, virtual environments enhance users' experiences and help them to enrich the structure and process of their experiences. This leads to knowledge construction, a process that takes place in the users' brains.

The physical structure of the human brain is affected by the way it is used. Different kinds of experiences configure the brain, especially children's brains. The reorganization of children's brains is an important factor in the educational process, specifically in the case of the involvement of media and educational technology. This article is an attempt to assess the experiences taking place in both a real and a virtual environment by measuring the electrical brain activity of users of VR systems. It is proposed that the brain operates in a different way when it gets signals coming from synthetic environments such as the computer-generated environments. These signals differ from those of the natural world. Things become more important with the virtual environments. These represent three-dimensional spaces and require more or less specialized peripheral devices such as 3D navigators, stereoscopic viewers, and trackers. Virtual environments put the user in a new philosophy concerning human–computer interaction. The user experiences an environment, interacts with it, and alters it using these devices affecting his or her reaction [1].

The goal of this article is exploratory. We record the users' cognitive activity in immersive virtual environments. The goal is not to measure cognitive activities as such, but to compare the electrical brain activity taking place in virtual versus real environments. A further goal is to measure and analyze the cognitive changes that users of educational VR systems experience and to evaluate the consequences of such a kind of educational software. The research is in accordance with findings showing that electroencephalography (EEG) can be used to probe the relation of hemispheric functioning to both emotion and cognition [2-4]. The EEG shows the electrical activity of a number of neurons that can be recorded from the scalp. Techniques have been developed to extract information from the signals recorded in order to obtain an understanding of the brain processes underlying psychophysical and cognitive functions. One of these techniques is the EEG as a time series accompanied by the Fourier transform of the EEG signal, which analyses it into its spectral distribution. The technique uses Fast Fourier Transform (FFT) and is applied when the main concern is to characterize a given brain state or a change in stage [5]. This spectral analysis of the EEG signals is the method followed by this research, because it gives results for the emotional and cognitive processes of the users of our educational virtual environments.

PREVIOUS RESEARCH

Only a few studies report results on electrical brain activity in virtual worlds. One by Cartwright and Zanni presents an attempt to distinguish virtual from real stimuli [6]. The research reports on the difference in alpha and theta rhythm in the frontal and occipital areas when seeing flashing lights perceived to move and when seeing real movement. Their results indicate significant differences in the brain's frontal area suggesting that perceived movement requires higher order cognitive processes outside the visual area. The virtual environment restricts on a circular object on a black background moving across a 13" computer screen. So, the word "virtual" in this work distinguishes the stimuli from a real movement, and it does not concern a VR system, virtual worlds, and virtual environments.

There are two more relevant studies. The first by Bayliss and Ballard reports findings on the interference of a VR helmet on EEG recording [7]. There the synthetic environment is not a virtual one, since it consists of a series of letters appearing on a computer screen. A further study by these two authors involves a VR driving world concerning the reaction of the subjects who were told to stop their virtual cars at the red traffic light [8]. The goal of the experiment is to recognize the existence of P300 evoked potential epochs and find the best one of three different signal analysis methods. This work does not report anything concerning the comparison between real and virtual environments.

Two other articles report findings by applying two different imaging techniques. Aguirre and D'Esposito measured the oxygenation of blood flowing to the brain using functional magnetic resonance imaging (fMRI) of VR users to determine if components of psychologically derived models of environmental representation are realized as distinct functional, neuroanatomical regions [9]. During the exploration within the virtual environment, four subjects were judging the appearance and position of familiar locations. The results show a dorsal/ventral dissociation in three of the subjects.

The second study by Maguire, Frith, Burgess, Donnett, and O'Keefe applied Positron Emission Tomography (PET) to measure regional cerebral blood flow changes while eleven normal subjects explored and learned in a VR environment [10]. There were two virtual environments, one containing salient objects and textures and the other one was empty. The findings show that learning in both cases activated a network of bilateral occipital, medial parietal, and occipitotemporal regions. The first environment resulted in increased activity in the right parahippocampal gyrus, while the region was not activated in the empty environment.

In sum, none of the above references reports on educational virtual environments; neither was their goal to find emotional or cognitive changes from a pedagogic point of view. Their results indicate that brain activity is different in virtual environments compared to real ones. A reason for the use of EEG in the present research is its excellent temporal resolution in comparison with fMRI and PET, which have excellent spatial resolution [11].

RESEARCH QUESTIONS

The research questions of the present article approximate Cartwright and Zanni's [6], in the sense of comparing electrical brain activity in a process occurring at both a real and a virtual environment. These are the following:

- Are there any differences between EEG signals coming from real and virtual environments?
- What kind of differences are there, if any, in the alpha, beta, theta, and gamma rhythms in real and virtual environments?
- Are there differences between EEG signals of male and female subjects?

The value of these questions is directly related to our interest in introducing VR in the educational process. It is important to know what cognitive processes are taking place in virtual environments since they enhance users' experiences or provide them with new ones. These questions are in the context of the evaluation of educational virtual environments using the proposed methodology in addition to the standard methodology of social sciences—that is, empirical research.

As a first approach of this kind of research, the present study attempts to record data concerning the above questions and comment on them. The main interest is to examine whether there are indeed differences in the brain processes in the two different working environments. The interpretation of the data are of main interest, but will be the topic of a future article involving EEG signals of a larger sample, a better EEG system with much more electrodes on various points of the subjects' scalps, and more specific educational virtual environments.

METHODOLOGY

Subjects

Subjects were twelve college students, both undergraduate and postgraduate, at the Department of Primary Education, University of Ioannina, Greece. Their mean age was approximately thirty years. All subjects were right-handed, did not report any medical problems, and had not used any medication, alcohol, or drugs in the twenty-four to forty-eight hours prior to the experimental procedure.

The selection of the sample was not random. Subjects were chosen based upon their familiarity with virtual environments, although most of the males had more experience than most of the females.

The System

The system for the EEG recording and analysis is a two channel system, the Interactive Brainwave Visual Analyzer (IBVA Technologies, Inc). The brain signals are amplified by an amplifier with maximum noise level of 0.4 V peak to peak, and impedance < 10 K The measurements are almost not influenced upon the reading area, because of the high input impedance (10 M of the transmitter. The signals are digitized by an 8 bit A/D converter per channel, coupled to the two serial ports of a Macintosh computer for signal acquisition and analysis. The electrodes are on a headband, and we read brain signals from the frontal lobes. This is mainly because the frontal area of the brain seems to be related to visual processing and to spatial working memory [12], and our environments and task relate to vision and movement. Although the EEG signals related to optical stimuli are stronger at the occipital lobe, such signals appear at the frontal lobes too, where our measurements were done. The restriction of measuring at the frontal lobes are the lower amplitudes of the EEG signals that are observed in our experiments.

The Task

The educational virtual worlds we design are landscapes for geography and astronomy teaching, buildings and rooms for environmental and physics education [13], and the inside of cell's organelles for biology teaching [14]. All of these environments allow free navigation in 3D space as well as interaction. One of the factors we have to take into account is the response of the users in such 3D synthetic environments comparing the users' movement towards specific places to similar tasks in the real world. To study this effect, we compared the electrical brain activity and, specifically, the alpha, beta, theta, and gamma rhythms (spectral regions) in both environments, which relate with cognitive and motoric functions and the selection of sensoric information flowing to the cortex.

Figure 1 depicts the virtual environment we have designed. It is a representation of a room of our lab, a place quite familiar to the users. We have developed it using the SUPERSCAPE Virtual Reality Toolkit on a windows based personal computer. Immersion has accomplished with virtual i-glasses, giving the sense of the 3D space. The task the users were asked to complete was to navigate, pass through the two objects (the chair and the flowerpot), make a circle around the flowerpot, and end at the starting point. This was a point far from the two objects, somewhere on the perpendicular bisector of the line connecting these two objects. The users were navigating using a joystick. Its degrees of freedom were locked in such a way allowing only the forward and backward directions, for the movement to be restricted for the purpose of the specific experiment. The real environment and the task in it were information equivalent and the same as in the virtual environment.

Each of the twelve subjects performed the same task first in the real and then in the virtual environment for a period of one minute each with simultaneous EEG

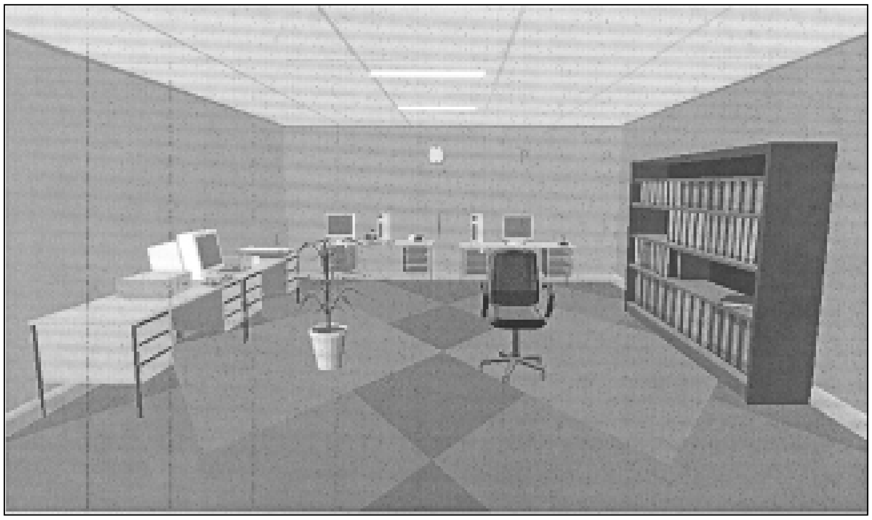

Figure 1. The virtual environment that is a representation of a real room. Users navigate through the chair and the flowerpot making a circle around it, ending at the starting point. The task in the real environment is exactly the same.

recording. After some trials, we found that each subject had completed the task after the twenty-sixth second. We analyzed the EEG signals during the twenty-fifth second, within one second of the recording. A baseline recording for each subject with eyes closed was used to check for noise disturbances and imperfect electrode contacts. Another baseline for each subject with eyes open looking at the computer screen was used to determine differences between the static screen and the task in the virtual environment.

RESULTS AND DISCUSSION

At first, clipping in the EEG recordings was analyzed for both tasks, real and virtual. Clipping is observed very often in the real environment as a result of eye-movement. Results showed that clipping was rare in the virtual environment. It may be that subjects were more attentive to the task in the virtual situation. Greater attention may be explained because subjects wore the virtual i-glasses which allow the user to have a limited angle of view, just that of the virtual environment. Another possible explanation points to the fact that users navigate in the virtual environment not walking as in the real one, but standing still and using the joystick.

The next step was to code and analyze EEG results from three situations: 1) eyes open with no stimulus present (EYES OPEN); 2) real task (REAL); and 3) virtual task (VR). Table 1 presents the values of the power spectrum for the eye movement

Table 1. Power Spectrum for Eye-Movement without Stimulus (EYES OPEN), in Real and Virtual Environments. The Signals are for the Right Eye (*M* = Male, *F* = Female)

Subject	Eyes Open (V^2)	REAL (V^2)	VR (V^2)
M1	0.1	1823.3	38.4
M2	79.2	2480.0	275.6
M3	17.6	1730.6	1.7
M4	2.9	2480.0	29.2
M5	23.0	275.6	1062.8
M6	156.3	576.0	712.9
F7	412.1	2480.0	1413.8
F8	23.0	2480.0	1459.2
F9	7.3	2480.0	1376.4
F10	57.8	1036.8	1011.2
F11	110.3	2480.0	1697.4
F12	21.2	2480.0	278.9

Table 2. Statistical Comparison between the Three Different Situations. Note that the 95 percent Confidence Interval of the Difference Does Not Contain the Value Zero in Any of the Situations

Mean Comparisons in Three Situations	*t*	*p*	95 percent Confidence Interval of the Difference: Lower	Upper
REAL-EYES OPEN	7.649	0.000	1299.3487	2349.2347
VR-EYES OPEN	4.084	0.002	324.5427	1083.2406
REAL-VR	3.801	0.003	471.5888	1769.2112

for the right hemisphere of all the subjects in the three situations. The signals are higher during the tasks in both environments, with the task in the real environment having higher values. The mean for the real task is 1900.2 V^2, while it is 779.8 V^2 for the virtual. The results of paired samples *t*-test with a confidence level of *p* at 0.05 showed impressive differences between three situations, as can be seen in Table 2. A comparison between the real and VR signals gave a *p* of 0.003, indicating a large difference. When results were analyzed according to sex, eye signals were higher in both environments for the female subjects. The difference of the signals between female and male subjects is statistically significant only for the virtual task giving a $t = 3.031$ and $p = 0.029$, with the mean value for male subjects being 353.4 V^2 and 1206.2 V^2 for women, respectively. These results can mean that men who had a little more experience in navigating paid more

Table 3. Power Spectrum for Alpha, Beta and Theta Rhythms in Real and Virtual Environments. The Signals are for the Right Eye (*M* = Male, *F* = Female)

	Alpha Rhythm		Beta Rhythm		Theta Rhythm	
Subject	Real (V^2)	VR (V^2)	Real (V^2)	VR (V^2)	Real (V^2)	VR (V^2)
M1	1049.8	54.8	510.8	17.6	2480.0	17.6
M2	299.3	158.8	342.3	118.8	1823.3	213.2
M3	449.4	46.2	249.6	13.7	852.6	72.3
M4	15.2	15.2	136.9	9.6	123.2	13.7
M5	745.3	320.4	835.2	249.6	2480.0	510.8
M6	1806.3	102.0	412.1	29.2	2480.0	23.0
F7	1288.8	557.0	231.0	237.2	2480.0	2480.0
F8	64.0	127.7	38.4	12.3	372.5	458.0
F9	102.0	595.4	57.8	94.1	278.9	625.0
F10	46.2	114.5	219.0	64.0	256.0	127.7
F11	269.0	691.7	179.6	269.0	1149.2	691.7
F12	54.8	23.0	21.2	57.8	449.4	114.5

attention to the task. In fact, almost all of the women were trying to walk just as in reality, instead of using only the joystick.

Alpha rhythm at 8–13 Hz have been shown to be related to the visual system and visual perception, and associated with attentional demands and degree of task difficulty. Moreover, the frontal area of the brain seems to be related to visual processing and spatial working memory [6]. The power spectrum of our signals in alpha rhythm gives an average of 515.8 V^2 in the real and 233.9 V^2 in the virtual environment (Table 3). This difference in real and virtual tasks for alpha rhythm was not, however, significant ($p = 0.145$). When EEG data were analyzed for each sex separately, there was a difference only for the male subjects, who gave lower signals in the virtual environment ($p = 0.056$). This attenuation indicates visual attention, perceptual, and judgment processing. This is probably because male subjects with little greater previous experience of exploring virtual environments knew how to “move” in the virtual environment. Female subjects’ results showed no significant difference, with four out of the six giving higher signals in the virtual environments. Again, it may be because the female subjects were trying to complete the virtual task as it was a task in the real environment.

For the beta rhythm, we looked at the 13–20 Hz band, which is usually called lower beta. This activity is encountered over the frontal region and it seldom exceeds 30 V which is in agreement with our measurements. The average power spectrum signal of the real environment is 269.5 V^2, while it is much lower (97.7 V^2) for the virtual. This is a significant difference, since the paired samples *t*-test gave a *t* of 2.695 at $p = 0.021$, without zero being at the 95 percent confidence interval of the difference. A significant difference is observed between males and females in the real task ($p = 0.032$). The difference between the real and the virtual task is also significant for the males, with $p = 0.005$. These two facts of blocked beta rhythms indicate that males sense motoric action in a greater extent in both environments [15]. We also observe a statistical significance in the difference of means between alpha and beta rhythms for the virtual task ($t = 2.678$, $p = 0.021$). This result is enhanced as well by the fact that zero is not included in the 95 percent confidence interval of the difference. The diminution of the signal in the virtual environment may be an event-related desynchronization (ERD) in our task that is a non-phase-locked response. This ERD is occurring in perceptual, judgement, and memory tasks [15], as well as in visual attention and mental effort. It seems that all the subjects place more attention for the same task in the virtual environment. This indicates a greater response to cognitive stimulation in the virtual environment. This may be because the task in the real environment is an every day task without cognitive load, while the same task needs more attention in the virtual environment.

Theta activity in the frequency range of 4–8 Hz correlates with visual perception, attentional demands, as well as with mental activities such as problem solving [6, 16]. The average power spectrum signals for theta activity are 122.6 V^2 with eyes open, 1185.4 V^2 in the real, and 445.6 V^2 in the virtual environment. The signals during the performance of the task are higher than the signal at real ($p = 0.002$ for the real and $p = 0.011$ for the virtual task), showing mental activity. It is remarkable the existence of the much higher signal in the real than in the virtual environment ($p = 0.018$). The reason may be that the task in the virtual environment followed and the subjects were already familiar with the task. The average signal for the male subjects is much lower in the virtual environment ($p = 0.02$), while it is almost the same for the female ones (Table 3). It seems that male subjects with greater previous experience in VR found less difficulty navigating in the virtual environment.

Gamma oscillations are present in the frequency band around 40 Hz, and have been reported with visual stimulation and movement tasks [11, 15]. Our measurements show activity around 40 Hz for both the real and the virtual tasks with mean values for the power spectrum 142.6 V^2 and 203.1 V^2 respectively. Their difference is not statistically significant. There is also no significant difference between the signals of men and women. These results give us the indication that all the subjects performing the virtual task feel the movement and act as moving in a real environment.

CONCLUSIONS

The present research is exploratory and its main aim was to report whether there are differences in students' experiences when they were performing the same task in both a real and a virtual environment. The assessment method is based on electrical brain activity and FFT analysis with the aim to record students' perception and cognitive activity in educational virtual environments.

Overall we have recorded differences in EEG signals and in the various rhythm bands of the subjects performing the real and the virtual task, as well as differences between male and female subjects.

Concerning the eye-movement of the subjects, all of them gave rare clipping of the EEG signals in the virtual task, showing that they were more attentive when navigating in the virtual world. This is a strong indication that users of educational software need environments that cut them off from other environmental stimuli and disturbances, setting their attention just to the computer environment. Such a context is offered by the educational virtual environments, especially those based on immersive virtual reality. The findings that male subjects showed less eye-movement in the virtual task might be because they were more experienced than women in navigating in virtual environments. A question that further research must address is whether previous experience and sex of subjects may play an important role.

Brain activity in the alpha band showed visual perception and attentional demands in both real and virtual environments. Male subjects gave significantly lower signals in the virtual task indicating a higher degree of visual attention, perception, and judgment in this environment. Here we may say that, since male subjects were more familiar than female subjects in navigating in virtual environments, previous experience must play an important role for the perception of the 3D virtual environment and the performance on the task.

Concerning the beta rhythms, male subjects showed greater motoric action in both environments. Results also showed a significant difference when subjects' alpha and beta rhythms for the virtual task were compared. This indicates that the sample placed more attention in the virtual environment as well as a greater response to cognitive stimulation.

We have also recorded theta activity in both environments, with the real task giving higher signals than the virtual. This is probably because while the virtual task followed the real, subjects were already familiar with the task and placed less mental effort. This is an indication for a possible transfer of experiences taking place between the two environments, giving a hint that virtual reality may provide educational environments suitable for knowledge transfer to real situations. The conclusion that previous experience plays an important role is confirmed by the theta rhythms too, since male subjects gave significantly lower signals in the virtual task.

In sum, the findings of the present study reported similar brain activity for the same task in both real and virtual environments in the alpha, beta, theta, and gamma band. This activity is connected with visual perception, attentional demands, and mental effort. The results thus indicate that users behave similarly in virtual and real environments. They also indicate that virtual reality provides educational environments for students to concentrate, perceive, and judge as a result of less eye-movement and alpha signal diminution. Finally, the findings give us indications that there is a need of previous experience and training for users of virtual worlds. Ours, as well as other recent research [17], proclaim that VR allows direct measures of brain activity to be made during ongoing environmental interactions. This holds considerable promise not only for neuroscience, but also for cognitive and educational research.

Our research is still in progress. The next step is the design of more complex and "strictly" educational virtual environments for the study of users' perception and cognitive activity in virtual tasks. New measurements will be carried out with the help of a multichannel EEG system, which will enable us to measure accurately specific points on the brain's lobes such as the occipital lobe where the area of visual perception is located.

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