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Evaluation of a VR system for Pain Management using binaural acoustic stimulation

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Abstract
The system proposed is oriented to evaluate the pain perceived by the user under a high controlled virtual reality environment (VR). A VR system is an implementation of a virtual world that the user perceives as the real one. The sensation of immersion affects the stimulus (visual, acoustic and haptic) perceived by the user and it is able to promote change in the brainwaves power and produce an activation of Autonomic Nervous System (ANS). The Electro-Dermal Activity (EDA) allow measuring the electrical properties of the skin by the sweat activity. This work proposes a VR environment combined with binaural beats (binaural sounds) and visual stimulus to evaluate the perception that the user has and comparing their sensation with real physiological data. It is believed that the use of different binaural beats in a long period of time can help patients to induce a relaxation state (mood) and consequently modulate the perception to pain. In this study we show two experiments. The first one applies 8 types of acoustic stimulus (4 binaural and 4 monaural) in a standard simple VR scenario and we propose the end users to select the experimented feeling they felt in any case, in parallel using the Empatica wristband we contrast the subjective users answers with physiological values given by the device. In the second experiment, an immersive environment based on the whole VR application is proposed for control and real users to evaluate chronic pain. The users are immersed in three VR equal scenarios but with random sound stimulation. With the results obtained, we can conclude that binaural beats work better than non-binaural beats if we talk about relaxation and meditation.

Keywords Virtual Reality · Brainwaves · Binaural Beats · Electro Dermal Activity · Autonomic Nervous System·

1 Introduction

In the past few years the Virtual Reality (VR) has become a popular tool for entertainment. In fact, its popularity is already growing up due to the benefits it is showing, not only in

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videogames, but also in medicine, psychology or rehabilitation tools [36, 39, 42], using commercial tools [28, 38]. Thanks to the power of high immersion that the VR has, one of the potential abilities is to be used for mood or pain management [1, 7, 12, 22, 24, 27, 41, 43]. Previous works have been done in order to explore the benefits of binaural sounds for user control and distraction [3, 5, 11, 14, 15, 23, 30–33, 40] and using functional magnetic resonance imaging (fMRI) to visualize the physiological effects [16, 17].

Although there are few studies that jointly use VR and the measurement of biological variables, it is worth highlighting the work of [13] which is a detailed study about the harmful effects of VR in people (VR sickness) and for this reason the following variables are evaluated: "Electrodermal activity, heart rate, skin temperature and respiration rate". Some of the conclusions of this work indicate that VR systems can affect the conductivity of the skin. Even though, in this work users are exposed to extreme experiences where they must control a rollercoaster which can induce a high level of vertigo and nausea. In our system, we use the latest generation of Head Mounted Display (HMD, Oculus Rift) [28] and, in addition, the scenarios do not involve movements. This way the potential problems of the VR are minimized or almost null.

Another interesting work involving the measurement of electroencephalogram (EEG) and neurofeedback is described in [26]. It is a case of a serious video game for the study and improvement of attention in children with Attention Deficit Hyperactive Disorder (ADHD). The Farmer Keeper system allows defining the aspects that could guide the design of (Brain Computer Interface) BCI videogames for neurofeedback training. Its main limitation is the small sample of participants. The study should be replicated with a much larger population to collect data and obtain a more realistic statistical significance.

In the field of pain analysis using multimedia techniques, the works of [34, 37] should be mentioned. The Android application PainDroid [34] uses multimodal functionality that could be improved with virtual reality (VR) technology and aims to help doctors or therapists to have a more objective assessment of pain. This system defines a new 3D version that was designed to run on both a portable platform and a PC. The acceptance of users is good and justifies the use of VR as a motivating tool. In the case of the system [34], the idea is to assess the intensity of pain but by analyzing face expressions. The objective is to objectively quantify the intensity of the pain and how it is perceived by the observers and experts. The methodology achieves 87% accuracy rate for classification of frames amid four levels of pain intensity.

Up to our knowledge, only few works considered binaural sounds as alternative new brain training technique. Even in some studies to indicate that, a technique does not work [9]. Fortunately in this work the exposure to the binaural sounds is very short (three minutes) and the sample used very small (14 people). In [19], we have a more exhaustive experiment using a 6 Hz binaural beat stimulus of 10 min that was suggested as a meditative state inductor stimulus.

We do not know any previous work that combine VR systems and binaural beats in order to modulate the mood states (relax vs active) and apply these benefits to chronic pain control. It is on this field where this work is classified. The purpose of this work is to create an interactive VR system which combines the power of VR with other multimedia technologies such as sounds (binaural), music or colors, to study how they can affect to mood state and also to the brainwaves and how they are sensed by the users. Also, a new evaluation method is considered. The Electro-dermal Activity (EDA) will be controlled in all the process of VR multimodal stimulation. With the EDA bio-signal we can compare subjective user perception against physical parameters variations. We would like to proof that the results of this system can lead to a VR application for pain management or others similar pathologies using physiological signals.

This work has the next structure. In section 2, brainwaves, electro-dermal activity and binaural beats will be explained. In section 3, the experiments and its methodology will be presented. In section 4, the results of the two experiments proposed will be shown and interpreted. Finally, in section 5, the conclusion and the introduction for future work will end this document.

2 Theory

In this study there are two key components that stand out among all the technology and concepts used. These are the binaural beats stimulus and bio signal (electro-dermal activity, heart rate, temperature) monitoring as evaluation tool of mood and/or pain perception. The combination of both techniques is implemented using a VR application. Our hypothesis is that binaural sounds can modulate the power of brain waves and reduce the electrodermal activity in order to change the mood to a more relaxed state.

2.1 Brain waves and electrodemal activity

The concept of brainwaves refers to all the electrical activity that takes place in the brain generated mostly for the brain cells (neurons) that can be measured with an EEG [33]. Active pyramidal neurons produce local current flows that travels through dendrites. EEG is capable to record the current flows due to the scalp electrodes, which amplify the electrical signals that penetrates the skin and skull. Finally, those signals are saved and displayed on a paper or screen in a wave form. Brainwaves commonly have a sinusoidal pattern with an amplitude range of 0.5 to 100 μV. Depending on their frequency, brainwaves are classified into five basic groups: Delta (0.5-3 Hz), Theta (3-8 Hz), Alpha (8-12 Hz), Beta (12-40 Hz) and Gamma (40-100 Hz). The brainwaves change depending on the human and psychology state and behavior. See [6] for more EEG details concepts.

The Electrodermal Activity (EDA) or also Skin Conductance (SC) is a reliable physiological signal for monitoring the sympathetic nervous system. Several studies have demonstrated that EDA can be a source of effective markers for the assessment of emotional states in humans [8, 34]. The EDA is simply the electrical properties of the skin as determined by sweat gland activity. The EDA or GSR (Galvanic Skin Response) activity is typically measured in "micro-Siemens (μS)" or "micro-Mho (μM)". Sweat secretion and the associated changes in skin conductance are unconscious processes that are solely under sympathetic control and reflect changes in arousal. In emotional situations, bodily processes are triggered automatically: The heart beats faster, the pulse rises, hands become sweaty.

There are two main components to the overall complex referred to as EDA. One component is the general tonic-level EDA which relates to the slower acting components and background characteristics of the signal. The most common measure of this component is the Skin Conductance Level (SCL) and changes in the SCL are thought to reflect general changes in autonomic arousal. The other component is the phasic component, and this refers to the faster changing elements of the signal - the Skin Conductance Response (SCR). Crucially, it is important to be aware that the phasic SCR, which often receives the most interest, only makes up a small proportion of the overall EDA complex [4, 8]. We are interested in Event-Related

SCR (ER-SCR) that can be attributed to a specific eliciting stimulus. More technical aspects about SCR complex and their application is found in [2, 10, 18].

In our proposed VR system, we can measure these parameters (SCR, Heart Rate, and Temperature) in real time with the Empatica wristband device [37]. We assume that if you expose, to by example a fear inducing stimulus, your sweat secretion and heart rate, increase and your arousal state is changing. Using a specific set of stimuli (acoustic and/or visual) we can measure the skin conductance and give a biofeedback to user in order to modulate their mood state. The study of EEG variations respect to binaural stimulus is delayed to a future work due of complexity of combine VR helmet with and standard 10-20 electro encephalographic hat.

2.2 Binaural beats

There are many ways that the brainwaves can be changed by using external stimuli in order to induce to the states mentioned above such as colors, sounds, music or human contact. One of the newest techniques proposed to do that is by making use of binaural beats. When two sinusoidal waves (tones) at a different frequency enters through the right and left ear respectively, the brain perceives a third illusory tone with a frequency that equals the difference of the other two in absolute value, called binaural beat [5]. For example, if we play a 70 Hz tone at the left ear and a 72 Hz tone at the right ear, the brain will perceive a binaural beat with a frequency of 2 Hz. While listening to binaural beats, the brain will try to adjust its own brainwave to the frequency of the external stimuli [5]. So, with this hypothesis in mind, it is relatively easy to be induced to a desired state. If we want to be induced to a relaxed state, we simply need a binaural tone with a frequency that matches the alpha brainwaves (8-12 Hz) or delta (0.5-3 Hz).

It is pertinent to mention that, for a better perception of the binaural beat, the two tones listened in each ear should have a difference frequency of less than 35 Hz. In [5] we can see the main differences between monaural and binaural beats. So binaural recording is a very special implementation of stereo sounds where we can guaranty that only one different frequency beat is presented in every ear. Conventional stereo or 360 sounds can't guaranty this condition with several loudspeakers.

In addition, in [5] the authors give a brief overview of research of auditory steady-state responses. In this work, we show the main differences between monaural and binaural sounds. A very important conclusion is that the neurophysiological processing of binaural sounds differs slightly from monaural. In binaural beat the central interactions occurs in the superior olivary nuclei. Thus, the binaural beat percept is caused by the major neural mechanism which enable sound localization. For our purposes in the VR system developed, we are interested to mood/pain modulation but from [5] also suggest that a cognitive effect of binaural sounds can be extended to memory, creativity and attention.

In short, an individual can get a better state of relaxation, creativity or focus by using the appropriate binaural beat [3, 5, 40]. For previous work about the effectivity of binaural beats to induce a frequency following response (FFR) in brain wave activity please check [6]. About Serious Games and Neurorehabilitation methods please check these references [24, 26].

This work is a new implementation of a previous preliminary system (please check [31] for first VR system) that use EDA measures in order to compare with subjective user perception. The new contributions from previous work is the use of objective biosignals values in order to obtain objective measurements to evaluate the pain variation. In addition, we use a basic Pain Assessment Questionnaire (PAQ) [35] before and after therapy.

3 Methodology

In this work, a whole VR application, made with the videogame development platform Unity [38], is presented. On that serious game, the player is listening binaural beats (combined or not with music) meanwhile you are exposed to a VR environment. As shown in fig. 1, on one hand the player interacts with the VR environment using Oculus Rift and Oculus Touch. The first are used for seen the environment and listening to the background music. The Oculus Touch is used to interact with menus, selecting the session and parameters to do and to see what time last to finish the game.

On the other hand, the player interacts also with the Empatica E4. This wristband is connected to a server which storage the EDA and HR values of the user (Temperature is discarded for this study). Also, an E4 client (using a TCP connection) demands that information to the server in order to save them with a timestamp related to each player who plays. Finally, the Oculus Rift and Touch interact with the VR Environment where the game is developed.

The immersive experience is controlled by our VR application script. Whenever the player starts the application, it enables the Oculus and the Touch devices to be able to interact with the VR system using the *OVRAvatar SDK* [29]. Then, the main menu is shown to the user. This main menu brings to the player the interaction where he is able to select the session he wants to start and the technical information about each session possibility. So now, is player turn to choose a session. When a session is chosen, a script setup the session with the parameters for the session chosen. Once the session is setup, an external Unity asset called *Koreographer* [21,] is used to enable the synchronous movements between the object located at the center of the environment and the background music presented to the player. Furthermore, at this point, another external Unity library, called *AccelBrainBeat* [21] is used to manage the binaural beat combined with or without the background music, depending on the session chosen previously.

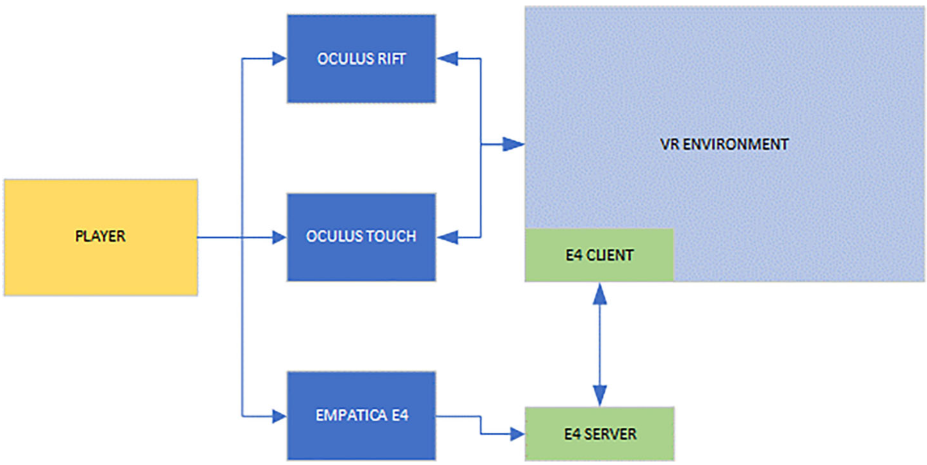

Fig. 1 System interaction

Instantly, the game starts a TCP connection between the E4 wristband server, located at the same computer as the VR system, and the E4 wristband client that is the wristband itself placed at player's wrist. This connection keeps working on background meanwhile the session is running storing EDA and HR information to be studied once the session is finished by the researchers.

Therefore, at this point, with the background music synchronized with the environment, binaural beat operative and E4 wristband ready to record player's information, the session starts. As it is going to be explained on the afterwards parts of this paper, this session is going to last X minutes depending on the experiment that is going through. Meanwhile this session is running, the E4 system is recording and storing information on the server that is been stored with an ID that identify this information to the player who is doing the experiment. That information is going to be analyzed to proceed the research.

Finally, whenever the session ends, depending on the minutes chosen to last, the VR application closes the socket used to the TCP connection between E4 wristband and E4 server, stops the background music along the synchronous movement with the environment and finishes the session. In consequence, the user is returned to the main menu and now it's the user turn to choose to start another session or exit the game.

The whole immersive experience has been developed following the flowchart shown in fig. 2.

The whole system has sessions with fixed values of binaural beat, music, colors and objects shown on the screen. As you can see on the fig. 3, there are 8 different sessions and, on fig. 5, is shown to the user (when he presses the information button) the technical parameters that makes that session unique and different from another seven possibilities. Each session has its own features that are distinctive from the others. First of all, each session has a changed environment where the immersive experience took place. In fig. 3, 3b and 4, 4b can be seen different environments: a lake (fig. 3b), a meadow (Fig. 4) and an office (fig. 4b).

Besides, each mode has different binaural beat combined with various types of music. What is more, the colors of the object viewed on the middle of the environment are also another gradient at each game. Incidentally, we must not forget that each session has particular countdown timer to finish. These distinctive features shown each technical aspect/parameter for each session. Moreover, there is a free mode where the player has the power to change whatever he wants to make his own experience of the virtual environment as shown on fig. 6.

The full menu is designed to bring the user the possibility of personalize factor of the experience. On the left, he has the capacity to choose between the 7 possible environments: lake, meadow, space, office, classroom, meeting or study. As well as the gradient colors of the object seen. If the players press the "X" button he can also change the object presented.

On the left, he has the explanation of the free mode and the authority to exit the game. Finally, on the center, he has the control of binaural setting as the predefined configurations or the slider to do it manually. Furthermore, he is able to pick one of the six songs configured on the game. Considering this, the player is capable to perform his own experience.

In all experiments proposed, Bioethics Committee of the University of Balearic Islands approved the protocol used. Before the experimental sessions, written informed consent was obtained from each participant (or legal tutor) after all the details of research (except the hypothesis) were explained to them.

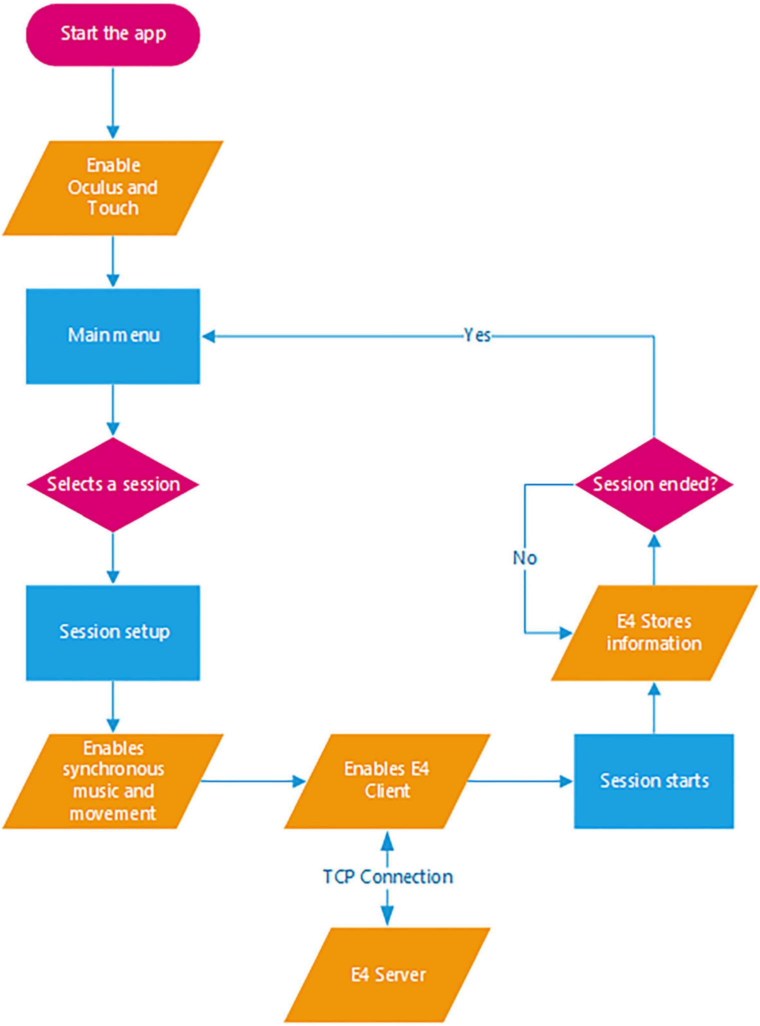

Fig. 2 VR Environment flowchart

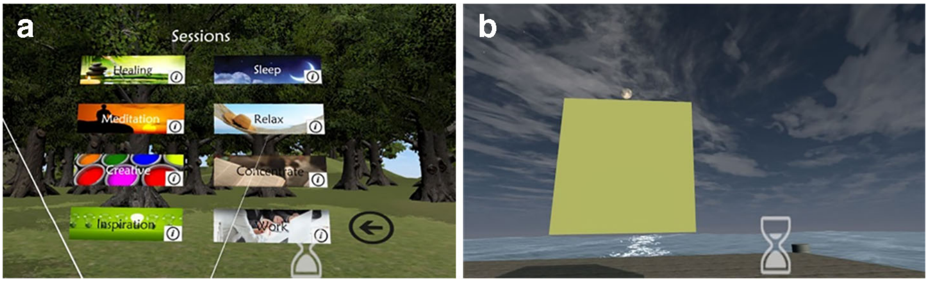

Fig. 3 **a** Session selection is shown. **b.** Lake Environment is shown

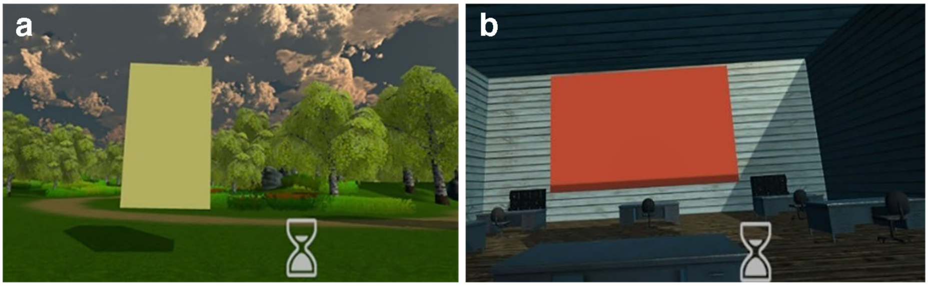

Fig. 4 **a** The Meadow Environment is shown. **b.** The Office Environment is shown

3.1 Case 1: Subjective pain perception vs eda validation

3.1.1 Application setup

In that case, a simple experiment has been done. It involves the listening and the classification of various binaural beats while watching a ball changing its color and its size in middle of scenario. The choices as well as the success rates made by each end-user are saved in a file in execution time.

The HMD used is Oculus Rift combined with Oculus Touch [28] for getting a proper interaction. The purpose of the experiment is to verify if in this technology combination mentioned before, the binaural beats have a relaxation or meditation effect, comparing the influence of binaural beats and non-binaural beats with a simple test. In this experiment the VR environment remain the same all the time that the user is hearing the binaural sounds. Our work initial hypothesis is based on the idea that relaxing binaural sounds combined with VR environments can reduce the beta power values and increase the alpha and theta power values in the brainwaves. We have the EDA and Heart Rate values from Empatica E4 wristband [37]. If the user can modulate (beta decrease) their EEG power signal values also we can assume that EDA and Heart Rate decrease by the effects of binaural sounds. In Fig. 7 and 7b we can view the whole scenario, menus and setting options.

Fig. 5 Sessions components with specific parameters (music, colors and binaural sounds)

Fig. 6 A free mode menu (with all settings). Color, Environment, Binaural and Music Settings

3.1.2 Participants

After rigorous psychometric screening for bio–psycho–social health, $N = 10$ young university students (4 females) entered in a within–subject randomized. The age range of 18-23 years old and an age average of 21 years. All 10 students participate separately in two sessions hearing real binaural sounds (verum) and placebo monaural beats.

We have a previous pilot study [31] with the same environment but without the use of biological signals in order to compare if subjective impressions of the user have correlation with EDA and heart rate values. So, this new data is very important in order to guarantee the effectivity of the binaural sounds for mood modulation. The temperature value is not considered in this experiment because the variation is too small and the heart rate and EDA changes are more significant.

From previous works we have several choices about the time needed for binaural beats. Some works [3, 5, 40] use a minimum time of 25 min. Others consider 5 min enough to achieve the effects of brain synchronization [31]. In our experiment we use 5 min per binaural beat and 2 min without non-visual (black wall) and auditory stimulus between beat modes. Also, we don't add any sound additional to binaural beat (pink noise, melody, etc.). It is recommended that the user not perform many movements or be as still as possible. We record EDA parameters from 1 min before starting stimulation and 1 min after finishing the experiment. That means that the whole session lasts 28 min of stimulus and rest states plus 15 min for initial procedure experiment explanation.

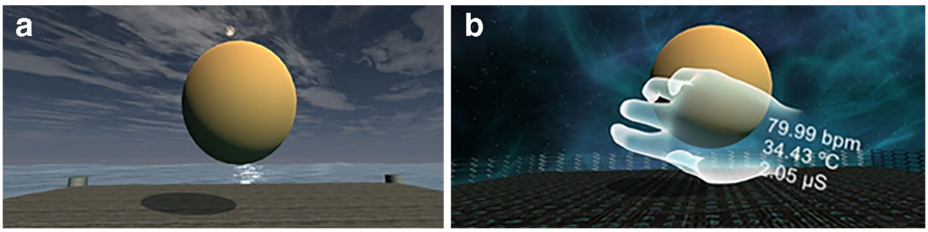

Fig. 7 **a** A standard VR environment used.**b.** VR feedback of biosignals values

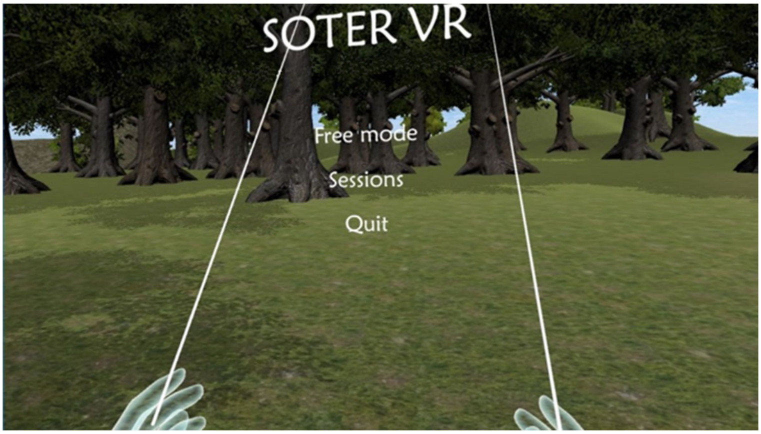

Fig. 8 Main menu

3.1.3 Procedure

The present research has been done in a highly controlled laboratory study with no interference from other users and stimulus. The experiment has two sessions, each one differenced in the binaural beats the user must listen and classify. Half of the participants do session 1 (verum BS) and the other half do session 2 (Placebo). So, in each session, the end-user starts the session, listen and classify four binaural beats and finish the session. In the start of a session, a little menu with a button appears asking the user to start the test. When the user pushes the button, a binaural beat (or placebo) starts to play. The end-user has to listen it for 5 min.

Once the time has finish, the user must classify the sound with an interactive menu, selecting one of the default binaural beat modes (feelings) [5, 25] that he or she felt thanks to the binaural beat and the VR environment.

The available feelings the user can choose are: Healing (H), Sleep (S), Meditation (M) and Relax (R) for the relaxation category; and Creative (Cr), Concentration (Co), Work (W) and Inspiration (I) for the concentration category. Once it is classified, the user must wait for the next binaural beat to be played for 2 min to avoid the carry-over effect. This process is repeated

Fig. 9 Sessions menu

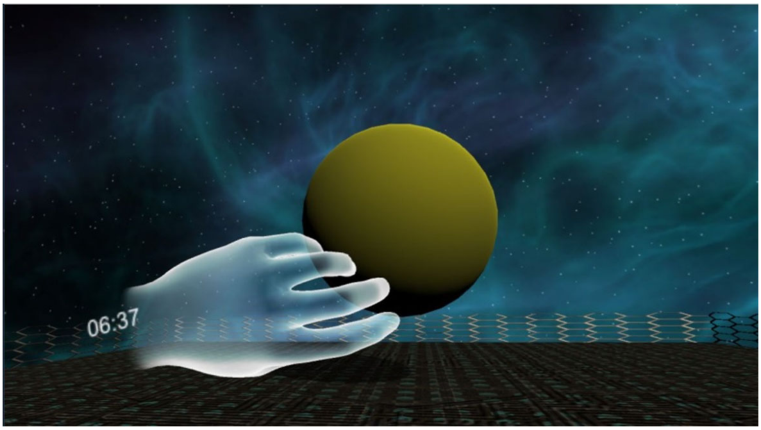

Fig. 10 Common scenario

four times and the session ends with a thanks message. During all this time, the EDA and heart rate is recorded every 10 s.

As mentioned before, two sessions are required. Session 1 allows to classify four binaural beats modes for relaxation and meditation. Session 2 plays four beats but without any difference frequency. That fact helps to determine if playing real binaural beats causes any peculiar feeling than playing normal beats.

Those modes are shown in Table 1. In the meanwhile, the user's avatar will be standing or sitting in a virtual platform located in outer space. The results of one session are saved. In this file, the name of the user, the choices he or she had made (with a timestamp) and the success rate (for session 1 or session 2) are stored and also the Empatica wrist band values (one value every 10 s).

3.1.4 Results

From previous study [31] most of the choices were done in the right category. Just 9 of the 40 choices (approx. 20%) were concentration modes, while 31 of the 40 choices (approx. 80%) were relaxing modes. It indicates that the end-users felt that they were relaxed or in a meditation state (the purpose of those binaural beats), but they could not hit the market with the right binaural beat mode. See [31] for more accurate details. In the previous work we don't use the EDA registrations to confirm this subjective selection.

Table 1 Binaural beats modes used in the experiment. Session 1 plays green binaural beats. Session 2 plays blue placebo beats

Binaural mode	Left frequency (Hz)	Right frequency (Hz)	Difference frequency (Hz)	Affects
Healing	88.00	80.00	8.00	Alpha
Sleep	73.00	75.00	2.00	Delta
Meditation	89.75	85.25	4.50	Theta
Relax	85.50	75.50	10.00	Alpha
Beat 1	82.00	82.00	0	None
Beat 2	91.20	91.20	0	None
Beat 3	87.55	87.55	0	None
Beat 4	89.00	89.00	0	None

In this paper the experiment done try to validate the subjective selection against the EDA variations values respect to binaural or placebo sound stimulus in the VR environment.

We have the following results by subjective user selection (Table 2).

From session 1, real binaural stimulation, the end users select the R and S mood with a 40% of successfully. Only a 25% of selections are outside of relaxing binaural tones. The 75% of selections done are related to relaxing tones (R = Relax, S=Sleep, M = Meditation, and H=Healing).

From session 2 (Table 3), non-binaural sound, the end users select more active tones (Cr = Creative, Co = Concentration, W=Work, I=Inspiration). Near 50% selections are from active tones. The placebo sound stimulus doesn't induce relaxing states in the 60% of users.

If we consider the EDA and heart rate values for every period (mean values, we can see the results in the Table 4, where we can observe that placebo sounds don't induce EDA reduction. The user 1 starts with an EDA = 0.2 μSiemens and the final state is EDA = 1.36 μSiemens. That means that the user 1 is in a more activate state, which confirms the user subjective selection. Except user 3, all users increase the activity feeling.

In the case of user 6 (Table 5), who has 2 wrong mood state selections, the EDA values confirm a decreasing tendency. The Starting EDA is equal 1.45 μSiemens and the final EDA value is 0.54 μSiemens. That means that the user moved to a relaxing mood state. In some binaural sounds the user also has very low EDA values (0.04 μSiemens).

The other users have similar variations except user 10 that start with a high EDA value and select active states, in any case this user finished with a lower EDA value (17.83 μSiemens).

In the Table 4 and 5 we can see also the EDA mean values for every group. For the heart rate values, we can't conclude any significant variations because all users are inside the range (55-75 ppm), which are normal values for low cardiac activity range. Of course, we need to extend the users data base and more test must be done to confirm that EDA parameter is significant to classify the mood state of the person.

3.2 Case 2: Pain management evaluation in childrens

3.2.1 Application setup

In this second experiment, a serious game based on the whole VR application, explained in the previous section, has been developed. In this case, our serious game has only two options to be selected on the menu. The patient can choose between the experiments or go through the free mode as it's shown in fig. 8.

Table 2 Choices from session 1. In red considered wrong selection category

Subject session 1	R	S	M	H	Success Exact/Category
Subject 1	S	S	S	R	25%-100%
Subject 2	Co	R	Cr	Wo	0%-25%
Subject 3	M	R	R	S	0%-100%
Subject 4	R	Co	S	Wo	25%-50%
Subject 5	R	S	R	S	50%-100%
Success	40%	40%	0%	0%	

Table 3 Choices from session 2. In red considered in concentration category

Subject session 1	Beat1	Beat2	Beat3	Beat4
Subject 1	Co	W	Co	W
Subject 2	W	Co	M	I
Subject 3	M	M	Co	M
Subject 4	R	M	R	Co
Subject 5	W	R	W	Co

That game has been developed to be used as an experiment. Once you have pressed the session button only one option is shown to the patient as is exemplified in fig. 9.

Whenever the patient presses the environment button, a random environment selected from 3 possible is started as a game. The three environments share the same view: the player is located at a platform on the space where he can see a sphere bouncing and changing it color synchronously as a 4 by 4 beat using *Koreographer*. On background, he can look at a skybox full of stars that try to imitate the space as shown in fig. 10.

Then, each scenario has distinctive features. The first scenario has only the environment explained before with any kind of stimulus. Therefore, the second scenario has also classical music as a background sound. In fact, the music played is Canon in D major of Pachelbel. Eventually, the last scenario has the same song and an Alpha binaural beat as background sound. Indeed, it has 100.22 Hz on the right ear and 91.22 Hz on the left ear (9 Hz difference). This beat is played around 40 dB intensity in each ear in order to be listened but not as a noise (low intensity).

These three scenarios appear randomly but only once when a player presses the start button. Last but not least, each patient has done the three scenarios in a random sequence at each session he does of that experiment. This patron is chosen doing a random value between 0 and 3, and then recalculated erasing the last value as a possible one. Finally, the last value that has

Table 4 Comparative EDA evolutions values for placebo user. P1 (Placebo 1), 2′(2′ black), P2(Placebo 2), P3(Placebo 3), P4(Placebo 4), µS(microSiemens), W(Work), Con(Concentrate), Med(Meditation), Insp(Inspiration) and Rel(Relax)

	EDA t_0	P1	2′	P2	2’	P3	2’	P4	EDA t_{end}	EDA t_0-t_{end}
User1										
GSR (µS)	0.20	0.19	0.69	0.48	0.26	0.21	0.82	0.58	1.36	−1.16
Mood Selected		Con		W		Con		W		
User2										
GSR (µS)	0.37	0.54	0.73	0.86	0.80	1.30	1.06	1.21	1.51	−1.14
Mood Selected		W		Con		Med		Insp		
User3										
GSR (µS)	0.38	0.28	0.28	0.30	0.29	0.28	0.27	0.29	0.17	0.21
Mood Selected		Rel		Med		Rel		Con		
User4										
GSR (µS)	0.33	0.4	0.43	0.57	0.47	0.62	0.68	0.85	0.85	−0.52
Mood Selected		W		Rel		W		Con		
User5										
GSR (µS)	0.75	0.45	1.9	0.92	1.60	0.72	0.66	0.61	2.87	−2.12
Mood Selected		Med		Med		Con		Med		
User Mean										
GSR (µS)	0.41	0.37	0.81	0.63	0.68	0.63	0.70	0.71	1.35	−0.95

Table 5 Comparative EDA evolutions values for binaural user. P1 (Placebo 1), 2′(2′ black), P2(Placebo 2), P3(Placebo 3), P4(Placebo 4), μS(microSiemens), W(Work), Con(Concentrate), Med(Meditation), Insp(Inspiration), Rel(Relax) and Cre(Creation)

	EDA t_0	Relax	2'	Sleep	2'	Meditation	2'	Healing	EDA t_{end}	EDA t_0-t_{end}
User6										
GSR (μS)	1.45	1.30	0.46	0.31	0.09	0.05	0.04	0.11	0.54	0.91
Mood Selected		Rel		Con		Sleep		Work		
User7										
GSR (μS)	4.13	4.32	5.27	3.81	5.31	5.74	4.28	4.75	4.42	−0.29
Mood Selected		Med		Rel		Rel		Sleep		
User8										
GSR (μS)	4.65	6.88	3.85	3.22	4.20	3.01	2.66	4.07	3.94	0.71
Mood Selected		Rel		Sleep		Rel		Sleep		
User9										
GSR (μS)	10.76	4.56	7.24	6.32	7.07	6.46	11.9	9.01	9.17	1.59
Mood Selected		Sleep		Sleep		Sleep		Rel		
User10										
GSR (μS)	18.92	30.37	29.05	29.05	20.33	18.62	21.45	19.27	17.83	1.09
Mood Selected		Con		Rel		Cre		W		
User Mean										
GSR (μS)	7.98	9.49	9.17	8.54	7.40	6.78	8.07	7.44	7.18	0.802

not shown, is selected as the last game played. Therefore, the game reads these three values to know in which order will be the scenarios presented.

3.2.2 Participants

After rigorous psychometric screening for bio–psycho–social health, we chose $N = 18$ teenagers with an age range of 7 to 16 years old and an age average of 12.38 years. After that, the patients had been divided in two groups. The first group as control formed by $N = 8$ with a null pain baseline, and the second group formed by $N = 10$ composed of the subjects who manifested pain in the pretest. Those in the pain group had a rheumatic disease (Behçet and juvenile idiopathic arthritis). All subjects of both groups participated in the same three sessions randomly sequenced. These three sessions share the same environment with different factors. As seen in the case 1 of this study, we are taking into account the EDA and heart rate values. Added to that, we have measured the temperature variation. We use the EDA and heart rate measures to figure out the relaxation level of the user. We used faint colors because of their neutral emotional effect on patients, which can help with relaxation [20].

As said before in the last experiment, minimum duration to be exposed to a binaural beat isn't clear. In our case we use a 7 min session given that is a medium value but no so long to cause fatigue in children subjects. Consequently, the whole duration of the experiment is 21 min for each patient due to the 3 sessions done. In this experiment is defined a difference in front of the previous, the binaural beat is sounding along to a melody at the same time.

3.2.3 Procedure

The present research has been done in a highly controlled laboratory study with no interference from other users and stimulus. The experiment has three sessions, in the first one the only stimulus is the environment and it is muted, the second one has the environment plus

Table 6 Intrasubject design comparing each variable

Group	RV(NoSound) A	RV + Music B	RV + Relax(BS) C
Pain test	2.85	2.50	2.10
Heart Rate change	17.07	−4.31	−9.87
Temperature	0.96	0.52	0.48
EDA	3.08	2.61	2.50

background music, and the third one has the environment plus background music mixed with binaural beats. All of the participants do all the sessions but in a random order to prevent the carry-on effect. The music of choice is the Pachelbel's Canon in major D as a previous study confirmed it induces a neutral state of tranquility [4]. The main goal of using three different VR sessions is to analyze which one produces a bigger effect in decreasing the pain.

Before starting, the subject has to answer a simple question valuing his pain in that moment from 0 (zero pain) to 10 (the worst pain), and the same procedure every time one of the randomized VR sessions ends. We also collect physiological data mentioned earlier, that way we can analyze subjective but also objective information. The intrasubject design of the three session include the virtual environment whit the options: Mute, Music non-binaural, Music and binaural sounds.

3.2.4 Results

As mentioned earlier, previous studies showed improvements in pain related with the use of VR or binaural beats [18, 26, 38]. In this case, the results reveal that the combination of VR plus binaural beats works much better than the other two categories. In the case of variables such as temperature or heart rate we do not take whole measures because each person has a different baseline, so we work with increases or decreases, that is, with differentials.

Combination 1. Environment The combination using just VR, without music or BS, in all cases the baseline pain decreased, that is, the pain with which they arrived. In a few cases it did not decreased after seven minutes of session but remained the same, it means, it did not increase. Before the session the average of baseline pain measured with the pain questionnaire was a 4.55 out of 10, were 0 was feeling good and 10 the worst pain they had ever felt. On the other hand, the average measured pain after using VR was 2.85 out of 10. The improvement is a 1.7 points.

Regardless of the order used in the sessions because they were random, during the use of this session there is an average increase measured with the E4 of 17.07 beats per minute above baseline. There is a temperature change of 0.96 °C upwards, almost a grade. Temperature increase is related with relaxation. Finally, the EDA has a value of 3.08 μSiemens.

Table 7 Comparing each variable differentiating by group: pain group in blue and control group in purple

	A	B	C	A	B	C
Heart Rate	30.48	−8.25	−7.06	3.66	−0.37	−12.68
Temperature	1.25	0.58	0.57	0.67	0.83	0.47
EDA	2.66	2.17	2.27	3.23	3.02	2.70

Combination 2. Music The average pain after using this session was 2.50, which corresponds a 20% improvement above baseline. The average change of heart rate is −4.31 beats per minute below baseline, which shows a sing of relaxation. There is a temperature change of 0.52 °C upwards. Finally, the EDA has a value of 2.61 μSiemens.

Combination 3. Relax The average pain after using the sessions combining VR, music and binaural beats was 2.10, which corresponds a 20.40% improvement above baseline, which is a statistically significant change. In this case, the average change of heart rate is −9.87 beats per minute below baseline, which indicates a decrease of almost ten beats per minute after seven minutes of session. There is a temperature change of 0.48 °C upwards. Finally, the EDA has a value of 2.50 μSiemens. This shows an improvement above the Environment session. As it mentioned above, we need to extend the users data base and more test must be done to confirm that EDA parameter is significant to classify the mood state of the person and get to know if this change is significant.

The boxes in Green (Table 6) show improvement in the results after the use of every session. In general terms, the relax session is the one with more profits, which shows that the combination of virtual reality plus binaural beats is effective. In the second place, the virtual reality mixed with music still shows profits. Which also makes the VR sessions but not as much as the other two. This difference is important because it goes from an average pain of 4.55 out of 10 to a pain below 3 in all cases, so there is a pain decrease indicator of VR's effectiveness. Of the three sessions, the one that works best is C, which combines VR and BB.

If we compare the results of both groups, we can see similar outcome. The heart rate change is consistent in both groups. As decrease the heart rate and EDA values, this is an indicative of relaxation. Finally, we can see less sweating in the pain group, which can be produced due to the effect of the VR system. It could mean that works better in people experiencing pain.

As we can observe in Table 7 there is a heart rate increment in session A in both groups, control and pain group. Even so, it is curious the big difference between session A of the pain group and the rest of groups, since there is an increase of 30.48 beats. In the rest of the combinations is observed a decrease in beats, which, as explained previously, is related to relaxation. Although this fact is positively related to our hypothesis, it is interesting that in future studies the reason why the VR produces an increase is determined. The implications of the combination B and C is highlighted positively.

Regarding temperature, we understand that an increase in temperature is indicative of a state of relaxation in the participant, which is related to a decrease in pain. We can see that all the results show an increase in temperature and, therefore, it can be considered that their level of relaxation has improved. Interestingly, session A of the pain group shows the greatest increase.

On the other hand, in all cases there is an increase in sweating (EDA). This is in all groups and in all sessions. The results obtained do not seem to indicate a decrease in activity, although all of them have shown a decrease in pain in the questionnaire.

On the other hand, in the case of sweating (EDA) we can observe in Table 7 a variation that seems to be unrelated to the session used, but instead in the Table 6 it can be seen that, as with the heart rate and the temperature, the best results are obtained in sessions B and C. All the results obtained in the different variables indicate that the session that works best is C, which combines VR and BB. The EDA is also an indication of relaxation [35] and these results fit with the pain questionnaires answered by the participants that indicate that session C is the one that reduces pain the most.

4 Conclusions and future work

The work introduced allows to analyze in a more objective way how the binaural beats combined with the VR technology can influence the emotional state or mood and consequently the pain perception. We have developed a complete VR system with different scenarios and multiple configurations. The systems have been evaluated with two users' groups. A psychometric screening for bio–psycho–social health of young university students is selected for first experiment. The end-users had listened to some binaural and non-binaural beats while they were in a passive VR environment. They classified them depending on their psychological state and the emotion they felt. The biosignals recorded (EDA, Heart rate) allow us to obtain some more objective conclusions. We can conclude that some binaural sound can induce relaxation mood because we observe a reduction EDA values.

The second experiment is oriented to evaluate chronic pain in children. We have a control group and initial reduced set of real users. We have applied three sessions, varying some variables, were we recorded biosignals with the E4 Empatica Wrist Band (EDA, heart rate and temperature). We also passed a test to the participants where they valued their pain perception at different moments. This combination of data sources allows us a greater reliability. In this experiment, the based pain line mean decrease in 1.7 points.

With the results obtained we can conclude that binaural beats work better than non-binaural beats if we talk about relaxation and meditation. The subjective perception is confirmed with bio signal values for relaxing mood states. The number of users is not enough to conclude general affirmations. In this study the users hear only binaural beats or placebo but not both sounds, so we need to extend the evaluation to all combinations in order to increase the reliability. Also, we think that we need to evaluate the time exposure to binaural beats more carefully using more cases and different time exposure and other binaural sounds sets. In the majority of the cases the pain questionnaires' results agree with the physiological data, but there is a contradictory case (1 out of 12), this is the case of VR (session A) and heart rate variable. We assume that this is a preliminary study and the conclusions are limited because it is a reduced sample. In a future study we expect to increase the sample.

For future work, it would be interesting to test all the possible stimuli combinations in different experiments (sounds, colors & objects motions, haptics, etc..). The next VR environment will include an EEG wireless 8 channel system in order to evaluate objectively the power wave variations and brain connectivity variations and to proof if these sound stimuli really produce a stable variation of EEG signals.

Finally, our idea is to develop a VR videogame environment, which will include sessions for relaxation, concentration, meditation…, each one with its own binaural beat mode, range of colors, background music and even environment (space, beach, mountain…). It will also implement a free mode, in which the user may explore and customize all the technology mentioned to find his or her favorite combination for self-training (biofeedback).

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