A Neurophysiological Approach for Measuring Presence in Immersive Virtual Environments

Arindam Dey*
University of Queensland
Australia

Jane Phoon†
University of Queensland
Australia

Shuvodeep Saha‡
CSIO
India

Chelsea Dobbins§
University of Queensland
Australia

Mark Billinghurst¶
University of South Australia
Australia

Abstract

Presence, the feeling of *being there*, is an important factor that affects the overall experience of Virtual Reality (VR). Higher presence commonly provides a better experience in VR than lower presence. However, presence is commonly measured subjectively through post-experience questionnaires, which can suffer from participant biases, dishonest answers, and fatigue. It can also be difficult for subjects to accurately remember their feelings of presence after they have left the VR experience.

In this paper, we measured the effects of different levels of presence (high and low) in VR using physiological and neurological signals. The experiment involved 24 participants in a between-subjects design. Results indicated a significant effect of presence on both physiological and neurological signals. We noticed that higher presence results in higher heart rate, less visual stress, higher theta and beta activities in the frontal region, and higher alpha activities in the parietal region. These findings and insights could lead to an alternative objective measure of presence.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Empirical studies in HCI; Human-centered computing—Visualization—Visualization design and evaluation methods

1 Introduction

Virtual Reality (VR) is a technology that enables users to be immersed in a fully computerised simulated environment, with interaction capabilities similar to that of the real-world and beyond. The experience of being in a virtual environment (VE) is largely affected by the feeling of *presence* [27, 64] and *being there*, while physically being in a different location [1, 48].

Earlier studies have indicated a few factors that positively influence presence in VR, such as the availability of multi-sensory input [14], audio spatialization [4], avatar fidelity [33], and interactivity [42], among others. There are also multiple validated questionnaires that are widely used to subjectively measuring presence in a Virtual Environment (VE).

Several of the most widely used questionnaires have been developed by Slater et al. [52] and Usoh et al. [60], as well as Witmer & Singer [64]. The questionnaire developed by Slater and Ushoh et al. (commonly known as the Slater-Usoh-Steed (SUS) questionnaire) measures overall presence using six descriptive questions themed around three main areas – the sense of being there, the VE becoming a reality, and remembrance of the VE as a place in reality. Witmer & Singer's questionnaire collects the degree of presence felt by the individual in six sub-scales—involvement, natural, auditory, haptics, resolution, and interface quality—as well as the amount of influence over the four factors of control, sensory, distraction, and realism have on the experience [64]. Schwind et al. also provides a comprehensive list of 15 published questionnaires [48] that measured presence in VE.

While questionnaires are a widely used instrument in human-based research, the responses can be biased [8] and dishonest [16]. Slater noted that post-experience presence questionnaires cannot be heavily relied on and that researchers should consider alternative methods [50]. This is because leaving the VE to answer the questionnaire causes a break in presence (BIP), which in turn confounds the responses [46]. Schwind et al. found that answering presence questionnaires within the VE yields different results than answering them outside of the VE [48]. These findings provide the core motivation of the current research, which is to investigate both the neurological and physiological effects of presence as an alternative measure.

There have been some earlier efforts in measuring presence using physiological signals. For instance, Meehan et al. proposed physiological measurements—using heart rate, skin conductance, and skin temperature—of presence using a scary VR environment [37]. They noticed change in heart rate and skin conductance. Whilst, Wiederhold et al. found significant correlations between presence questionnaire ratings and heart rate and skin resistance [63].

However, there has not been much previous research in terms of utilising neurological signals to measure presence within VEs. An earlier study using Functional Magnetic Resonance Imaging (fMRI) identified different types of neural activity in adults and children in response to high and low presence non-interactive VEs [2]. Kober et al. [29] identified a positive relationship between presence and parietal brain activation and a negative relationship between presence and frontal brain activation. Recently, Jeunet et al. [28] identified neurophysiological markers of sense of agency in VR environments. There are several studies that have used neurological signals to enable and/or measure rehabilitation of neurological conditions [6, 9, 65], however, they did not focus on measuring presence.

To our knowledge, there have not been any other studies that have used both physiological and neurological signals to measure presence within the same VE. This investigation is important because understanding the neurological and physiological effects of presence will enable an alternative real-time method to measure presence and avoid shortcomings of post-experience questionnaires. Furthermore, a real-time measurement of presence can enable adaptive VR interfaces that can change its features to maintain a suitable level of presence based on the user's emotional and cognitive states.

Novelty and Contribution:

The main novelty of this work is the use of both neurological and physiological signals to measure presence in calm VEs and

*e-mail: a.dey@uq.edu.au
†e-mail: j.phoon@uq.net.au
‡e-mail: shuvodipsaha74@gmail.com
§e-mail: c.m.dobbins@uq.edu.au
¶e-mail: mark.billinghurst@unisa.edu.au

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to investigate the relationships of these signals with two different widely used presence questionnaires.

The key contribution of the work is the identification of both neurological and physiological effects of presence in calm virtual environments. We have found that the lower presence environment, which was subjectively validated through the questionnaires responses, requires more coherence in the occipital regions of the brain, between the neural hemispheres in the lower beta range and more coherence is observed in the upper beta range for high presence in the frontal region than the higher presence environment. Higher presence environment causes higher heart rate than the lower presence environment. However, electrodermal activity remains largely unaffected in calm VEs.

The rest of the paper is organized as follows. Section 2 reviews some of the relevant earlier work. In Section 3, we describe the methodology of the research, including the experimental system and design. Next in Section 4, we present the results followed by a detailed discussion in Section 5. We then conclude and point towards future work in Section 7.

2 Related Work

Presence, defined as an illusion of being somewhere else, has been a widely researched concept in the field of VR for over two decades [53]. Presence has an important effect on the experience of the VEs. Riva et al. identified a circular relationship between presence and emotions in VR [44]. Whilst, Murray et al. identified that presence is significantly correlated with dissociation and locus of control [38]. Tussyadiah et al. found that higher presence increases enjoyment in a tourism context [59].

There are different factors in the virtual environment that have been found to influence the feeling of presence in VR. Earlier work by Hodges et al., based on acrophobia, found that presence in VR is not affected by earlier exposure to the same VE and user's behavior in the VE is influenced by their earlier experiences of the same real-world situation [23]. Slater et al. noticed providing detailed dynamic shadows [55], the availability of a virtual body [54], and natural methods of navigation, such as walking, increases the feeling of presence [56]. Lok et al. reported that being able to interact with real objects in VEs increases presence, however, fidelity of the self-avatar has no significant effect on presence [33]. A similar effect was reported by Dinh et al., where they did not notice any significant effect of visual fidelity on the sense of presence and memory, however, they noticed a significant positive effect of multi-sensory input [14]. Recently, in a collaborative VR scenario, Pan and Steed reported that self-avatars have an important effect on presence [39]. Another work by Steed et al. noticed that self-avatars had a positive effect on presence and embodiment [57]. The advantage of body-ownership on presence has also been reported by Waltemate et al. [62], who noticed that personalized avatars cause higher presence. Ling et al. found that the feeling of presence is influenced by individual characteristics [32], whilst Buttussi and Chittaro found that the higher fidelity VR displays cause a higher feeling of presence [5].

Different methods have been adopted in the past to measure presence. However, most of them are based on post-experience surveys. A recent work by Schwind et al. [48] provides a thorough overview of the current surveys being used to measure presence so far. In the same work, the authors have compared two of the most cited presence questionnaires developed by Slater et al. [52] and Witmer & Singer [64], which is the same questionnaires that we have administered in our current work. The instrument designed by Slater, Usho, and Steed (SUS) [52] has six questions, which are primarily directed towards measuring the sense of being in the virtual environment, the extent to which the virtual environment becomes the dominant reality, and the extent to which the virtual environment is remembered as a physical place. Witmer & Singer's [64] instrument has 32 items in it and they are divided into six subscales – involvement/control, natural, auditory, haptic, resolution, and interface quality. Further they also have four factors – control, sensory, distraction, and realism.

In previous work, Meehan et al. proposed physiological measurements of presence using a scary VR environment [37]. They found a significant correlation between presence and skin conductance (electro-dermal activity or EDA). Additionally, Wiederhold et al. used a stressful VE and found significant correlations between the presence questionnaire ratings and heart rate and skin resistance [63]. In a pilot study, Slater et al. used physiological responses to measure BIP [51]. Although, their results were not conclusive. Meanwhile, Riva et al. established connections between presence and emotion [44]. While these few studies measured presence using physiological signals, they used a stressful environment as their experimental VEs.

While neurological signals in VR have been used to make the interface adaptive [13] and to create brain computer interfaces [34], use of neurological signals to measure presence is limited. Using a non-immersive computer screen and non-interactive VE, Baumgartner et al. was the first to examine cortical activity and reported that increase in spatial presence experience was correlated with an increased event-related desynchronization (ERD) in the Alpha band (8–13 Hz), thus indicating higher cortical activity. Kober et al. reported one of the first studies to measure neural activities in the context of presence [29]. However, their setup was non-immersive and projection-based. Using a 21-channel electroencephalogram (EEG) device, they identified a positive relationship between presence and parietal brain activation and a negative relationship between presence and frontal brain activation. A recent work by Jeunet et al. [28] identified neurological markers as a sense of agency in VR environments, which is a key element of presence [46] but not presence as a whole.

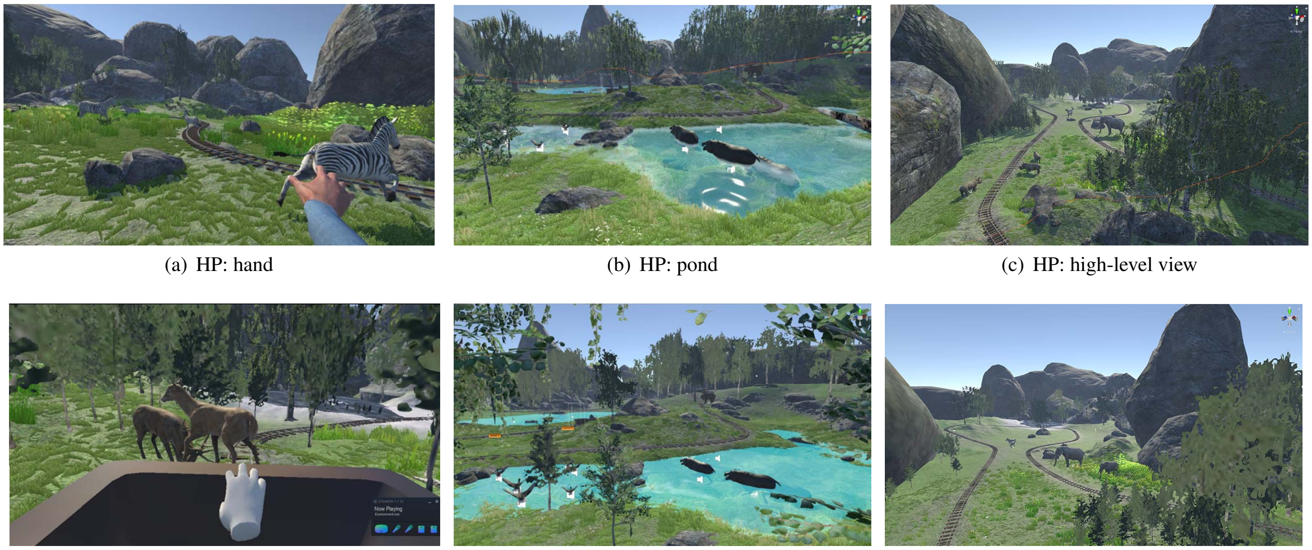
In summary, earlier works have identified different factors that influence the feeling of presence in VR, which has helped us in designing our experimental VEs. Whilst several researchers have developed survey instruments to measure presence, there has been limited effort in measuring presence using neurological and physiological measures. However, no earlier study has measured both neurological and physiological in the same experimental setup using calm interactive immersive VEs.

3 User Study

To investigate the effect that exposure to different presence levels in VEs has on neurological and physiological data, we designed a one-way *between-subjects* user study. The only independent variable was the Virtual Environment with two levels—High presence (HP) and Low presence (LP).

3.1 Virtual Environments

We designed two similar VEs with different characteristics that induced different levels of presence (Figure 1). The design of the VEs was informed by earlier literature and a subsequent validating pilot study. In both of the VEs, the participant was placed in a virtual cart that was travelling through a jungle at a constant speed, past non-aggressive animals and birds. The path was fixed to ensure that all participants in both experiences went through exactly the same path and encountered animals at exactly the same locations. Participants were seated on a revolving chair that enabled them to easily look around, and to minimize noise in the neurological and physiological signals that can occur due to body movement. Both experiences lasted for four minutes. The VEs were developed using the Unity3D gaming engine and HTC Vive hardware displays. An Alienware gaming laptop ran the VEs and had an RTX 2080 graphics card, 32GB memory, and Intel Core i7 processor (8th generation).



(a) HP: hand (b) HP: pond (c) HP: high-level view

(d) LP: hand (e) LP: pond (f) LP: high-level view

Figure 1: Representative Screenshots of the virtual environments: a high presence (HP) environment had higher visual fidelity, embodied hand representation, higher interactivity (a-c). A low presence (LP) environment had lower visual fidelity, detached hands, and less interactivity (d-f). The HP environment had object-based sound effects, whereas the LP environment had only an ambient sound.

3.1.1 Pilot Study

The pilot study mentioned above was conducted with six university students (all male, ages ranged between 21 to 25 years). Two of them had prior exposure to VR and all of them had normal or corrected to normal vision. We used the same environments as in the main user study (Figure 1). We used a between-subjects design with three participants rating each environment. As our primary purpose of this pilot study was to identify whether the environments provided different levels of presence, we only used the SUS questionnaire and did not use any other subjective or physiological measurement. The SUS questionnaire showed noticeable, but not significant, difference in rating between the environments. HP environment (M=28.7, SD=7.8) received higher ratings than LP environment (M=22.7, SD=4.5). We were not expecting a significant difference due to the low number of participants but the difference in rating and their subjective comments validated the differences in presence between the environments.

3.1.2 Differences between HP and LP environments

The HP environment was rendered with higher visual fidelity than the LP environment. We also provided an embodied hand with human-like skin color in HP, whereas LP only had a white detached palm, which represented the hand. In HP, animals could also be touched and they would respond by mostly running away. However, in LP the animals did not respond to touch. In HP, participants could control (start and stop only) the movement of the cart by pressing a button, whereas no such facility was provided in the LP environment. Finally, in the HP environment there was also both ambient and object specific sounds, whilst in LP there was only ambient sound.

3.2 Procedure

The experiment was ran in an air conditioned room, with no external noise. We first welcomed the participants and explained the experiment and their rights to them. They were then given an information sheet, which has been approved by the University's ethics committee. After reading the information sheet and asking any clarifying questions to the experimenter, they signed an informed consent form. They were then fitted with a Shimmer3[1] 5-lead electrocardiogram (ECG) and galvanic skin response (GSR) sensors and an Emotive Epoc+ EEG headset. Then they put on the HTC Vive headset, with the help of the experimenter to ensure it fit properly together with the EEG headset. The connections were then established between the sensors and the computer, where we ran the iMotions[2] biometric data collection software. Participants used a Logitech G533 wireless gaming headset.

After the connections were established, we collected baseline data for 30 seconds with the participants eyes open, followed by another 30 seconds with their eyes closed. During this baseline period, we did not show anything through the Vive display. After the baseline data was collected, the experimental environment was started. As it was a between-subjects experiment, each participant experienced only one environment. After the experience ended, participants removed the headset and filled in two online subjective presence questionnaires—SUS [52] and Witmer & Singer [64]—on another computer. Participants were then debriefed about the study and were provided with cookies and/or chocolates for their voluntary participation (no other reward was given). This then ended the experiment for the participant. Depending on the time it took to establish a proper connection between the sensors and the computer, the experiment lasted between 45 minutes to an hour.

3.3 Dependent Variables

In this experiment, we collected four dependent measures, including 1) raw electrocardiogram (ECG) signals, which were used to derive heart rate, 2) galvanic skin response (GSR) to derive phasic and tonic electrodermal activity (EDA), 3) electroencephalogram (EEG) to derive frequency bands and 4) subjective presence ratings using the SUS [52] and Witmer & Singer questionnaires [64].

3.4 Participants

We recruited 24 participants (9 female) through our personal contacts, advertising on the University's notices boards, and invitations

[1] http://www.shimmersensing.com/
[2] https://imotions.com/

Figure 2: Participants donned the EEG device and the HTC Vive display. They were sitting on a revolvable chair.

through social media and emails. The participants were randomly assigned to either of the groups, with 12 participants in each group. Their ages ranged between 20 and 30 years (Mean = 22.21, SD = 2.12). Six participants had prior experience with VR (self-reported in a screening questionnaire) and they were distributed equally amongst the two groups. Except for three, all other participants reported playing computer games regularly. All participants had normal or corrected to normal vision

3.5 Hypotheses

We postulated the following hypotheses before running the experiment -

- **H1.** As we purposefully designed, informed by earlier work and a pilot study, our environments to elicit different levels of presence, we expected the two environments will provide significantly different levels of presence when measured using both subjective questionnaires.

- **H2.** Following insights from an earlier experiment [37], we expected EDA to be higher in the HP environment.

- **H3.** As the HP environment provides more opportunities to interact, it will cause heart rate to increase in the HP environment, as opposed to the LP environment.

- **H4.** The LP environment will cause different brain activity than the HP environment. Particularly, we expected higher visual stress and less engagement in LP environment than HP environment.

4 Results

In this section, we first present the subjective questionnaire data, followed by the neurological and physiological data. In summary, our results indicate that there is a clear difference in brain activities in the frontal, occipital, and parietal regions between differing levels of presence in VEs. Heart rate was also found to be higher in the high presence VE than in the low presence VE. However, there was no significant difference in electrodermal activity.

4.1 Presence Questionnaires

We developed two environments to induce different levels of presence, which has been informed by earlier literature and a pilot study. It was expected that there would be significant differences in subjective presence, when measured using the questionnaires. We indeed noticed that the two environments were significantly different in presence when measured by both questionnaires—WS (Witmer & Singer) and SUS (Slater-Usoh-Steed).

4.1.1 WS Questionnaire

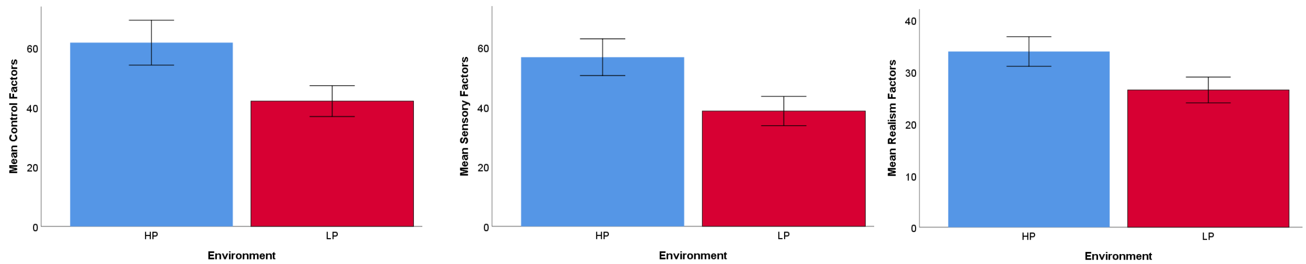
Significant differences were noted between the two environments using the WS questionnaire scores. We first report on the four factors (Figure 3), then the six sub-scales.

Factors: For the *control factor*, we noticed a significant effect of environments—$t(22) = 4.7, p < .001$. Participants reported to have significantly higher control in the HP environment (M=61.6, SD=11.8), than in the LP environment (M=42, SD=8.1). For the *sensory factor*, we noticed a similar significant effect—$t(22) = 5.0, p < .001$. The HP environment (M=56.6, SD=9.7), reported a higher sensory control than the LP environment (M=38.6, SD=7.7). We did not notice a significant difference in terms of distraction factors. For the *realism factors*, we noticed a significant effect of the environments—$t(22) = 4.3, p < .001$. The HP environment (M=33.9, SD=4.5) reported having higher realism than the LP environment (M=26.5, SD=3.9).

Sub-scales: For the *involvement and control* sub-scale, we noticed a significant effect of environments—$t(22) = 4.8, p < .001$. The HP environment (M=68.9, SD=12.9) received higher scores than the LP environment (M=48.3, SD=7.5). For the *natural* sub-scale, a similar significant effect was noticed—$t(22) = 3.0, p = .006$. The HP environment (M=14.2, SD=4.5) rated higher in this sub-scale than the LP environment (M=9.17, SD=3.5). For the *auditory* sub-scale, we noticed a significant effect of the environments—$t(22) = 4.1, p < .001$. Here, the HP environment (M=18.5, SD=2) received higher scores than the LP environment (M=14.3, SD=2.9). For the *haptic* sub-scale, the HP environment (M=9.3, SD=3.2) was rated significantly—$t(22) = 4.9, p < .001$—higher than the LP environment (M=3.7, SD=2.3). For the *resolution* sub-scale, we noticed a significant effect—$t(22) = 2.3, p = .03$. The HP environment (M=10.75, SD=3.1) also rated higher than the LP environment (M=8.25, SD=2.2). For the *interface quality* sub-scale, we did not notice any significant difference between the environments.

4.1.2 SUS Questionnaire

We noticed a significant effect of environment on presence—$t(22) = 2.9, p = .001$ (Figure 4). Matching our expectation, the HP environment (M=29.7, SD=7.5) had higher subjective presence scores than the LP environment (M=21.8, SD=5.9). This finding validates that the environments we designed were appropriate for the purpose of this experiment.



(a) Control Factors (b) Sensory Factors (c) Realism Factors

Figure 3: Responses to Witmer & Singer Questionnaire. Whiskers represent ±95% confidence interval.

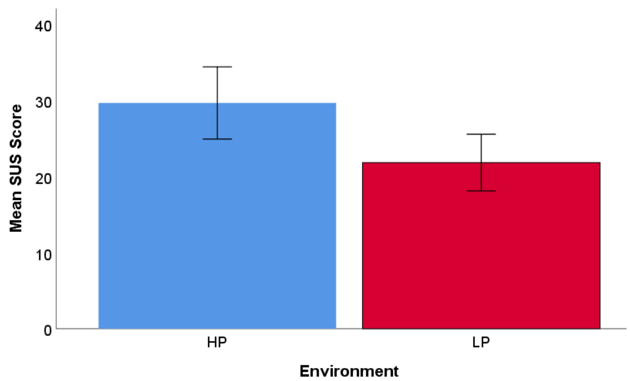


Figure 4: SUS score. Whiskers represent ±95% confidence interval

4.2 Neurological Signals

We collected neurological data using a 14-channel mobile EEG device, called Emotiv Epoc+[3], with a sampling rate of 256 Hz. The raw data set from the 24 subjects was then separated into the two groups of high and low presence. To remove the power line interference, an infinite impulse response (IIR) notch filter, with a cut off frequency of 50 Hz was used. EEG signals also contain a variety of artifacts, including physical and environmental. Significant physical artifacts include eye blinks, facial muscle movement and other kinds of motor artifacts. Independent component analysis was used to decompose the data set into the same number of components as the channels. In this case, 14 components were received and the noisy components were recognized by inspecting each and every component separately. The noisy components were then removed and the remaining components were composed back to get the 14-channel signal, which were artifact free. Later, a bandpass filter was used to obtain the frequency bands of interest. A finite impulse response (FIR) bandpass filter of order 150 and Chebyshev window was applied with desired cut off frequencies. The Theta band (4-7 Hz), Alpha band (8-13 Hz), and Beta band (13-24 Hz) were extracted from the whole signal for primary processing and a further small section was acquired by segmenting Alpha into two sections of 8-10 Hz, 11-13 Hz and Beta into two sections of 13-17 Hz and 17-24 Hz. For the two different environments, the data groups of 12 different subjects was averaged afterwards representing one data set of 14 channels against each presence. However analysis was carried out in both ways, considering average data set of all subjects and processing individuals separately. The process is described in following sections.

[3]https://www.emotiv.com/epoc/

4.2.1 Chirplet Transform

The Chirplet transform was used to obtain the time frequency characteristic of the averaged EEG signal, at the two different VEs with different presence levels. Chirplets are the small parts of the chirp family that contains variable frequency with time. These chirplets are used to decompose the signal against frequency components of a given range. Both temporal and spatial resolution can be contained by this transform [35].

Prior to the application of the Chirplet transform, the data was down sampled by 8 to reduce the complexity of the calculation, which leaves the sampling frequency at 32 Hz. Hence, the transform provides the signal frequency range up to 16 Hz. The Chirplet transform gives a time frequency representation, which is a three dimensional relationship between time, frequency, and amplitude, which can be visualized by plotting as a spectrogram.

Figure 5 shows the spectrogram of the transform of channel AF3. Between 10-15 Hz increased power is reflected through the time domain. Moreover, for statistical analyses, the mean and standard deviation were also calculated for every channel. In this range of frequency, P7 and P8 do not show significant difference in power. The channels with the most noticeable results are F3, O2, T8, F4, F8 and AF4 (Figure 6). In order to obtain the specific band wise differences, the beta and theta band activity from the frontal region along with the alpha band response from the parietal band was calculated. As such, the Chirplet transformed power was calculated from AF3 and AF4 in beta band; F7 and F8 in theta band; and P7 and P8 in alpha band. As the data was not normally distributed, a non-parametric Mann Whitney U test was performed to evaluate the difference between the HP and LP environments in terms of power. We observed significant differences in—F7 $U(HP=6371,LP=6371)=13408514, Z=-33.169, p<0.001$, F8 $U(HP=6371,LP=6371)=13259798, Z=-33.885, p<0.001$ in theta frequency range, P7 $U(HP=6371,LP=6371)=11385312, Z=-42.914, p<0.001$, P8 $U(HP=6371,LP=6371)=17903936, Z=-11.516, p<0.001$ in alpha frequency range, and AF3 $U(HP=6371,LP=6371)=5541623, Z=-71.061, p<0.001$, AF4 $U(HP=6371,LP=6371)=6053439, Z=-68.596, p<0.001$in beta frequency range, where the HP environment had higher rank than LP environment in every cases. High U values was obtained due to large number of data set.

4.2.2 Inter-Hemispheric Phase Coherence

The EEG signal provides an interpretation of neural activity from a large collective population. It is believed that the two hemispheres of the brain have independent functionality [10]; however, in specific situations, they can respond in a similar and synchronized manner. Earlier work has demonstrated that the electrical activities generated from two cortical areas require to be temporally correlated while specific activities are performed by an individual [47]. Therefore,

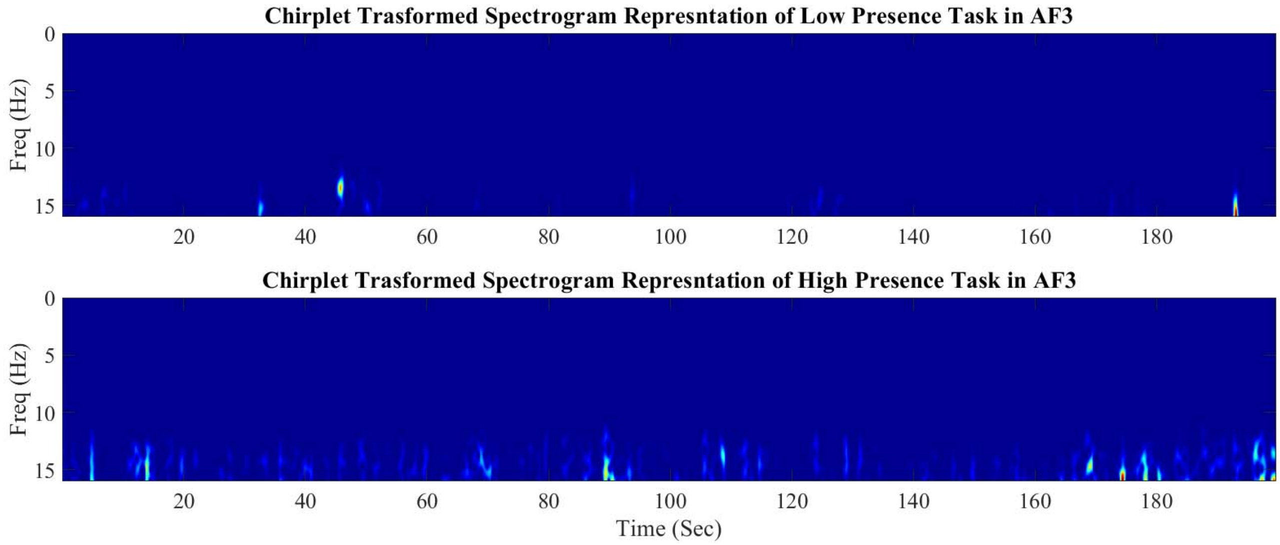


Figure 5: Spectrogram representation of chirplet transform of channel AF3. Here, the time frequency representation of the signal shows the comparison between LP and HP environments in the channel AF3. We observed higher neural activity in the HP environment, through the heat area in terms of power, than the LP environment.

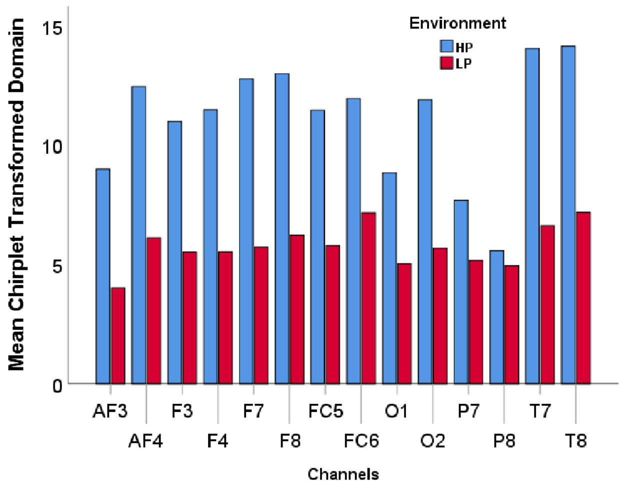


Figure 6: The Mean value of the chirplet transformed signal over time for all 14 channels showing the power distribution against frequency components through total duration. The comparison shows the intensity level difference between two environments, where the higher the task engagement, the larger the value.

synchronization of electric impulses between selected areas of the brain play an important role for various functional attributes, such as motor activities, visual perception, attention, and cognition [25]. Phase synchronization can be used as an effective tool to quantify cognition and to get an idea of the interconnection between brain areas [26]. Research has shown that visual perception towards unfamiliar visual presence can lead to an increase in coherence in the alpha and gamma frequency bands. Provided that the subject is not involved in any kind of intellectual or mental tasks, other than only visual perceptual activities, the upper Alpha EEG activity phase coherence provides significant information [43,58]. In another study, research has shown that temporal, parietal, and frontal areas of the brain exhibits high phase synchronization in the beta frequency range, when visual attention is required during a task [22].

We considered time domain data for further study of phase coherence. After pre-processing, the Hilbert transform was applied to process the analytic signal, from the time domain data composing the original dataset and the Hilbert transformed dataset. This can be obtained by rotating the positive and negative frequency components of the Fourier transformed data, respectively, by $-\pi/2$ and $\pi/2$. This process helps to restore the phase of the signal. Therefore, the phase angle was determined from the signal of all the 14 channels, for the different frequency ranges: theta, alpha, beta and gamma. Following that, the phase component was segmented into 1 sec epochs, with 50% overlap (Figure 7). For each epoch, phase cross correlation was evaluated for 7 pairs of channels, taken from both hemispheres. It has been observed that there are significant differences between the high presence and low presence outcome of the phase coherence. Figure 7 shows a graphical comparative representation of phase coherence between the two presence levels, in all channel pairs for the alpha band. The figure depicts that the cross-correlation factor is high in the high presence condition, where it is more spread out for the low presence task. Although, the difference is not visually prominent in the parietal region. The data set also exhibited skewness in distribution and therefore, statistical analysis, using the Mann Whitney U test, showed identical results; apart from the parietal region coherence of theta, beta and gamma bands, all other coherence sets showed major differences with $U(HP = 398, LP = 398) = 80,000, Z = -15.508, p < 0.001$ and for the parietal region that is $U(HP = 398, LP = 398) = 25,000, Z = -2, p < 0.05$.

4.2.3 Power Spectral Density

A Fast Fourier Transform was applied to obtain the frequency domain response of the signals in the alpha and beta range. Following this transform, the power spectral density (PSD) was calculated to visualize the difference in the two environments. It was observed that HP environment generated higher power spectral density in almost all of the channels than LP environment. Therefore, all the ratios have magnitude greater than 1. However, the two different frequency levels of alpha and beta showed different behavioral characteristics. The ratio in the beta band signal components is comparatively less

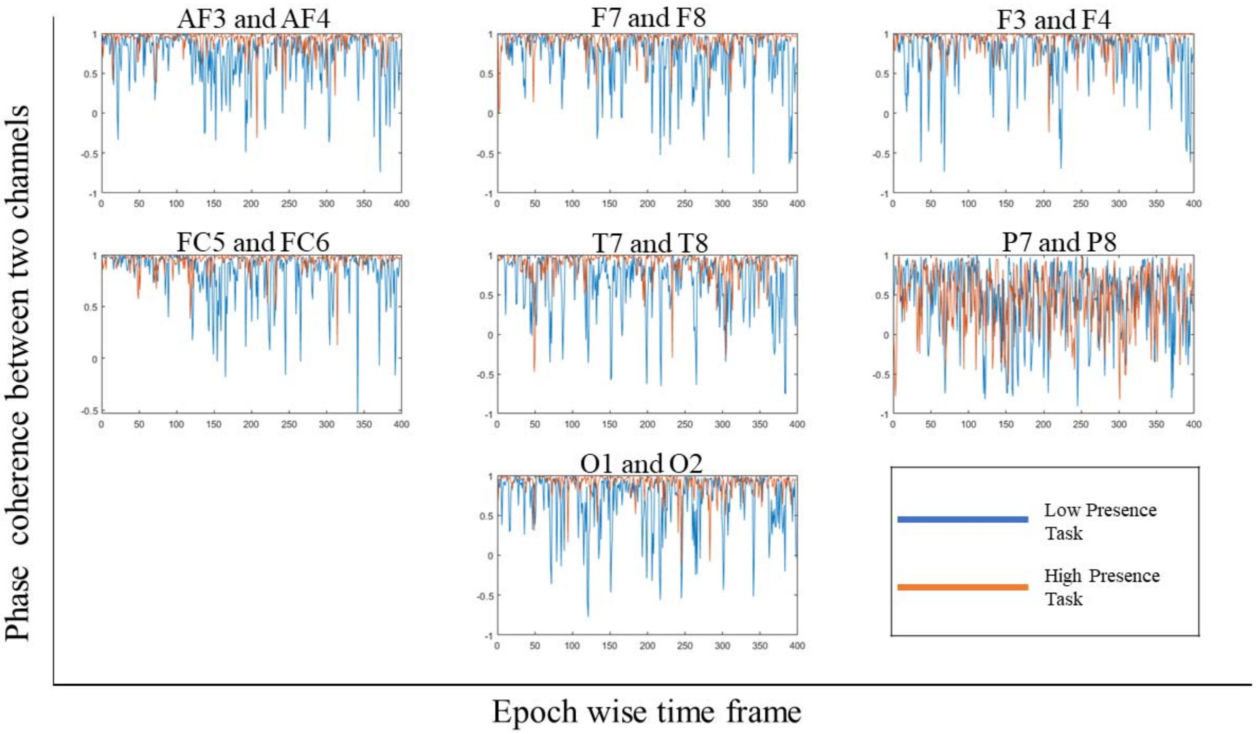


Figure 7: Phase coherence between seven pairs of channels from two hemispheres in alpha frequency range, the orange lines show the HP environment results and the blue lines show the LP environment results. This depicts that high presence task demands highly synchronized activity between two hemispheres. The closer that values are to 1, the higher the correlation between phases.

than that of alpha band signal components in most of the channels (Figure 11). In FC6, O1 , P8 and T8 the beta band ratios are higher than alpha band ratios. In the frontal regions alpha band shows notable high HP PSD to LP PSD ratio values. The activity in the right parietal region, extracted from channel P8 displayed significant alpha suppression in HP, and higher ratio of beta band, which is an important observation in terms of higher task engagement. Therefore, the PSD ratio in both the frequency bands support higher task engagement in high presence task. The mean PSD of the alpha region has also been calculated and is illustrated in Figure 8.

4.2.4 Power Load Index

Earlier studies have found that band power plays a vital role in determining cognitive load. The relative change of EEG power in theta, alpha and beta bands showcase the variability of task engagement for an individual [18, 24]. For the present study, a ration index was derived using band power values from different regions of the brain. Firstly, the band power of the three frequency bands were evaluated separately for the two VEs. One study was done for the averaged signal of all subjects and another one was done for 12 different subjects in both presences. Different ratios were defined as indices for distinguishing the cognitive engagement between two types of presence inducing VEs.

The bandpower of the signal against individual frequency bands was evaluated and used to form the following indexes. Specifically, the beta band power from channels FC5, FC6, theta band power from AF3, AF4 and alpha band power from P7 and P8 have been considered. Moreover, the alpha band power from O1 and O2 has been also taken into account for another observation. The power has been calculated epoch wise and then they have been averaged.

$$BTAindex = \frac{(Beta\ FC5 + Beta\ FC6 + Theta\ AF3 + Theta\ AF4)}{(Alpha\ P7 + Alpha\ P8)} \tag{1}$$

$$TAindex = \frac{(Theta\ AF3 + Theta\ AF4)}{(Alpha\ P7 + Alpha\ P8)} \tag{2}$$

$$BAindex1 = \frac{(Beta\ FC5 + Beta\ FC6)}{(Alpha\ P7 + Alpha\ P8)} \tag{3}$$

$$BAindex2 = \frac{(Beta\ FC5 + Beta\ FC6)}{(Alpha\ O1 + Alpha\ O2)} \tag{4}$$

The results deduced from the index evaluation illustrates that the high presence task holds a higher ratio than the low presence task. The difference in ratio index can be interpreted as cognitive load variation, within the defined states. The BTA index, TA index and BA index 1 are depicting the above mentioned phenomena as an increase in load is reflected in the high presence task (Figure 9). Another observation has been made from BA index 2, which shows a reduced value in the case of the high presence task, compared to the low presence task. It may be a possible indication that there is a stress factor in the occipital region, due to the poor visual presentation, which can suppress the load. Figure 10 shows a comparison between BA index 1 and BA index 2. Figure 12 depicts the difference between BA index 1 where the bandpower data from individual subjects have been taken and grouped for evaluation. Furthermore, Mann Whitney U tests were also performed on the cumulative data set of all subjects to find the difference. Prior to the statistical analysis, outliers from data set of each group and each presence were removed on the basis of the quartile method. The remaining set contains 307 HP environment data and 324 LP environment data. The test provided significant result for the following indices—BTA: $U(HP = 307, LP = 324) = 14,240, Z = -15.508, p < 0.001$, TA: $U(HP = 307, LP = 324) = 16,319, Z = -14.599, p < 0.001$, BA 1: $U(HP = 307, LP = 324) = 22,626, Z = -11.844, p < 0.001$, and BA 2: $U(HP = 307, LP = 324) = 43,774, Z = -2.604, p < 0.001$.

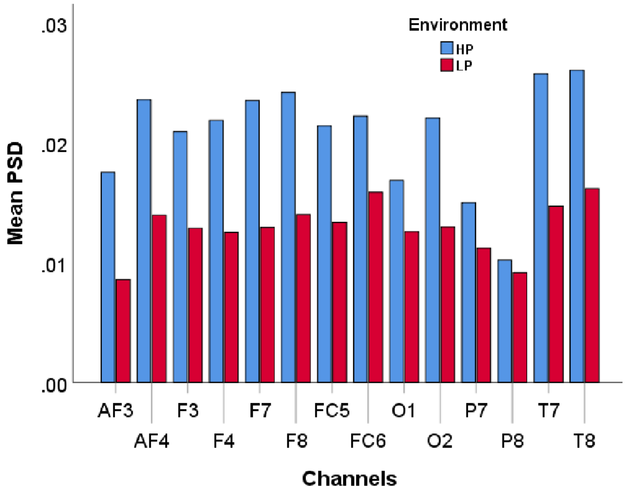


Figure 8: The mean of the power spectral density in the Alpha range (8-13 Hz) is shown between high and low presence for all the channels. This shows the comparative power distribution in the specific frequency region.

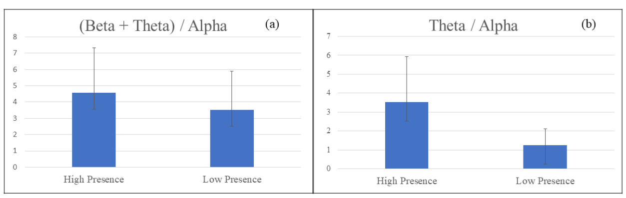


Figure 9: The (a) BTA index, and (b) TA index averaged in the high and low presence signals. The higher BTA and TA index represents better task engagement that demands increasing cognitive load. It compares the cognitive load between the two environments, which is higher in case of HP environment than LP environment in both cases.

4.3 Physiological Signals

Physiological data enables us to capture spontaneous and subconscious aspects of the user's state as they interact with different environments and controllers [17]. Heart rate (HR) is controlled by the sympathetic and parasympathetic branches of the autonomic nervous system [12], while EDA refers to the "variation of the electrical properties of the skin in response to sweat secretion" [3]. A raw EDA signal is composed of two components—Skin Conductance Level (SCL) [tonic component] and Skin Conductance Response (SCR) [phasic component]. SCL is a general measure of psychophysiological activation that is slow moving [49], whilst SCRs depict higher-frequency changes that are directly related to an external stimulus [20]. Typically, SCR and HR are the best discriminative signals for arousal detection [7]. These signals have been used in this study to evaluate the short-term effects of each environment by determining sympathetic activity (sympathetic arousal), which elevates heart rate, blood pressure, and sweating [41].

The raw ECG signals were sampled at 512Hz and were preprocessed using the algorithm developed in [15], which corrects artefacts, such as missing peaks. The raw ECG signal was then transformed into heart rate (HR). The raw EDA signal was sampled at 128Hz and was pre-processed using the cvxEDA algorithm [21], which decomposes the signal into the SCL and SCR components. Statistical features were then extracted from the HR and SCL/SCR

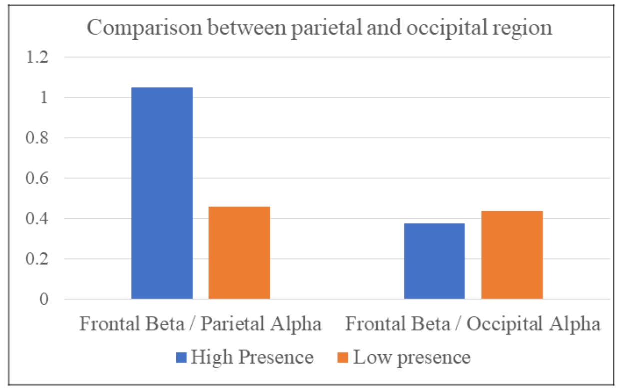


Figure 10: Comparison between BA index 1 and BA index 2. The opposite phenomena can be observed here between the parietal and occipital alpha values. When the alpha range of the occipital lobe is considered, the low presence ratio is higher than the high presence ratio.

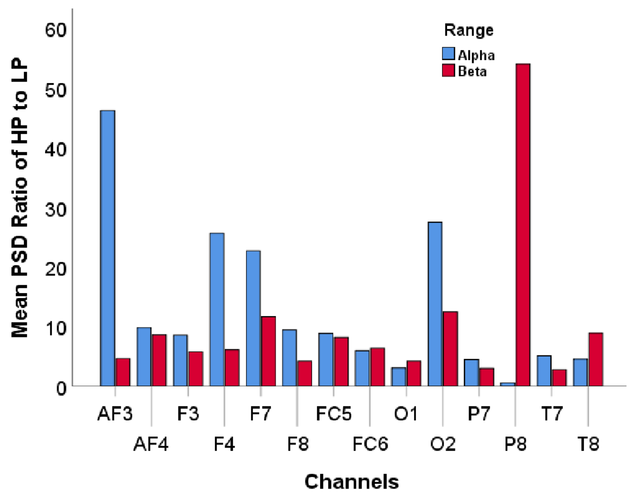


Figure 11: Power spectral density (PSD) ratio. The PSD is calculated from the corresponding data set of presence in Alpha (8-13 Hz) and Beta ranges (13-24 Hz) respectively. Then the ratio between high to low is evaluated to compare within channels.

signals, including mean, median, standard deviation, minimum, maximum, variance and 25th/75th percentiles. This analysis was undertaken using MATLAB R2019b.

In terms of physiological signals, due to an error in the data collection, reliable ECG data was collected from only 18 participants (10 in HP and eight in LP). However, we did notice a significant effect of environments on the heart rate using a two-tailed independent samples t-test—$t(16) = 2.4, p = .03$ (Figure 13). Participants in the HP environment (M=81.9, SD=7.2) had a higher average heart rate than those in the LP environment (M=73.5, SD=7.9). We did not find any significant difference between the two environments for the SCL/SCR data.

5 Discussion

In this section, we discuss the results in the context of the four hypotheses we postulated before the experiment. Our first hypothesis (H1) predicted that the HP environment will indeed provide higher presence than the LP environment, when measured using both the

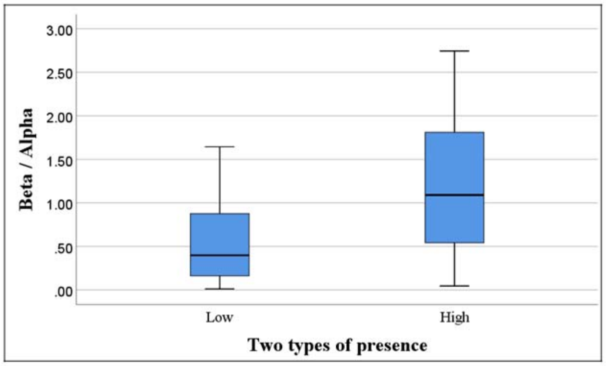


Figure 12: Beta / Alpha index: The HP environment shows higher first quartile, median, and third quartile values than the LP environment.

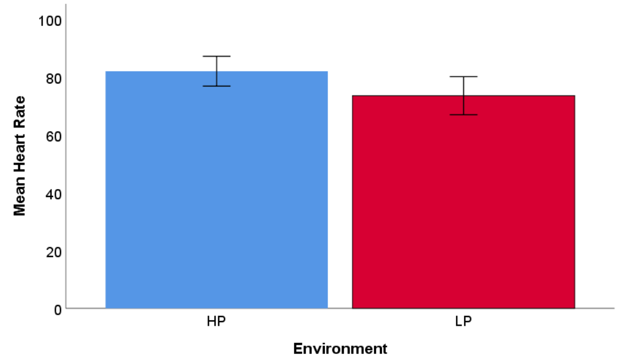


Figure 13: Mean of heart rate. Whiskers represent $\pm 95\%$ confidence interval.

WS and SUS questionnaires. This hypothesis was *accepted*, as in both questionnaires, we noticed a significant difference between the environments in terms of presence ratings. The design of the environments was based on earlier literature and a pilot study with six participants. Better graphical fidelity, opportunities to interact with the environment, more localized object-based audio, and embodied hands with human-like skin tone, caused higher subjective presence in the HP environment than in the LP environment. However, not finding a significant difference in the interface quality sub-scale was surprising. This response could be because the participants in the LP group did not have a reference of better interface quality and the novelty of experiencing the VR made them rate both of the environments similarly.

Our second hypothesis (H2), based on the findings of Meehan et al. [37], predicted that higher presence will cause higher electrodermal activity. This hypothesis was *not accepted* as we did not notice any significant difference between the environment in either the tonic or phasic components of EDA. One possible explanation of this contradiction was the use of different types of environments. Meehan et al. used a virtual pit experience that created a stressful situation, due to the fear of heights. However, in our experiment we used a calm experience, where participants enjoyed a jungle ride with non-aggressive animals. As there were not many surprising and fearful incidents, EDA remained similar in both high and low presence VEs. Another difference between their setup with ours is that the participants were standing in their experiment, whereas they were sitting in our experiment. A third reason for this difference could be the less number of participants in our study (12 participants in each group) compared to Meehan et al.'s study (52 participants). These findings require a more focused investigation, with multiple different types of VEs.

Our third hypothesis (H3) predicted that a high presence environment would cause a higher heart rate, as it provides interactivity, which causes motor movement and eventually increases heart rate. This hypothesis was *accepted* as we noticed a significantly higher heart rate in the high presence VE. In our HP environment, we enabled opportunities to interact with the environment, using the HTC Vive controllers. Participants could start and stop the cart that they were riding in by pressing a button. They could also touch the animals, which activated an action, e.g. running away. All of our participants interacted with the environment, through mostly playing with the animals. We also noticed they tried to touch the leaves of the trees, which did not produce any response. However, all of those activities were performed while being seated and no physical locomotion was involved. Hence, the increase in heart rate can be attributed to both the interaction and the feeling of presence. A more focused experiment is needed to factor out the influence of interaction and feeling of presence on the increased heart rate.

Our final hypothesis (H4) predicted different brain activities in the low and high presence VEs, as these environments had different visual quality, auditory feedback, and interaction opportunities. This hypothesis was *accepted* as we have identified differences in neural activities between the two VEs. Through coherence analysis between O1 and O2 in the occipital region, which is primarily responsible for visual processing, we noticed that the HP environment caused less visual stress than the LP environment. It is expected as the HP environment provided better visual quality than the LP environment. We believe participants were more comfortable with high-quality graphics in HP environment as these were easy to watch and perceive than in the LP environment which contained low-quality graphics and required more effort to perceive the environment than HP. While, LP caused more brain activity in the occipital region, HP environment increased brain activities in the frontal region. We observed significantly more theta activities in the F7 and F8 electrodes. Higher theta activity is associated with improved focused concentration, sustained attention, spatial working memory [19]. We believe, the higher visual quality, auditory feedback, and interaction in the HP environment caused a better experience, thus resulting in higher theta activities in the frontal region than the LP environment. We also noticed higher beta activity, which is related to consciousness and motor behaviors [45], in the AF3 electrode of the frontal region. Kweon et al. identified higher beta activity in the frontal region for dynamic VR content than less dynamic 2D content [31]. We believe the higher interaction possibilities and overall better audio-visual experience in the HP environment resulted in this increase in the beta activity in the frontal region. In the parietal lobe, which integrates sensory information—for P7 and P8 electrodes—we observed higher alpha activities in the HP environment than the LP environment. Alpha activity increases in resting but not sleeping states [61]. An earlier study by Park et al. identified that higher simulator sickness decreases alpha activity [40]. While we did not explicitly measure simulator sickness in our study, we believe that the lower visual quality of the LP environment increased visual stress and potentially simulator sickness, resulting in lower alpha activities. Overall, the visual load in the LP environment was more than the HP environment, but the overall cognitive engagement is more in the HP environment than the LP environment.

6 Limitations

We have identified significant neurophysiological effects of high and low presence VEs. However, our experiment had a few limitations as discussed below.

First, our experimental VEs were purposefully designed to be calm, which makes our findings not directly applicable to other type of VEs, such as scary or sad. We intend to validate our approach of measuring presence in other types of VEs in the future.

Second, we used a consumer grade 14-channel Emotiv Epoc+ EEG device, which limited the resolution of the neural activities recorded. It will be interesting to explore the neural activities of differing presence scenarios in VEs using higher resolution EEG devices. However, it is important to note that previous studies have validated the use of the Epoc+ device as a research tool [30, 36].

Third, to avoid movement of the EEG device on the head, which could have caused noise in the EEG data, we designed the task to have the participants seated during the experiment. However, most VR applications do not require participants to be seated and afford more interaction and body motion than we did in our experimental VEs.

7 Conclusion & Future Work

In this paper, we presented a between-subjects experiment to measure the neurological and physiological effects of presence in a calm virtual experience. We had four hypotheses. Three of them were accepted and one was not accepted. Overall, we identified significant differences in neurophysiological activities at different levels of presence. From our experiment, it can be concluded that higher presence in calm virtual environments can be characterised by increased heart rate, elevated beta and theta activities in the frontal region, and increased alpha activity in the parietal region of the brain.

We noticed a different finding from earlier research by Meehan et al. [37], where they noticed a significant difference in electrodermal activity, which we did not notice. However, their experimental VE was stress evoking, whereas our experimental VEs were calm. To investigate this contradiction, we would like to investigate the reasons further by designing VEs that cause different emotions, including stressful VEs, and explore if neurological and physiological activities in response to differing presence depends on the experienced emotions in the VEs. This experiment will also help validate the results we observed in the current experiment.

In the future, we would like to explore the collected data further and attempt to identify more features in the neurological and physiological data using deep learning [11]. In this experiment, in both VEs, the participants were virtually moving. We would like to investigate the neurological and physiological effects of presence in stationary virtual environments, where the participants would not move in the VE.

Overall, our results indicate that neurophysiological data can provide more implicit measurements of presence and, following Slater's suggestion [50], using these measurements we can decrease our reliance on subjective questionnaires to measure presence.

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