Brain Activity Reflects Sense of Presence in 360° Video for Virtual Reality

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Abstract

Over the past decade virtual reality (VR) has shown some major advancements in research and development. One of the most important aspects of VR user experience is the sense of presence, the feeling of being present in the virtual environment. So far, sense of presence has been most commonly measured through subjective post-experience questionnaires. In the current study, we aimed to examine whether objective measures of brain activity can provide additional insights. Participants watched an affective 360° VR video while their brain activity was monitored using electroencephalography (EEG). Moreover, participants reported their subjective sense of presence after the VR experience. Compared to a baseline and a post measure, EEG alpha power decreased during the VR experience. Furthermore, this change in brain activity was related to the participants' subjective sense of presence. These findings highlight the high potential of brain imaging techniques in assessing a user's experience in VR.

Keywords: Virtual Reality, Sense of Presence, Human-Technology Interaction, Brain Activity, EEG

1. Introduction

The past decade has seen a rapid development of virtual reality (VR) technology due to lower cost and better quality of both hardware and software. VR technology generally consists of a computer and a head-mounted display and allows its users the experience of being surrounded by a computer-synthesised environment [6], [8]. This can also include immersive experiences with 360° videos that allow users to experience the feeling of "being there" by presenting a full field of view of a scene [18], [34]. To date, VR has been deployed in several fields ranging from education, healthcare, marketing, sport, entertainment and industry [6], [11], [20]. With VR becoming mainstream, it becomes increasingly important to also pay attention to user experience. The experience of the user in VR is commonly evaluated through the sense of presence [8], [17], [20], [31, 32], the psychological immersion, which is considered to be a state that is independent of the technology itself and is closely related to the concept of flow in which the user loses sense of time and space [31]. An important aspect of the sense of presence is the feeling of being physically located in the virtual environment, also referred to as spatial presence. Spatial presence is especially important since it portraits the relationship between the virtual environment as a space and the own body [29]. Traditional media, such as print, telephone, television, and film rely primarily on auditory and visual channels and provide little possibility for the user to feel spatially present in an environment. VR, however, uses a combination of visual, auditory, and haptic channels, enabling the user to experience and interact within a virtual environment thus resulting in a higher sense of spatial presence [32]. Previous research has established that an increased sense of presence enhances user experience (e.g., the user responses to virtual stimuli in the virtual environment and the perception of the virtual environment) and increases the effectiveness of the virtual environment (e.g., the practical use of the virtual environments as tools for entertainment, learning or therapy) [20], [28], [31].

The sense of presence, and specifically spatial presence, is an important construct for research and in the design and evaluation of immersive experiences, as it is often used to measure how people experience the virtual environments including those with 360° video [11], [20], [28], [30], [35]. To date, the most commonly used measurement for the sense of presence has been a subjective self-reported questionnaire administered after the VR experience. However, evidence suggests that subjective measurements of presence can potentially be unreliable or biased [15, 16]. The subjective measurements of presence are most often post-test measures, which depend on memory of the virtual environment or event [35]. Studies have tried to eliminate post-test measures by measuring presence during the virtual experience by for example using a hand-held sliding scale [10]. However, with this method participants' responses will be affected by the disruption of continuously assessing one's own experience [35].

To address these issues related to subjective measures, studies have assessed the efficacy of objective measures such as physiological responses and/or brain activity to corroborate the subjective measurement of presence [1], [3], [17]. The advantage of such objective measurements is that, unlike subjective questionnaires, they can be recorded during the VR experience with a high temporal resolution. Hence, the outcomes will not only explain the user experience with a better accuracy, but can also be employed in development of physiology-driven adaptive VR simulations that customize the experience to the user in order to optimize the intended effects. One such objective measurement that can be used in VR presence research is electroencephalography (EEG) [1], [3], [5], [13–15]. One of the benefits of using EEG as a measure of brain activity is that EEG is relatively non-invasive, and can easily be combined with the VR technology [1], [3].

To date, only a few studies have investigated the neurophysiological correlates of presence in VR using EEG [3], [5], [15]. These studies have mainly focused on the parietal areas of the brain, an area that is associated with spatial processing and spatial navigation. Spatial abilities are important and often researched in relation to presence, because these functions play an important role in understanding the outside world [21]. These abilities are also essential in processing outside information and interaction with the environment, which play an important role in presence experience [22]. There is, however, also evidence for the dorsolateral prefrontal cortex being involved in experiencing presence [13]. Within these brain areas, the most studied frequency band in the EEG signal in relation to presence is alpha (8 -13 Hz) [9]. Previous studies generally contained two conditions: a low presence condition versus a high presence condition, demonstrating reduced activity in the alpha band in parietal areas of the brain in high presence conditions [5], [15], [21]. There is also evidence that decreases in alpha activity in parietal areas are linked to an increased sense of presence [13], [14], [25].

On the other hand, the theme and content of a VR environment is an important aspect that is often neglected in presence research. For instance, affective content can produce emotional responses and influence how people interact with a technology and attribute meaning to an environment [2]. Studies that tested the effect of affective (inducing emotions) versus neutral (not specifically inducing emotions) virtual environments showed that affective environments were able to elicit a higher sense of presence than neutral environments [4], [27]. Furthermore, affective environments were experienced as more engaging, more natural, more believable and more real than neutral environments. Thus, affective content could be considered as one way to promote sense of presence in VR environments.

In sum, most studies on presence have used subjective self-reports often ignoring objective measures of presence. Yet, in order to gain better insight in the user's experience and sense of presence, it is important to understand how subjective measurements of presence are related to more objective measures. Given the fact that affective virtual environments increase the sense of presence [4], [27] and given the need for objective measures of presence in such environments, the current study aimed to investigate the relationship between subjective self-reported sense of presence and brain activity during an affective experience during a 360° immersive video. Subjective presence was measured through questionnaires and brain activity was measured through EEG. Based on the research discussed above, we expected to find a decrease in alpha power during the immersive experience in frontal and parietal areas of the brain. Moreover, we expected that a higher subjective sense of presence would lead to a stronger decrease in frontal and parietal alpha power.

2. Method

2.1. Participants

Fifty-two Tilburg University students (19 male, 33 female) aged between 18 and 26 years (*M* = 20.3, *SD* = 2.3) completed the experiment in exchange for 1.5 course credit. Participants were included if they were native Dutch speakers and if they reported no current cardiovascular or neurological disorder. The study was approved by the Research Ethics Committee of Tilburg School of Humanities and Digital Sciences.

2.2. Materials and apparatus

Measure of subjective sense of presence

Subjective presence was measured using the ITC-SOPI questionnaire [19]. The questionnaire was divided into two parts. Part A comprised of six questions and referred to the participants' impressions and feelings after the virtual reality experience had finished. Part B comprised of 38 items referring to the respondents' feelings and impressions during the VR experience. Both parts of the questionnaire used a five-point Likert scale (ranging from 1 'strongly disagree' to 5 'strongly agree).

The ITC-SOPI questionnaire scores can be divided into four presence scales: spatial presence, engagement, ecological validity, and negative effects. The scores of the ITC-SOPI cannot be combined into one 'overall experience score' [19]. For the purpose of the current study only the first scale 'spatial presence' was used since this construct is the most studied aspect of presence and is most directly related to the presence experience itself.

Measure of brain activity

The wireless B-Alert X10 system (ABM) was used to measure EEG at 256 samples per second continuously throughout the experiment. This system collected EEG signals in three different areas (frontal, central, and parietal) through nine-channels (Fz, F3, F4, Cz, C3, C4, Pz, P3, and P4). The data was collected by the software program AcqKnowledge 4.4 (BIOPAC Systems, Inc.) running on a computer solely dedicated to collecting EEG data.

VR environment

An HTC Vive (resolution: 1080 x 1200 pixels per eye; refresh rate: 90 Hz, field of view: 110 degrees) was used to display the VR environment. Two 360° videos were displayed as VR environments, one neutral and one affective video. The neutral video, which served as a VR familiarization video, showed different cities around the globe (e.g. Madeira, Volendam, Dubrovnik) and had a duration of 2 minutes and 18 seconds.

The affective video was from charity organization 'Terre des Hommes' [33] and showed the story of a 12-year-old Kenyan girl, named Amani, working for a middle-class family in Kenya. The video had a duration of 4 minutes and 43 seconds. The content in the video concerned child labor, physical violence, and sexual abuse.

2.3. Procedure

After obtaining written informed consent, participants received a set of instructions about the experiment and completed a demographics questionnaire. Next, the EEG sensors were placed on the participant's scalp, after which the collection of EEG data began. The experiment was divided into four phases: 1) Familiarization (i.e. neutral video), 2) Baseline, 3) Affective VR, and 4) Post-VR.

1) Familiarization: the participants were first shown the neutral 360° video in order to limit novelty effects, the tendency for an individual to have a stronger response the first time that individual is presented with a new technology [7].
2) Baseline: a baseline of three minutes was recorded to measure participants' EEG activity before the affective VR experience. Participants were presented with a black fixation cross on a gray background and were instructed to sit calmly and still while keeping their eyes open and fixated on the fixation cross.
3) Affective VR: participants were shown the affective 360° VR video. They were allowed to move their head to explore the virtual environment during the video.
4) Post-VR: another baseline of three minutes was recorded while participants watched a fixation cross.

Following the Post-VR phase, participants were asked to complete the ITC-SOPI questionnaire. After finishing this questionnaire, the experiment was finished and participants were debriefed about the experiment. Each experimental session took approximately 45 minutes.

2.4. Data processing and analysis

Processing of subjective presence

The scores for the spatial presence scale of the ITC-SOPI were generated by calculating a mean of all items contributing to the spatial presence scale.

Processing of brain activity

The FieldTrip EEG processing toolbox (version 2018–07–27) [24] in MATLAB (version R2018a) was used to process all EEG data. First, quality check reports provided by FieldTrip were visually inspected for each individual participant by three researchers. In this way, the quality of each data file was assessed and noisy files were removed from further analysis. The remaining data was low-pass filtered at 45 Hz and the relative alpha power (8 - 13 Hz) was computed for each channel using the multitaper method with Hanning tapers. The average alpha power in frontal, central and parietal areas was computed for three time phases, the Baseline, Affective VR and Post-VR phase.

Statistical analysis

Statistical analyses were performed using SPSS software (version 24) and R (version 3.4.4). The data were first tested for normality, using Kolmogorov-Smirnov tests. The assumption of normality was violated for EEG alpha powers and therefore nonparametric tests were used for all analyses. Kruskal-Wallis tests were conducted to examine the difference in alpha powers at the frontal, central and parietal areas of the brain. Where significant main effects were found, Dunn-Bonferroni post-hoc tests were conducted for pairwise comparisons between the three time phases.

Furthermore, in order to examine the relationship between the subjective self-reported sense of presence and the objective EEG measurement, the change in EEG alpha power from the Baseline phase to the Affective VR phase ($\Delta Alpha_1 = Alpha_{VR} - Alpha_{Baseline}$) and from the Affective VR phase to the Post-VR phase ($\Delta Alpha_2 = Alpha_{Post} - Alpha_{VR}$) were computed and used for regression analysis. Linear regression analyses were used to examine the relationship between self-reported spatial presence and $\Delta Alpha_1$ and $\Delta Alpha_2$ in frontal, central and parietal areas. Before running regression analyses, Cook's distance was used to detect and remove outliers.

3. Results

Six participants were excluded as they did not follow the procedure of the experiment, such as speaking during the video. Based on the visual inspection of Fieldtrip's EEG quality check reports, EEG data of another 6 participants were excluded from further data analyses. Thus, data of 40 participants (14 male, 26 female, age $M = 20.53$, $SD = 2.14$) were used in the analyses reported below. The average relative EEG alpha power at frontal, central and parietal sites during the Baseline phase, the Affective VR phase and the Post-VR phase are depicted in Figure 1.

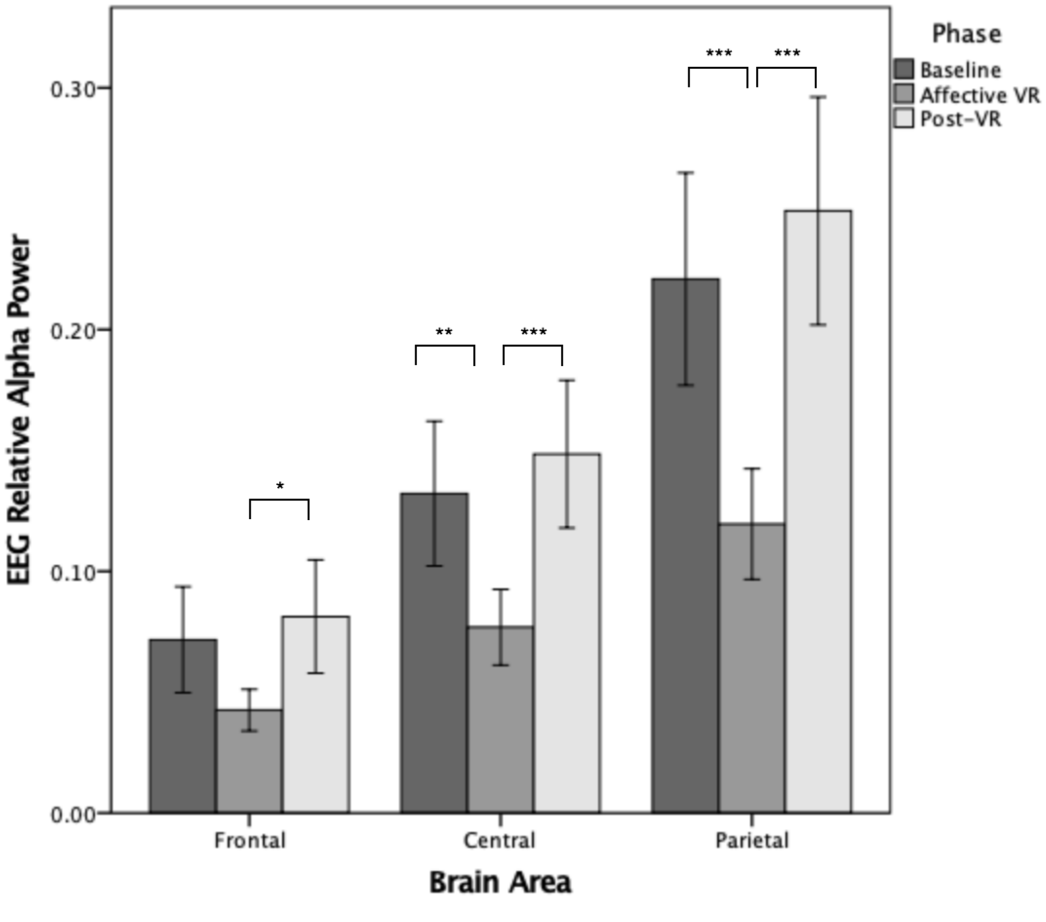

Fig. 1. EEG alpha power in the frontal, central and parietal areas of the brain during Baseline, Affective VR and Post-VR. * $p < .05$, ** $p < .01$, *** $p < .001$. Error bars represent 95% CI

3.1. Change in alpha power

On average, frontal alpha power decreased from Baseline (*M* = 0.07, *SD* = 0.07) to the Affective VR phase (*M* = 0.04, *SD* = 0.03) and increased again in the Post-VR phase (*M* = 0.08, *SD* = 0.07). A Kruskal-Wallis test provided evidence of a difference between the mean ranks of at least one pair of phases, $\chi^2(2) = 7.87$, $p = .02$. Pairwise comparisons showed a significant difference between the Affective VR and the Post-VR phases ($p = .02$).

The average central alpha power decreased from Baseline (*M* = 0.13, *SD* = 0.09) to the Affective VR phase (*M* = 0.08, *SD* = 0.05) and increased again in the Post-VR phase (*M* = 0.15, *SD* = 0.10). A Kruskal-Wallis test provided evidence of a difference between at least one pair of phases, $\chi^2(2) = 20.66$, $p < .001$. Pairwise comparison found significant differences between the Baseline and Affective VR phase ($p = .001$) and between the Affective VR and Post-VR phase ($p < .001$).

The average parietal alpha power decreased from the Baseline (*M* = 0.22, *SD* = 0.14) to the Affective VR phase (*M* = 0.12, *SD* = 0.07) and increased again in the Post-VR phase (*M* = 0.25, *SD* = 0.15). A Kruskal-Wallis test provided evidence of a difference between at least one pair of phases, $\chi^2(2) = 26.17$, $p < .001$. Pairwise comparisons found significant differences between the Baseline and Affective VR phase ($p < .001$) and between the Affective VR and Post-VR phase ($p < .001$).

3.2. Relationship between alpha power change from Baseline to Affective VR and subjective presence

A significant relationship was found between the change in frontal alpha power from Baseline to Affective VR (Δ $Alpha_1$) and self-reported spatial presence, $b = -3.41$, $\beta = -0.37$, $t(40) = -2.43$, $p = .02$. The results of the linear regression are presented in Figure 2.

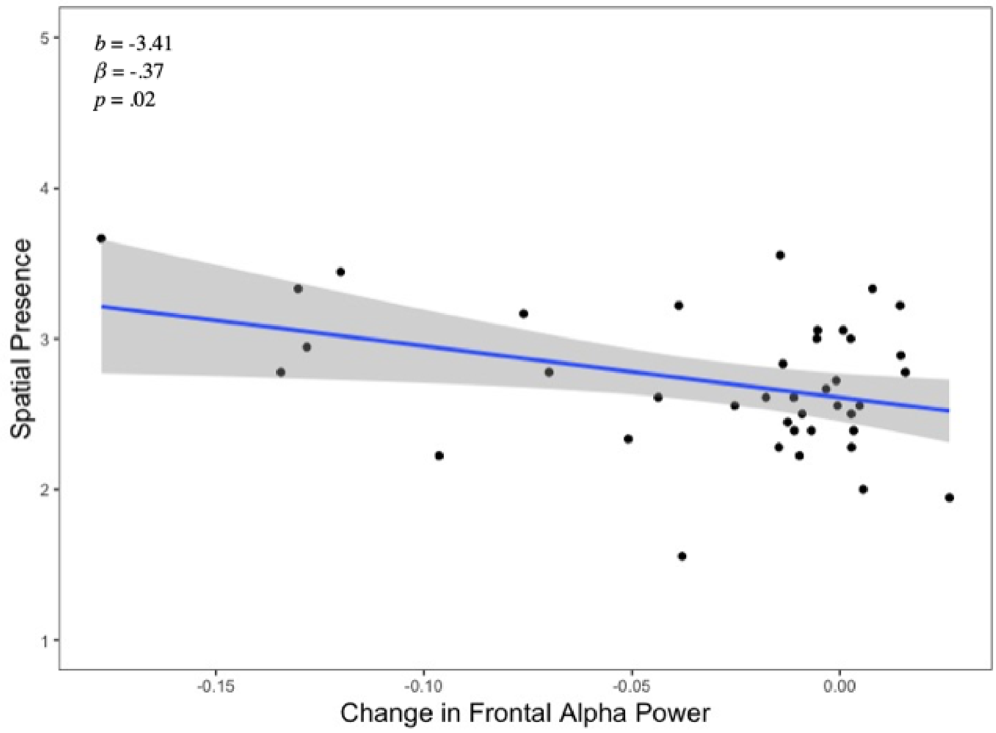

Fig. 2. Relationship between self-reported spatial presence and change in frontal alpha power from Baseline to Affective VR

No significant relationship was found between the change in central and parietal alpha power and spatial presence, $b = -2.24$, $\beta = -0.29$, $t(40) = -1.89$, $p = .07$ and $b = -0.74$, $\beta = -0.15$, $t(40) = -0.92$, $p = .36$, respectively.

3.3. Relationship between alpha power change from Affective VR to Post-VR and subjective presence

No significant relationship was found between the change in frontal, central, and parietal alpha power from Affective VR to Post-VR ($\Delta Alpha_2$) and self-reported spatial presence, $b = 1.27$, $\beta = 0.16$, $t(40) = 0.99$, $p = .33$, $b = 0.45$, $\beta = 0.07$, $t(40) = 0.41$, $p = .69$, and $b = -0.06$, $\beta = -0.01$, $t(40) = -0.09$, $p = .93$, respectively.

4. Discuccion

The aim of this study was to examine whether objective measures of brain activity collected during a VR experience were able to provide insight into the sense of presence, traditionally measured using subjective questionnaires. Participants watched an affective 360° video while their brain activity was monitored using EEG and reported their subjective sense of spatial presence after the experience. Our results showed a significantly lower alpha power in all three brain areas (frontal, central, and parietal) during the VR experience compared to pre- and/or post-baselines. More importantly, the subjective sense of presence that participants reported was significantly correlated with the decrease of alpha power they demonstrated in the frontal area.

The general decrease of alpha power over the whole scalp during the VR experience could be discussed in terms of VR engagement. The parietal and frontal areas of the brain are shown to be involved in the processing of peripheral information and play an important role in motion and behaviour control [5]. A decrease in alpha power in both frontal and parietal areas of the brain found in this study indicate a stronger engagement with the virtual environment during the VR experience. This can be explained by the fact that during the baseline phase, there was not much of cognitive load induced by the virtual environment as participants were not given a specific task whereas the VR experience contained an affective 360° video which might have required emotional processing and processing of the content of the presented story. This is in line with previous research demonstrating that alpha power decreases with increased cognitive load induced by experiencing a task in VR [12], [15], [25].

Furthermore, the significant relationship found between self-reported sense of presence and frontal alpha power changes can provide an objective index for the user experience in VR. Few studies report an effect in frontal alpha power in relation to spatial presence [13], [26]. Previous studies have demonstrated that an increase in spatial presence is accompanied by a decrease in alpha power in parietal areas of the brain [5], [15]. However, in the current study we did not find support for this relationship. This discrepancy could be attributed to the fact that during those studies participants were involved in spatial navigation tasks (such as a virtual maze) whereas in our experiment, subjects only watched an immersive video. The parietal cortex is generally associated with spatial processing and navigation [15] and hence this can explain why the effect in those studies was mainly seen in the parietal area.

It should be noted that although in this experiment a subscale of a commonly used presence questionnaire, namely spatial presence, was used, the feeling of presence experienced by the participants was inherently different from those who experienced a non-affective navigation task. In our experiment, subjects were present in a room where they watched an affective scene. Previous research refers to this as “social presence” or “co-presence”; the feeling of being there with a “real” person [23]. The findings of this study suggest that these two presence experiences recruit different neural mechanisms and are reflected in different brain areas. Future studies should attempt to differentiate between the two by employing different questions that clearly distinguish between the concepts of “being there” compared to “being in a shared space”.

Examining whether EEG frontal alpha power is not only associated with but is also predictive of presence might additionally be an interesting focus for future research. Understanding a construct such as presence involves both explaining and predicting behavior. Previous research has demonstrated that statistical differences do not necessarily have predictive power [36], therefore machine learning algorithms should be employed to put the predictive power of frontal alpha power to the test. The current study at least demonstrated that there is high potential in examining frontal alpha power when it comes to gaining insight in presence.

5. Conclusion

The present study found that the feeling of presence during an affective VR experience using 360° video is associated with a decrease in EEG frontal alpha power and that this change is significantly correlated with the level of self-reported spatial presence. Our results indicate that objective measures of EEG in frontal brain areas are reflective of the sense of presence, highlighting the potential of brain imaging techniques in assessing a user's experience in VR. This is a promising approach for future VR technologies, as headsets equipped with EEG sensors could provide real-time estimation of user experience and enhance the environment based on the user's needs with a sense of presence in virtual reality being reflected in brain activity.

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