EEG signature of out-of-body experiences induced by virtual reality: a novel methodological approach

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Abstract

Out-of-body experiences (OBE) are subjective experiences of seeing one's own body and the environment from a location outside the physical body. They can arise spontaneously or in specific conditions, such as during the intake of dissociative drug. Given its unpredictable occurrence, one way to empirically study it is to induce subjective experiences resembling an OBE using technology such as virtual reality (VR). We employed a complex multisensory method of virtual embodiment in a VR scenario with seven healthy participants to induce virtual OBE-like experiences. Participants performed two conditions in a randomly determined order. For both conditions, the participant's viewpoint was lifted out of the virtual body towards the ceiling of the virtual room, and real body movements were (visuo-tactile ON [VT] condition) or were not (visuo-tactile OFF [noVT] condition) translated into movements on the virtual body below –the latter aiming to maintain a feeling of connection with the virtual body. A continuous 128-electrode EEG was recorded. Participants reported subjective experiences of floating in the air and of feeling high up in the virtual room at a strong intensity, but a weak to moderate feeling of being 'out of their body' in both conditions. The EEG analysis revealed that this subjective experience was associated with a power shift that manifested in an increase of delta and a decrease of alpha relative power. A reduction of theta complexity and an increase of beta-2 connectivity were also found. This support the growing body of evidence revealing a prominent role of delta activity during particular conscious states.

Keywords: out-of-body experience, virtual reality, EEG, consciousness

Introduction

It is now known that humans can experience a disturbed sense of self in varying situations and conditions, sometimes amounting to an out-of-body experience (OBE) which refers to the subjective experience of seeing one's body and the environment from a location outside the physical body (Blanke et al., 2004). OBEs are often reported in near-death experiences (NDEs) (Martial et al., 2020a, 2020b), but also in many other types of contexts, such as sensory deprivation (Blackmore, 1982), drug intake (Timmermann et al., 2018), and sleep paralysis (Herrero et al., 2022). Their incidence is estimated around 10-25% in the normal population (Alvarado, 2000; Blackmore, 1982; Irwin, 1985). Considering the unpredictable occurrence of OBEs, induction methods may be used to empirically study the phenomenon in laboratory settings. Recently, several researchers have successfully induced subjective experiences resembling OBE using non-invasive techniques such as hypnosis (e.g., Facco et al., 2019; Palmieri et al., 2014; Martial et al., 2019) or virtual reality (VR) (e.g., Bourdin et al., 2017; Ehrsson, 2007; van Heugten-van der Kloet et al., 2018). A few researchers also had the opportunity to study OBE artificially induced by direct electrical cortical stimulation in epileptic patients (e.g., Blanke et al., 2002). Current theories assume that OBEs may be a distorted body representation elicited by illusory perceptions arising due to a failure to integrate complex somatosensory and vestibular information (Blanke et al., 2002). In parallel, some psychological theories have also been suggested, such as the one proposing that the OBE is triggered by changes in perception of the physical body boundaries and dissociative processes associated with disruption of somatic inputs (Blackmore, 1984; Irwin, 2000).

Considering that a recurrent feature of the OBE is a convincing impression of reality with all the qualities of three-dimensional perception (Blackmore, 1982, 1987; Blanke & Mohr, 2005; Blanke et al., 2004), VR is a good candidate for studying OBEs in laboratory settings. The particularity and originality of VR is that this method allows the deliberate creation of rich visual experiences that may not match bodily signals and perceptions, which turns out to be essential in the study of the phenomenon of OBE (Tseng & Juan, 2013). Using VR may thus allow to disentangle various components of self-consciousness such as bodily self-location and the sense of ownership and help for the development of a neurophysiological model of OBE and, more broadly, of the sense of selfhood.

In laboratory settings, the VR experience can be accompanied by neurophysiological techniques such as electroencephalography (EEG), a technique that enables the detection of fast synchronized firing of cortical neurons (Núñez et al., 2019). By recording the EEG activity during the experiment, the dynamics of the ongoing oscillations can be detected and characterized by means of a variety of spectral and non-linear methods (O'Neill et al., 2018; Ruiz-Gómez et al, 2018), as well as measures of statistical interdependence between brain regions (functional connectivity, FC) (Friston et al., 2011). Spectral methods are based on representations of the power spectrum of a signal and enable the detection of shifts in the EEG power distribution over the different conditions in the experiment.

The continuous wavelet transform (CWT) is a time-frequency representation of a time series that is well-suited to the analysis of non-stationary signals such as EEG compared to traditional Fourier analysis (Rioul & Vetterli, 1991). In particular, the relative power (RP) derived from the CWT has been shown to be affected by disorders of consciousness, where higher power in the theta, alpha and beta-1 bands has been linked to higher levels of consciousness (Piarulli et al., 2016). The Lempel-Ziv complexity (LZC) is a non-linear measure that reflects the compressibility of a signal and can be used to measure the local diversity of the EEG over time and has been shown to decrease during general anesthesia (Schartner et al., 2015). Thus, EEG-derived measures may provide useful tools to characterize altered states of consciousness such as OBE.

So far, no study has ever used a 128 system EEG to measure changes in brain activity associated to an OBE experimentally induced by VR. In the present preliminary study, we used a protocol adapted from Bourdin and colleagues (2017) in order to induce OBEs using a method of virtual embodiment in a virtual environment in healthy participants. We wanted to induce a “full body ownership illusion” (Kilteni et al., 2012) through a multisensory virtual environment, including a wide field-of-view head tracked stereo head-mounted display, real-time motion capture, a virtual reflection of their body in a virtual mirror, a virtual shadow, and synchronous vibrotactile stimulation on the person's real body. These experimental conditions may permit to induce a dissociative state with a drift of the subjective experience of the body to a position outside one’s usual bodily borders. More specifically, participants performed two distinct experimental conditions in a randomly determined order. For both conditions, the participant’s viewpoint was lifted out of the virtual body towards the ceiling of the virtual room, and real body movements were (visuo-tactile ON [VT] condition) or were not (visuo-tactile OFF [noVT] condition) translated into movements on the virtual body below. The latter condition aimed to maintain a feeling of connection with the virtual body, as shown in Bourdin and colleagues (2017). In their study, Bourdin and colleagues (2017) found that there was a shift in self-location up and out of the body in the noVT condition but less in the VT one. We expect to replicate these results, as well as to study associated electrical brain activity using a 128 system EEG. We investigated the spectral changes of the EEG during this potential subjective experience drift by means of CWT-based RP, complexity using the LZC and we also applied the phase-locking value (PLV) to quantify the phase synchrony between electrodes.

Methods

Participants

Seven healthy participants (3 women; mean age 34±7 years) participated in the study. They were recruited via word of mouth and announcements at the Faculty of Psychology of the University of Barcelona. Participants had to be aged at least 18 and not suffer from epilepsy.

Participants were compensated for participating in the study. Because the present study was intended to be a proof-of-concept, we did not perform a power analysis.

The present study was approved by the ethical committee of the Faculty of Psychology of the University of Barcelona in accordance with the tenets of the Declaration of Helsinki and its later amendments, and all procedures were followed.

VR apparatus

The virtual environment was the one used in Bourdin and colleagues (2017). The environment was designed and rendered using Unity3D (Unity Technologies, Copenhagen, Denmark). It consisted of a virtual room with some virtual standard furniture (see Figure 1; please also see https://www.youtube.com/watch?v=u2Dc6BKqIP0). This was displayed in an Oculus head-mounted-display (Oculus VR, Irvine, California, USA) at 75 Hz using a 1080p OLED panel, split to 75 Hz 960×1080 per eye rendering. We used an Intersense Wand joystick connected to an Intersense IS-9006 hybrid inertial/acoustic 6-DOF tracking system (Intersense, Billerica, Massachusetts, USA) with data streamed over a VRPN network (Taylor et al., 2001) to the computer running the application. The virtual body used was a 3D model of a female or male character available from Rocketbox Studios (Hannover, Germany) according to the participant’s gender. Participant movements were tracked by a Natural Point's Optitrack infrared system (NaturalPoint, Inc. Corvallis, USA), including 12 cameras, tracking 3 triplets of reflective markers on each foot, wrist and forearm. We used the Natural Point's Tracking Tools software (NaturalPoint, Inc. Corvallis, USA) with the VRPN protocol (Taylor et al., 2001) to calculate in real-time the positions and orientations of each marker and to stream to the VE. Tactile stimulations were administered using four vibrotactile devices (vibrated for 100 ms at a frequency of 150 Hz) on both wrists and ankles of the individual and controlled by an Arduino (Arduino SRL., Ivrea, Italy) board. See Bourdin et al. (2017) for more details.

Please insert Figure 1 above here

Procedure

After being instructed about the experimental procedure, participants were invited to sign the informed consent. They were asked to what extent they had experience with VR (using a Likert scale as follows: 1 = “novice” to 7 = “expert”). They were then invited to wear a black tracking suit and black socks. For each participant, we scaled the virtual body based on the measures of their limbs. Participants were seated in a chair with their arms on their thighs and their legs lying stretched on a low table. We attached vibrators to their wrists and ankles, and several tracking markers were collocated on their limbs. We set up the EEG cap (gHIamp recorded 128 active EEG channels). Afterwards, a resting state recording was performed for 4 min with eyes open. We then set up the head-mounted-display (on top of the EEG cap). During the whole VR experience, we tried to ensure as much as possible that the head-mounted-display did not disturb the EEG signal. Once the full set-up was completed, instructions were given thanks to a recorded voice. The experimental session started with the instruction of orally describing the virtual environment, permitting the participant to explore and become familiar with the virtual environment. When looking down at themselves in the virtual environment, participants could see a virtual body (with black clothes) from a first-person perspective in the same posture as their real body, moving congruently and synchronously with their real movements. They could also see this virtual body in a virtual mirror placed in front (see Figure 1). This was followed by the three trials of a Mental Ball-Dropping (MBD) task in which participants were invited to estimate the time (by clicking a button of the wand) an imaginary apple would take to fall from their hand to the floor (Lenggenhager et al., 2009). This was used as an estimate of the sense of self location. After the three MBD task trials, two tasks were performed to induce body ownership through synchronous visuomotor and visuotactile stimulation. First, the voice asked them to look towards their legs and follow with their feet the path that virtually appeared on the low table, as described in Kokkinara and Slater (2014). Second, participants felt virtual balls hitting the virtual body through corresponding vibrotactile stimulations. After all these familiarization tasks, participants randomly performed two conditions: the noVT condition (visuo-tactile OFF) and the VT condition (visuo-tactile ON) (see Figure 2). Each condition was divided into two phases: an initial embodiment phase (*in-the-body* phase) that was the same for both conditions, and the out-of-body phase (*out-the-body* phase) which was different for the two conditions. In the latter, for both conditions, the viewpoint of the participant was lifted out of the virtual body towards the ceiling of the virtual room, and just behind the body, so that the body could be seen below. The noVT condition consisted of the balls going up with the invisible body (i.e., the elevated viewpoint) and striking the space around the participant's visual center of perception. In this condition, real body movements were not translated into movements on the virtual body below; the virtual body below remained stationary. By contrast, the VT condition consisted of the balls striking the virtual body that participants could see below but they still felt the vibrations. In this condition, real body movements were translated into movements on the virtual body below. After the *in-the-body* phase of each of the two conditions, participants were asked to what extent they felt as if the body they were seeing was their own body (using a Likert scale as followed: 1 = “I did not feel that at all” to 7 = “I felt it in its maximum intensity”) and to what extent they felt as if the body they were seeing belonged to someone else (using a Likert scale as followed: 1 = “I did not feel that at all” to 7 = “I felt it in its maximum intensity”). After the *out-the-body* phase of the two conditions, participants were asked these two same questions, and four additional questions (see Table 1 for details). The *obe* and *otherbodyobe* questions of this set of questions (see Table 1 for details) were used to specifically assess potential subjective experience resembling OBE. The experimental session ended with a black screen. In total the experiment lasted between 60 to 90 minutes, including about 40 minutes in the VR.

Please insert Figure 2 above here

After removing trackers and vibrators with the minimum interaction possible, participants were invited to answer two Visual Analog Scales (VAS) asking them to what extent they felt absorbed in the tasks (ranging from 0 to 10) and to what extent they felt dissociated in the tasks (ranging from 0 to 10) (subjective ratings from Vanhaudenhuyse et al., 2019). Finally, they were debriefed about the experiment.

EEG analyses

Preprocessing

The EEG recordings were first segmented into three sequences corresponding to the resting state (4 minutes), noVT (32 seconds) and VT (32 seconds) conditions. Each segment was filtered between 1 and 70 Hz by means of zero-phase finite impulse response (FIR) filter, as well as with a 50 Hz FIR notch filter to remove powerline artifacts. Both filters were designed by means of a Hamming window, with a filter order of 2000. Afterwards, an independent component analysis (ICA) was carried out on each of the sequences in order to discard ICA components with clear artifacts, such as heartbeats and eye blinking, after visual inspection. Subsequently, each sequence was segmented into 1-s epochs and the epochs in which artifacts remained after the ICA were discarded. 1-s epochs were used as a tradeoff between epoch length and the total number of discarded segments. All subsequent analyses were conducted on five frequency bands: delta (δ, 1-4 Hz), theta (θ, 4-8 Hz), alpha (α, 8-13 Hz), beta-1 (β1, 13-19 Hz), and beta-2 (β2, 19-30 Hz). The gamma (γ, 30-70 Hz) band was not included due to the presence of high frequency muscle activity present in parts of the recordings, which were unavoidable due to the length of the experiment and the nature of VR headsets. Nonetheless, the EEGs were rigorously visually inspected after filtering to ensure these artifacts were successfully removed.

Continuous wavelet transform

The continuous wavelet transform (CWT) is a time-frequency representation of a time series that provides a good compromise between the time and the frequency resolutions compared to the short-term Fourier transform (Tallon-Baudry et al., 1996). The CWT provides control over the frequency and time resolution in which neuroelectric components can be detected (Samar et al., 1999). In order to adequately model the EEG signal, a biologically plausible fit was provided with the Morlet wavelet acting as “mother wavelet” (Núñez et al., 2017; Roach & Mathalon, 2008). Two of its parameters (center frequency and bandwidth) need to be adjusted and were set to 1 to obtain a good balance between the time (Δt) and frequency resolutions (Δf) at low frequencies (Bachiller et al., 2015; Núñez et al., 2017). Additionally, the Heisenberg box was set with a width of two times Δt and

Δf as a tradeoff between frequency and time resolutions (Bachiller et al., 2015; Núñez et al., 2017). Finally, the cone of influence was taken into account to overcome the issues of edge effects introduced by discontinuities in the epochs (Torrence & Compo, 1998).

Relative power

In order to analyze the spectral content of each sequence, the relative power (RP) was computed from the CWT. The RP characterizes the contribution to the power spectrum of each frequency band and is computed as the sum of the contribution of each spectral component in each band to the total power (Núñez et al., 2017). The RP was computed as follows:

$$PSD(f) = \sum_{n=1}^{n=N} CWT_n(f, n\Delta t), \tag{1}$$

$$RP_{band} = \sum_{f=f_{b1}}^{f_{b2}} PSD(f), \tag{2}$$

where CWT_n is the normalized CWT scalogram (absolute value of the CWT squared) to the sum of the absolute values in the 1-30 Hz range to ensure the RP was a relative measure, N is the number of temporal samples in the CWT of a single epoch, and $f_{b1}$and f_{b2} represent the lower and upper frequency limits of each band.

Lempel-Ziv complexity

The Lempel-Ziv complexity (LZC) is a measure of complexity and uncertainty which is related to the number of distinct patterns in a symbolic sequence and the rate in which they appear, with higher LZC values indicating a higher level of complexity in the data (Abásolo et al., 2006; Schartner et al., 2015). In EEG data, the grand-average LZC over channels can be considered a measure of differentiation, as it measures the diversity of patterns across time and space (Schartner et al., 2015). The LZC algorithm can only be computed on strings composed of a limited number of symbols, therefore an EEG time series needs to be transformed into a symbolic sequence before its computation. To achieve this, a coarse graining of the EEG is performed by means of a thresholding procedure as follows (Abásolo et al., 2006):

$$s(t) = \begin{cases} 0 \; if \; x(t) < T \\ 1 \; if \; x(t) > T \end{cases} \tag{3}$$

where the threshold T is the median of the time series $x(t)$. After conversion into a binary sequence, the LZC algorithm is applied. A full description of the LZC implementation used in this study can be found in Abásolo et al. (2006). The LZC was normalized by dividing it with the upper bound of the complexity, which has been proven to be $n/log_{\alpha}(n)$, where α is the number of different symbols in the set and n is the length of the sequence in samples (Lempel & Ziv, 1976) and was applied across individual frequency bands (Kim et al., 2022; Tanabe et al., 2022).

Connectivity estimation

In the present study, we chose a phase-based connectivity measure, the phase-locking value (PLV) (Lachaux et al., 1999), which quantifies the phase synchrony between two signals in a specific frequency band by means of estimates of the instantaneous frequency (Colclough et al., 2016). The PLV looks for latencies in which the phase difference between the two signals are stable across time, which is known as "phase locking". For resting-state recordings, the PLV is computed over the epochs in which the recording is divided (in the present study 1-s epochs were used, following the artifact rejection step of the preprocessing). The PLV can be computed as follows (Bruña et al., 2018):

$$PLV_{X,Y} = \frac{1}{T}\left|\sum_{t=1}^{T} e^{-i(\phi_X(t)-\phi_Y(t))}\right|, \tag{4}$$

where ϕ is the instantaneous phase of the signals X and Y and T is the length of each epoch in samples.

In order to eliminate spurious correlations due to volume conduction and field spread, the time series were orthogonalized before the computation of the connectivity. For each epoch, each channel was orthogonalized with respect to a linear projection of the other by means of a pairwise linear regression, and the results of the PLV after both regressions were averaged (Brookes et al., 2012; O'Neill et al., 2018).

Statistical analyses

Demographic data and scores are expressed as mean and standard deviation (SD) or as medians with interquartile range (Q1-Q3) for asymmetric distribution. We compared the scores obtained after the VT and noVT condition using paired-sample Wilcoxon signed-rank tests ($p < 0.05$).

Regarding the EEG data, an exploratory analysis was performed to check the distribution of the RP and PLV values from all three conditions by means of the Shapiro-Wilk test (normality) and Levene test (homoscedasticity). Both conditions were not met by the data, and therefore nonparametric tests were conducted to evaluate the statistical differences between the conditions. Friedman tests were performed to determine interactions across the three conditions (resting state, VT and noVT) on the five frequency bands under study. If statistically significant differences were found, pairwise Wilcoxon signed-rank tests were performed to evaluate differences between specific conditions. A false discovery rate (FDR) correction was completed to control for the number of comparisons with a significance level set to $\alpha = 0.05$ (Benjamini & Hochberg, 1995). Both the statistical analyses and the signal processing were achieved using MATLAB® software (version R2019a, Mathworks, Natick, MA).

Results

Participants

Participants reported having a little to no level of prior experience with VR (median = 2.28; interquartile range [IQR] = 1-2.5).

Regarding the *in-the-body* phase, participants reported higher responses to *mybody* question than to *otherbody* question for both conditions, suggesting an overall body ownership for both conditions (see Table 1 for details).

Regarding the *out-the-body* phase of the noVT condition, participants reported particularly high responses to *floatingobe* and *elevatedobe* questions. In the noVT condition, they tended to disown the virtual body (*mybodyobe* and *connectionobe* question), while in the VT condition, participants tended to report connection with the virtual body that they saw below (*connectionobe* question). For both conditions, participants reported they had felt ‘out of their body’ at a moderate intensity (*obe* question). No significant differences between the scores were observed between the two conditions, although the *connectionobe* question was closed to the threshold value (see Table 1 for details).

Participants reported a high score of absorption (median = 7.34; IQR = 7.7-8.65) and a moderate score of dissociation (median = 5.58; IQR = 5-7.05).

Table 1. Participants’ responses to the body ownership and out-of-body questions for both conditions (noVT and VT). The latest two columns report median scores reported by the participants from Bourdin et al. (2017).

Variable name	**Questions on a Likert Scale (1 = “I did not feel that at all” to 7 = “I felt it to the maximum intensity”)**	**noVT**	**VT**	**Z statistic**	***p***	**Effect size**	**Bourdin et al. (2017)’s median scores**	**Bourdin et al. (2017)’s median scores**
							noVT	**VT**
Immediately after the *in-the-body* phase: Please indicate to what extent you felt each of the sensations that I will indicate now.								
mybody	I felt as if the body I was seeing was my own body.	5 (2-6)	4 (3-6)	4	0.850	-0.200	6 (5-6)	6 (5-6)
otherbody	I felt as if the body I was seeing belonged to someone else.	2 (1-4)	1 (1-3)	5.5	1	0.100	3 (1.5-5)	2.5 (1.5-3.5)
Immediately after *the out-of-body* phase: Please indicate to what extent you felt each of the sensations that I will indicate now. When you answer these questions, please refer to your experience when you were watching the room from above.								
mybodyobe	I felt as if the body I was seeing was my own body.	3 (1-3)	4 (2-6)	5	0.281	-0.524	2 (2-5.5)	4 (2-5)
otherbodyobe	I felt as if the body I was seeing belonged to someone else.	4 (3-5)	2 (1-3)	9	0.197	0.800	6 (3.5-7)	4.5 (2-6)
floatingobe	I felt as if I was floating in air.	7 (6-7)	5 (4-6)	10	0.098	1	7 (7-7)	6 (6-7)
elevatedobe	I felt as if I was in an elevated position in the room.	7 (6-7)	6 (5-7)	4.5	0.586	0.500	7 (6-7)	7 (7-7)
connectionobe	I felt a connection with the body, as if I was looking down at myself.	1 (1-2)	5 (3-6)	0	0.054	-1	2.5 (2-6)	5 (4-7)
obe	I felt out of my body.	2 (1-4)	3 (2-5)	2	0.170	-0.733	6 (4.5-7)	6 (4-7)

EEG results

The RP values averaged over all electrodes are displayed in Figure 3. Statistically significant differences were found in the delta ($p = 0.018$, $\chi^2(2) = 8$, Friedman test; $p = 0.030$ after FDR correction), alpha ($p = 0.005$, $\chi^2(2) = 10.57$, Friedman test; $p = 0.025$ after FDR correction) and beta-1 bands ($p = 0.018$, $\chi^2(2) = 8$, Friedman test; $p = 0.030$ after FDR correction). In the delta band, the statistical tests showed significant differences between the resting state and the noVT condition ($p = 0.015$, $W = 28$, Wilcoxon, signed-rank test; $p = 0.046$ after FDR correction). In the alpha band, the statistical tests revealed significant differences between the resting state and both the VT ($p = 0.015$, $W = 28$, Wilcoxon, signed-rank test; $p = 0.023$ after FDR correction) and noVT condition ($p = 0.015$, $W = 28$, Wilcoxon, signed-rank test; $p = 0.023$ after FDR correction). In the beta-1 band, significant differences between the resting state and noVT condition ($p = 0.015$, $W = 28$, Wilcoxon, signed-rank test; $p = 0.046$ after FDR correction) were found. Figure 4 shows topographic maps of the RP values and the statistical differences between conditions ($p < 0.05$, Wilcoxon, signed-rank test). In the delta band, the noVT condition displayed a significant increase in power in the fronto-central area compared to the resting state condition that was more localized to the central region in the VT condition. In the theta band, there were for the most part no clear differences between conditions, except for some very localized areas in the central regions between the noVT and VT condition, while the alpha band displayed a clear decrease in centro-parietal RP during both conditions. Interestingly, in the beta-1 band, the noVT condition showed a localized decrease in RP in the frontal and central areas that was not as apparent in the VT condition.

Please insert Figure 3 above here

Please insert Figure 4 above here

The LZC values averaged over all electrodes in the theta band are shown in Figure 5. Only the theta band is shown for ease of visualization, as it was the only band with statistically significant differences between conditions. As previously mentioned, statistically significant differences were found in the theta band ($p = 0.028$, $\chi^2(2) = 7.14$, Friedman test; $p = 0.140$ after FDR correction). In said band, the statistical tests indicated that there were significant differences only between the resting state and noVT condition ($p = 0.015$, $W = 28$, Wilcoxon, signed-rank test; $p = 0.046$ after FDR correction).

Please insert Figure 5 above here

The PLV values averaged over all electrode pairs are displayed in Figure 6. Statistically significant differences were again found in the alpha ($p = 0.021$, $\chi^2(2) = 7.71$, Friedman test; $p = 0.105$ after FDR correction) and beta-2 bands ($p = 0.049$, $\chi^2(2) = 6$, Friedman test; $p = 0.124$ after FDR correction). In the alpha band, the statistical tests revealed significant differences between the resting state and the VT ($p = 0.031$, $W = 28$, Wilcoxon, signed-rank test; $p = 0.046$ after FDR correction) and between the VT and noVT condition ($p = 0.015$, $W = 26$, Wilcoxon, signed-rank test; $p = 0.070$ after FDR correction). In the beta-2 band, the statistical tests showed significant differences between the resting state and the noVT condition ($p = 0.046$, $W = 2$, Wilcoxon, signed-rank test; $p = 0.109$ after FDR correction).

Please insert Figure 6 above here

Discussion

At a phenomenological level, our VR protocol induced a feeling of subjective body ownership over the virtual body during the embodied (*in-the-body*) phase for both VT and noVT conditions in a sample of healthy participants who reported having a rather low level of prior experience with VR. Our participants' median scores for the two conditions were nonetheless slightly lower than the median scores found in Bourdin and colleagues' (2017) study. Next, in the *out-the-body* phase of the noVT condition, although participants reported particularly high responses to the questions asking if they felt high up in the virtual room and floating in the air, they also reported they had felt 'out of their body' (*obe* and *otherbodyobe* question) at a weak to moderate intensity. Nevertheless, participants tended to report a disownership of the previous owned body, although this feeling seems weaker than what participants from Bourdin et al.'s (2017) study reported. The scores did not significantly differ between the two conditions for all questions, although the *connectionobe* question tended to be significant. Indeed, as expected, in the *out-the-body* phase of the VT condition, participants tended to report a maintained feeling of connection with the virtual body, which was much less reported in the noVT condition. Moreover, our participants reported high scores of absorption and a moderate score of dissociation for the whole VR experiment session. Therefore, at a phenomenological level, the present VR protocol combining the first-person perspective, visuomotor and visuotactile synchronous stimulation, seemed to induce a feeling of subjective body ownership over a virtual body during the *in-the-body* phase and a strong sensation of floating in the air but a weak to moderate feeling of being 'out of their body' in the *out-the-body* phase for both conditions.

In terms of EEG activity changes, the VT and noVT condition did not differ much, except for PLV values. Nonetheless, it is worth mentioning that for the grand-average RP values, significant differences were found only between the resting state and noVT conditions in the delta and beta-1 bands, and for the LZC in the theta band. The altered alpha and beta-1 connectivity patterns showed an increase of high frequency connectivity associated to the noVT condition (but not the VT condition), while grand-average alpha connectivity was lower in the VT condition compared to both the eyes-open resting state and noVT condition. EEG beta phase connectivity has been shown to increase during transitions between the baseline to unresponsive, and unresponsive to baseline states in propofol-induced sedation compared to consciousness and unconsciousness (Lee et al., 2017), thereby perhaps indicating that the OBE brain activity could behave similarly to a state of transition between states of consciousness.

Regarding the noVT condition specifically, the EEG RP analysis demonstrated a decrease in parietal alpha band RP, a localized decrease in beta-1 band RP in the frontal and central areas, as well as a significant increase in delta band power in the fronto-central area. Interestingly, this is consistent with the EEG pattern found by Timmermann and colleagues (2019) who studied immersion into a N,N-Dimethyltryptamine (DMT)-induced state: the DMT experience was associated with decreases in total spectral power in alpha and beta bands paralleled by increases in spontaneous signal diversity and the emergence of delta (and theta) oscillations during peak effects of the hallucinatory experience. Importantly, DMT is known to induce OBE associated with vivid visual imagery and somatic effects (Lawrence et al., 2022; Timmermann et al., 2018), just like what we intended to study in the present work. Interestingly, a constantly growing body of evidence from research has recently revealed a prominent role of delta activity during conscious states (see Frohlich et al., 2021 for a discussion), while a historically rooted consensus was that the delta rhythm is an indicator of unconsciousness (or highly diminished consciousness), such as in anesthesia, slow wave sleep, and coma.

Alpha power was shown to be related to self-identification and self-location during a VR experiment inducing multisensory conflicts, that is, in which subjects were shown a life-sized, back facing virtual body or a cubic control object while synchronously or asynchronously stroking the back of the participant and the character or cubic control object (Leggenhager et al., 2011). EEG alpha power significantly decreased in the sensorimotor areas when subjects were asynchronously stroked compared to the visual baseline (Leggenhager et al., 2011). The authors suggest that alpha oscillations in sensorimotor cortex and medial prefrontal cortex may capture self-location (Leggenhager et al., 2011). More generally, alpha band power over central areas has been repeatedly associated with body perception and sensorimotor processing (see Pineda, 2005 for a review). The pattern of decreases in alpha power observed in the present study might be related to modifications of self-location induced by the two VR conditions. In this study, alpha is the band which shows the most RP values decreases, mostly in central areas. This alpha decrease is nonetheless not consistent with what was observed in a previous study that invited NDE experiencers to recall the OBE they experienced during their NDE using hypnosis (Martial et al., 2019). This may be due to the fact that the latter was based on the recall of an autobiographical memory, thus probably reflecting working memory load.

The significant decrease of theta band LZC in the noVT condition compared to the resting state condition could be linked to an artificially induced state of altered consciousness. Another complexity-based index, the perturbational complexity index (PCI) is one of the most reliable indicators of the level of consciousness and is based on the complexity of electrocortical responses after transcranial magnetic stimulation (TMS) (Casali et al., 2013). Additionally, complexity of brain activity by itself without TMS has also been shown to be reduced in anesthesia (Schartner et al., 2015). The results here suggest that complexity might be partially reduced, pointing towards the experience of OBE-like sensations of floating in the air and feeling high up followed patterns similar to those of altered levels of consciousness.

Interestingly, Bourdin et al. (2017) showed that a virtual OBE results in a reduction of death anxiety. The authors hypothesized that it may be due to an implicit learning that consciousness may be separated from the physical body. Extrapolating from this study, one can assume that OBEs artificially induced by VR may be used as a therapeutic tool in end-of-life patients since the authors showed that their VR paradigm can have psychological effect, in relation to death anxiety.

Some limitations of this study should be acknowledged. Firstly, the EEG recordings were obtained during long sessions where a restart of the protocol was not feasible, and thus artifacts related to muscle activity had to be removed or dealt with during the preprocessing stage, which prevented the inclusion of the gamma band in the analyses. Secondly, it is worth noting that the low level of experience could indicate that the observed effects of the experiment were increased by the lack of expectations due to previous experience with VR and the novelty of the OBE-like experience was enhanced. Thirdly, the presence of the EEG cap, which may have caused a feeling of discomfort or strengthened proprioception and perception from the real body, may have influenced the relatively weak to moderate perception of being out of their body reported by the participants. Fourthly, with the notable exception of the RP, the results for the most part did not survive a FDR correction, which led to a more cautious approach to the interpretation of results. This was, however, to be expected given the small sample size. Nonetheless, the present results are encouraging of a follow-up study with a larger sample. Even though the phenomenology reported by our participants did not significantly differ between the two conditions, and the noVT tended to induce a stronger feeling of dissociation with the virtual body, which they were seeing below from the ceiling of the virtual room, one can hypothesize that significant differences between both conditions would be observed in a larger sample such as in Bourdin et al. (2017). It would also be interesting to add further questions regarding the subjective experience of body ownership and bodily borders to detail their phenomenological experience. Future empirical studies are needed to better understand OBEs and other disturbed self-perceptions. However, this study represents a step in exposing the neurophysiological underpinnings of a virtually induced OBE.

In conclusion, at a phenomenological level, the present VR protocol seemed to induce a feeling of subjective body ownership over a virtual body during the *in-the-body* phase for both conditions. In the *out-the-body* phase, we succeeded in inducing subjective experiences of floating in the air and of feeling high up in the virtual room without any adverse effects in a small sample of healthy participants, but the feeling of being ‘out of their body’ reported by our participants was relatively weak. Although some improvements can be done in the methodology, this study provides a proof-of-concept methodology for studying the phenomenon of OBEs and presents promising EEG results.

Author contribution

CM and SL secured the funding. CM, HC, PB, AM and OR collaborated on data acquisition. All authors contributed to conceptualization and study design. CM and PN did the analyses and wrote the original draft. All authors contributed to reviewing the manuscript in detail and approved the final manuscript.

Data availability statement

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

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Figure 1. **The virtual environment and set-up**.

(A) One of the participants wearing the equipment, including the head-mounted display and the EEG. (B) The participant can see their virtual body from a first person perspective, including the wand. (C) Part of the virtual environment from a first person perspective, including the mirror and the virtual balls. Images (B) and (C) were taken from Bourdin, Barberia, Oliva, and Slater (2017).

Figure 2. **The OBE and VTO conditions**.

(A) The VT condition in which the balls hit the virtual body that participants could see below but they still felt the vibrations. (B) The noVT condition in which the balls went up with the invisible body (i.e., the elevated viewpoint) and hit the space around the participant’s visual center of perception. Images were taken from Bourdin, Barberia, Oliva, and Slater (2017).

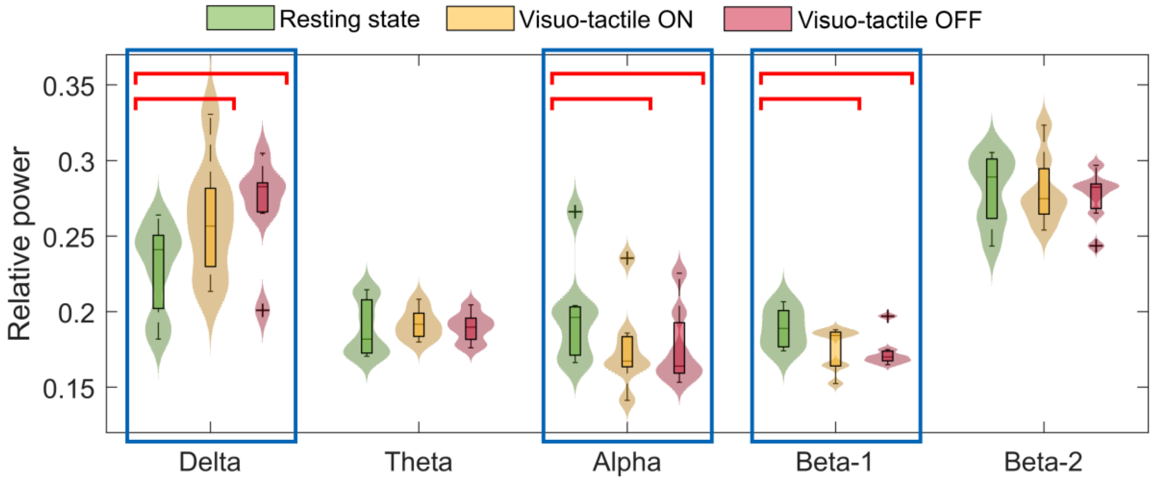

Figure 3. **Distribution plots depicting the RP values averaged over all electrodes for all three conditions under study.**

Statistically significant between-condition differences are indicated with blue rectangles (*p* < 0.05, Friedman test, FDR corrected for multiple comparisons), while statistically significant post-hoc differences between pairs of conditions in bands that showed significant group interactions are indicated with red brackets (*p* < 0.05, Wilcoxon, signed-rank test).

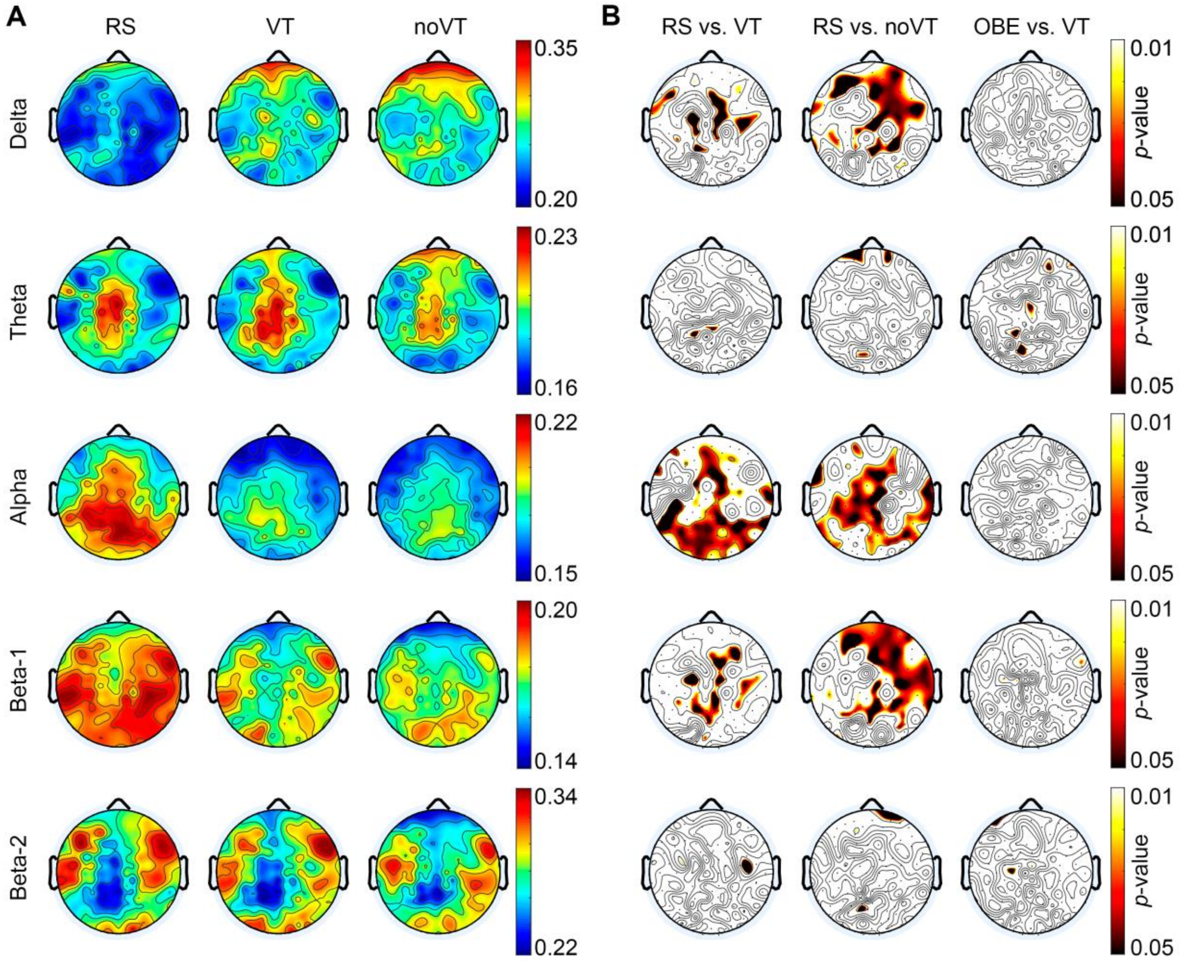

Figure 4. **Topographic maps of (A) the RP values and (B) the statistical comparisons between conditions for each electrode location and frequency band**.

(A) Each column corresponds to a specific condition of the VR experiment, while each row corresponds to a frequency band under study. (B) Each column represents statistically significant between-condition differences ($p < 0.05$, Wilcoxon, signed-rank test), while each row corresponds to a frequency band under study. RS: resting state; VT: visuo-tactile ON; noVT: visuo-tactile OFF.

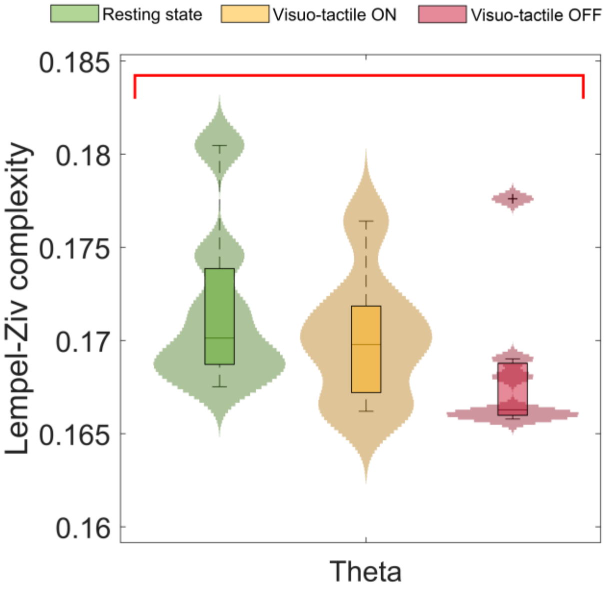

Figure 5. Distribution plots depicting the Lempel-Ziv complexity (LZC) values averaged over all electrodes for all three conditions under study in the theta band. Statistically significant post-hoc differences between pairs of conditions are indicated with red brackets ($p < 0.05$, Wilcoxon, signed-rank test). Only the theta band is shown for ease of visualization.

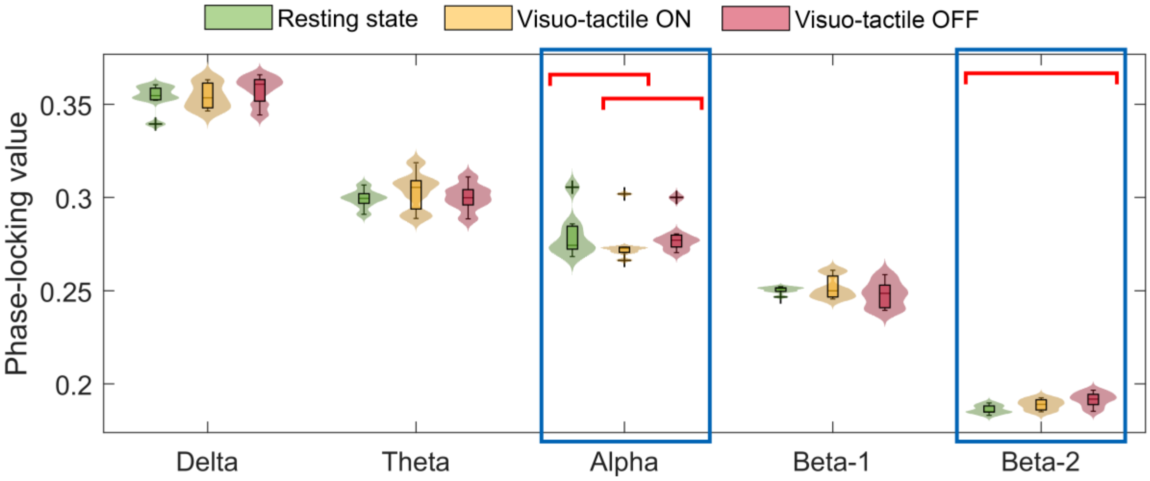

Figure 6. Distribution plots depicting the grand-average PLV values averaged over all electrode pairs for all three conditions under study. Statistically significant between-condition differences are indicated with blue rectangles ($p < 0.05$, Friedman test), while statistically significant post-hoc differences between pairs of conditions in bands that showed significant group interactions are indicated with red brackets ($p < 0.05$, Wilcoxon, signed-rank test).