



Virtual Reality Experience as Reflected in EEG Microstates

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Abstract

The development of virtual reality technology has provided psychological research with powerful tools by presenting stimuli and constructing scenarios, and the combination of VR and neuroimaging techniques begins to provide particularly interesting insights into the experience of virtual events and scenarios, similar to real life. Here we combined VR with EEG technology, so to record and analyze EEG microstates evoked by VR experiences. Our findings suggest that microstates A, B, C, and D reflect cognitive activities during VR experience, while microstate E specifically corresponds to immersion and presence in VR. These findings provide crucial insights into the neural underpinnings of the experience of virtual reality.

Keywords Virtual reality · EEG · Microstates

Introduction

Virtual Reality (VR) refers to computer-generated three-dimensional virtual environments in which user is enclosed in a space that is sealed off from the physical environment at least visually (Rauschnabel et al. 2022). Head-mounted displays (HMDs), which facilitate the physical isolation from the real world (Witmer and Singer 1998), serve as hardware devices for VR. Compared to traditional planar displays and other input devices, VR provides more realistic and engaging experiences (Reer et al. 2022). VR provides good ecological validity and allows for tight experimental controls, which has driven its growing popularity among researchers (Riva et al. 2007). Moreover, VR enables researchers to develop novel and cost-effective research paradigms that ensure safety and avoid ethical issues (Jin et al. 2024).

However, although VR is often used as a tool for psychological experiments, and considered a useful method to

induce mental and behavioral changes in human participants by means of specific tasks, it is not yet well understood exactly how VR itself affects human perception and experience. To address this issue, we were interested to assess participants' psychological states in a VR environment, and we made use of electroencephalography (EEG) to measure and compare the underlying electrophysiological states changes before, during, and after VR experience.

Presence and Immersion

When using VR, users typically experience immersion and presence, and they experience these more intensely than when using other technological means (Cadet and Chainay 2020). Previous studies reported that the sense of immersion and presence felt by participants can affect their performance or the effectiveness of experimental manipulations (Cadet and Chainay 2020), which suggests that studying these two phenomena is important for understanding the impact of VR on experimentation.

Presence refers to the subjective feeling of being in a certain environment despite the body not being physically present in it (Witmer and Singer 1998). Usually, the more similar the VR environment is to the real world, the higher the sense of presence. Immersion refers to a psychological state or experience, as a perception of being surrounded by and interacting with an environment that provides continuous stimuli and experiences (Witmer and Singer 1998;

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Dickinson et al. 2020). In a high immersion state, people focus their attention on the virtual environment, feel isolated from the outside world, and lose track of time. For example, when playing a game like Tetris, which consists of simple graphics, players are unlikely to feel as though they are in a world of blocks, thus they hardly experience a sense of presence, yet they still become deeply immersed in the game (Jennett et al. 2008).

In current research on immersion and presence, most studies utilize questionnaires as measurement tools (Shin 2018; Dickinson et al. 2020). A minority of studies use indirect measurements with physiological methods (Pavic et al. 2023). Some studies have attempted to measure presence by incorporating the oddball paradigm during VR experiences, and analyzed event-related potential (ERP) signals elicited by standard and deviant tones to measure participants' sense of presence (Burns and Fairclough 2015; Terkildsen and Makransky 2019; Grassini et al. 2021). However, by including external stimuli, these methods primarily measure participants' attentional states. Such stimuli not only disrupt the VR experience but also create a dual-task situation, and introduce additional noise into the data collection. To understand the electrophysiological impact of VR experiences without disrupting the experience or introducing additional interference, non-intrusive measurements are therefore recommended.

EEG Microstate Analysis

EEG is a powerful and widely used neuroimaging technique that non-invasively measures scalp electrical activity. This method enables high temporal resolution non-invasive assessment of neural activity arising from both local and long-range neural coordination (Ingber and Nunez 2011). An increasing number of studies have integrated EEG and VR for the investigation of presence (Burns and Fairclough 2015; Terkildsen and Makransky 2019; Grassini et al. 2021), emotional arousal (Hofmann et al. 2021), and virtual exercise (Burin et al. 2020). These researches predominantly employed ERP techniques - a widely utilized EEG technique in psychological research that establishes relationships between controlled stimuli, behavioral responses, and neural activities. This approach necessitates multiple repetitions of identical condition trials and the superposition of trials during data processing to form waveforms (Sauseng et al. 2007). However, the requirement for stimulus repetition limits its application and compromises ecological validity.

Due to the limitations of ERP techniques, researchers have proposed various analytical approaches based on the stochastic and multidimensional nature of EEG signals to quantify and characterize different features of neural activity and their functional roles (Khanna et al. 2015). EEG

Microstate analysis is one such method, it is considered capable of reliably assessing synchronous large-scale brain networks and their temporal dynamics, with different potential topographies representing the activation of different neural networks (Khanna et al. 2015). These topographies show two notable characteristics. First, most neural signals can be represented with a few topographies (Strik and Lehmann 1993). Second, these topographies do not gradually change over time; instead, one topography remains dominant for approximately 80–120 milliseconds (ms) before abruptly transitioning to another topography (Lehmann et al. 1987). These transiently stable topographies have been termed as EEG microstates.

According to a recent review of resting-state microstates (Tarailis et al. 2023), among 50 included studies, 37 employed four microstates, and the remaining studies identified five to seven microstates. However, when matching microstates across studies, studies using the same number of microstates may cover different types of microstates. The review categorized microstates into seven classes (A-G). Microstates A-D can be stably reproduced and often explain most of the variance (Michel and Koenig 2018). Specific topographies include: right-frontal to left-posterior distributions (microstate A); left-frontal to right-posterior patterns (microstate B); symmetrical fronto-posterior configurations (microstate C); and centrally dominant frontal topographies (microstate D; Koenig et al. 1999, 2002).

There are several temporal indices representing the temporal dynamics of microstates. One is the mean duration (or lifespan), defined as the average period a microstate remains stable (Lehmann et al. 1987). This index is measured in milliseconds and considered to reflect synchronized activity of intracortical generators (Khanna et al. 2015). The average number of times a microstate dominates within one second is called occurrence (Lehmann et al. 1987), which is believed to reflect the tendency for synchronous activation within the cortex and is measured in hertz (Hz; Khanna et al. 2015). The proportion of the total recording time during which a microstate dominates is called the coverage or contribution rate (Lehmann et al. 1987), which reflects the relative time of microstate activation and is measured as a percentage (Murray et al. 2008; Khanna et al. 2015). Global explained variance (GEV) is the sum of the explained variance weighted by the global field power (GFP) at each moment (Murray et al. 2008).

Microstate analysis has demonstrated significant efficacy in characterizing and evaluating brain network activities across various psychiatric and neurological disorders, including depression levels (Qin et al. 2022), autism spectrum disorders (Jia and Yu 2019), schizophrenia (Kindler et al. 2011), and gaming disorder (Cui et al. 2021). Recently, studies have also reported microstates can be used to

differentiate individuals with different personality traits, such as attitudes toward supernatural beliefs (Schlegel et al. 2012), and extraversion (Tomescu et al. 2022).

Although microstates have been widely investigated, their relationships with specific functional and cognitive domains are not yet fully understood (Gschwind et al. 2016). Current evidence tentatively associates microstate A with auditory and visual processing, microstate B with visual input and visualization, and microstates C and D with cognition and executive functions (Tarailis et al. 2023).

Current Study

In this study, we combined VR and EEG technologies and employed microstate analysis to assess the electrophysiological activity changes of participants during VR experience in a non-intrusive and non-invasive manner. We aimed to analyze changes induced by VR experience by comparing temporal indices in microstates during pre-VR (experience), VR experience, and post-VR (experience). By examining the impact of VR stimuli on EEG data, this research aimed to provide a reference for future studies utilizing VR as an experimental presentation method.

We refrained from predefining the number of fitted microstates but expected to identify at least the common four classes of microstates. We hypothesized significant changes in temporal indices of these four microstate classes between VR experience and/or post-VR relative to baseline (pre-VR). Specifically, microstates A and B were predicted to exhibit significantly higher levels of presence during the VR experience compared to the pre-VR, followed by a rapid return to baseline levels after VR experience finished. In contrast, microstates C and D were expected to change significantly during VR experience and to partially recover after the experience, but still show significant differences compared to the pre-VR.

Method

Participants

A total of 33 healthy adults, 19 males and 14 females, took part in this study. All of them were university students, with an average age of 22.24 years, $SD=2.20$, age range 19–26. All participants voluntarily engaged in the experiment and signed an informed consent before the experiment. They had normal or corrected-to-normal vision, no history of psychological or psychiatric disorders, no history of psychoactive medications or drug use, and had not used psychoactive substances (such as coffee, tea, alcohol, cigarettes) within the last 24 h. Participants were compensated with cash for their participation in the experiment. All participants finished the experiment but the EEG data of three participants during VR experience were lost, thus their data were excluded, leaving data from 30 participants. The Ethics Committee of Southwest University approved this study (IRB NO.H24093), and all procedures were performed in accordance with the seventh revision of the Declaration of Helsinki (2013).

Apparatus and Materials

The VR apparatus employed in this research consisted of the Oculus Rift headset and Oculus touch controllers. A 2×2 m safety area was demarcated, which was enough for participants to complete the experimental tasks, and freely explore the virtual environments provided by the VR games within the experiment.

Participants in the experiment sequentially experience two VR games developed by Fun Bits Interactive/Oculus (America, www.meta.com). Figure 1 is the screenshot of the games and more are provided in Appendix 3. In these two games, only two translucent blue hand models were used as the virtual hands of the participants. The first game

Fig. 1 Screenshot of the VR game *Oculus Touch Basic Information* and *Oculus First Contact*



was *Oculus Touch Basic Information*, designed to familiarize participants with the basic operations of the controllers. Participants were immersed in a virtual environment constructed with a gray background and white dimensional lines, where they learn how to use the controller with pressing buttons and making hand gestures. This game presents participants with virtual hands and virtual controllers, also arrows, visual cues, and spoken instructions. All participants complete the first game within 3 min (min). On average, this stage cost 85 s (s).

The second game was *Oculus First Contact*. In this game, participants were set in a single room and engaged in a series of tasks following visual cues: activating a robot, greeting the robot, inserting a disk into a console to start the room's equipment, inserting a disk into a 3D printer to generate virtual objects, catching virtual butterflies, shaking virtual rattle, launching virtual model rocket, shooting with virtual gun, and lastly shutting down the Game. The second game lasts for 11.5 min on average. Due to differences in participants' operation proficiency, repeated playing with certain game content, and exploration of the virtual environment, the duration of the second game was from 9.3 to 17.6 min.

Neither of these games required participants to make distant positional movements, thus participants could fully experience the games in the provided safety space. This greatly reduced the likelihood of suffering cybersickness, and reduced movements causing EEG noise.

Questionnaires

We recorded participants' basic demographic information (such as participants' gender, age, and education level). After the VR experience, participants completed questionnaires about their feeling about the immersion, presence, and discomfort during VR experience. Scores of immersion and presence questionnaires were used to assess the effectiveness of experimental manipulation—whether participants adequately experienced the VR environment. And scores of the discomfort questionnaire were used to

evaluate whether participants' experimental data is needed to be excluded. The questionnaire employed in this study is presented below.

The Immersive Experience Questionnaire (IEQ), developed by Jennett et al. (2008), was utilized to measure the sense of immersion during playing video games; it is equally applicable to VR (Dickinson et al. 2020). This questionnaire assesses immersion through the lack of awareness of time, loss of awareness of the real world, engagement, and involvement. The questionnaire comprises 31 items and employs a 5-point Likert scale ranging from 1 (not at all) to 5 (a lot or very much so) for scoring. In the present study, its Cronbach's alpha score was 0.71, indicating the internal consistency was acceptable.

The Multimodal Presence Scale (MPS) was developed by Makransky et al. (2017), based on Lee's theory of presence (Lee 2004). The questionnaire consists of 15 items and is divided into three dimensions: spatial, social, and self-presence. Each dimension can be used single or together according to the needs of research. In this study, the spatial and self-presence dimensions were administered, encompassing a total of 10 items. The scale employs a 5-point Likert scale for scoring, ranging from 1 (strongly disagree) to 5 (strongly agree). In the present study, the Cronbach's alpha score was 0.83, indicating good internal consistency.

The Virtual Reality Sickness Questionnaire (VRSQ), developed by Kim et al. (2018), is a motion sickness measurement tool specifically designed for virtual reality. The questionnaire asks participants if they have nine types of motion sickness and uses a four-point Likert scale for scoring, ranging from 1 (none) to 4 (very much), the Cronbach's alpha score in the present study was 0.67.

Experimental Procedure

Figure 2 shows the experimental procedure. When participants arrived at the laboratory, they were asked to read and sign an informed consent that included instructions for the experiment. Participants were then seated and the experimenter helped them to put on the EEG cap. They were

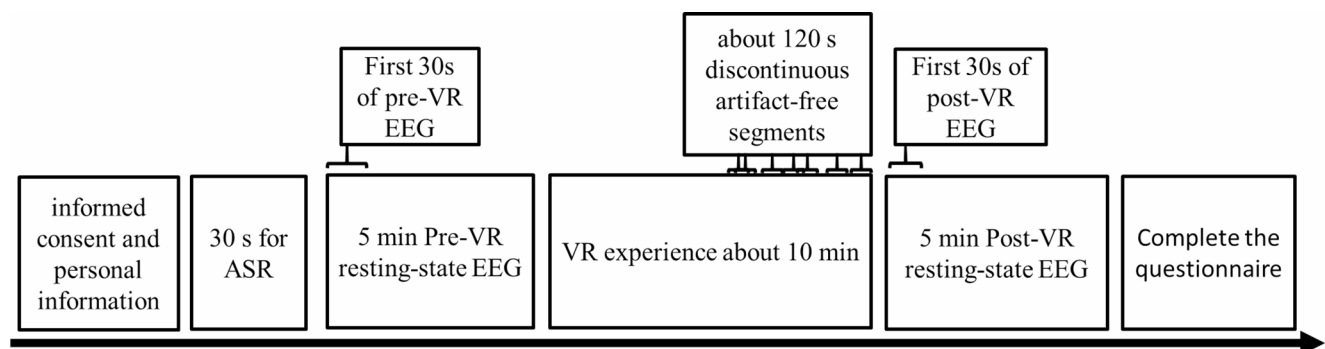


Fig. 2 Experimental procedure diagram including time periods of EEG data

instructed to maintain a comfortable seating position with their eyes closed, to remain still, stay awake, and refrain from deliberate thought during resting-state EEG data collection. Thereafter, the experimenter activated the artifact correction function, which required 30 s to complete. Then, pre-VR resting-state EEG data were collected over approximately 5 min.

Next, the experimenter instructed the participants to open their eyes and helped them to put on the VR HMD. The experimenter introduced how to adjust the HMD and to hold Oculus Touch controllers, and then adjust the HMD lens until participants reported a clear view. The criterion for a clear view was that the participants could read the text on the VR interface. After participants confirmed that the equipment was fastened, the experimenter instructed the participants to stand, then removed the chair, and guided the participants to step to the center of the safety area. EEG recording and the two VR games were then initiated sequentially. Throughout the entire VR experience, the experimenter avoided any interaction with the participant and remained silent to foster the participant's immersion and presence experiences. After the VR games ended, the experimenter guided participants to sit on the chair. Then, participants were asked to close their eyes and the VR equipment was removed.

Finally, the experimenter informed the participant that another resting-state data collection would start, with the same requirements as the pre-VR. Approximately 5 min of post-VR resting-state EEG data were collected. After the data collection was completed, the EEG equipment was removed from the participant, who then filled in the post-VR questionnaire. The entire experimental session typically lasted approximately one hour.

EEG Recording and Preprocessing

EEG data was recorded using the SMARTING PRO 32-channel wireless EEG device produced by mBrainTrain company (Belgrade, Serbia, www.mbraintrain.com), along with its mbtStreamer software. Electrodes were positioned according to the international 10–20 system. The reference electrode was set at FCz and the ground electrode was placed at AFz. The data sampling rate was set to 500 Hz, and electrode impedance was maintained below 10 k Ω . As in the VR experience, participants needed to wear an HMD on the electrode cap, electrode impedance was checked again after the experiment. In the present study, no increase in impedance was observed after the experiment, indicating that wearing an HMD did not lead to electrode displacement or connectivity decrease. Since it was necessary to collect EEG data during participants' VR experience, which could cause participants' body movement and potential power frequency interference from the HMD at close range, the

EEG device's built-in Artifact Subspace Reconstruction (ASR) feature was utilized to eliminate possible artifacts. Researches demonstrates that ASR cleaning can improve the quality of subsequent independent component analysis (ICA) decomposition (Pion-Tonachini et al. 2018; Chang et al. 2020). An additional 30 s of eyes-closed resting-state EEG data before experience was record as a baseline for ASR.

The EEG data were preprocessed using MATLAB version R2022b with the EEGLAB toolbox (Delorme and Makeig 2004). The EEG data were down-sampled to 128 Hz, then, bandpass filtering with the frequency range of 2–20 Hz was applied (Tarailis et al. 2023). Bad channels were interpolated using spherical methods (only one participant had one bad channel). Then ICA was applied to correct and remove components associated with eye movements and eye blinks. To facilitate further analysis, we segmented the data. We extracted fully continuous data from the first 30 s of the pre- and post-resting-states, and about 120 s discontinuous artifact-free segments from the latter portion of the VR experience.

Microstate Analysis

Microstate analysis was performed for data from five time periods separately (whole pre- and post-resting-states, the first 30 s of the pre- and post-resting-states, and 120 s from VR experience). The time periods are shown in Fig. 2. We used the *Microstates Toolbox* plugin of EEGLAB (Poulsen et al. 2018) and followed its standard procedure.

First, data extraction was performed. The data type was set to Spontaneous-GFP peaks. EEG maps representing the peaks in the GFP time curve were used for segmentation to improve the signal-to-noise ratio (Michel and Koenig 2018), and average reference was calculated (Poulsen et al. 2018; Michel and Koenig 2018). Exclusion criteria for GFP peaks were applied (Musaeus et al. 2019; Kim et al. 2024). The minimum peak distance in GFP maps was set to 10 ms, and maps with GFP that exceeds one time the standard deviation of GFPs was reject (Poulsen et al. 2018). In the tutorial of the analysis package, Poulsen et al. (2018) used 1000 peaks for per approximately six minutes of EEG. Thus, for 30 s epochs, we reduced the number of GFP peaks proportionally and extracted 100 peaks; and for 120 s epochs, we extracted 500 peaks. Importantly, the resulting topographies with this parameter closely matched classic microstate templates.

Second, the modified K-means clustering algorithm was used for microstate segmentation, and the number of clusters was set to range from 3 to 7. Fit degree was also calculated. The modified K-means algorithm uses cross-validation (CV) to optimize clustering (Pascual-Marqui et al. 1995). Therefore, CV is taken as the fitness criterion. After the

microstate clustering, the optimal number of clusters was assessed based on Global Explained Variance (GEV) and CV. We found that the obtained optimal number of clusters was always 5 each time. Then, they were classified based on morphological characteristics, and each set of clusters could be classified as microstates A, B, C, D and E. Then, a similarity analysis is conducted between the obtained microstate topographies and those reported in a large normative study (Custo et al. 2017). Specifically, the microstate topography is deemed to be consistent with the previous research when the Pearson correlation coefficient between a microstate topography and the corresponding microstate topography in previous study exceeds 0.8, and the correlation coefficients with other topography maps are all below this threshold. If the microstate topography failed to meet the criteria, the microstate analysis process would be repeated.

Third, after the microstate topographies were determined, they were fitted back to the original EEG data of each subject with back-fitting approach. And polarity was ignored when back-fitting. Microstate labels were temporally smoothed after the back-fitting. The reject small segments method was selected as the smoothing method (Poulsen et al. 2018). Minimum duration that microstate segments were allowed to last was set to 30 ms (Poulsen et al. 2018). Temporal indices for each microstate of each subject were calculated, including occurrence, duration, coverage, and GEV.

Result

First, scores of the IEQ, MPS, and VRSQ questionnaires were computed to validate the effectiveness of experimental manipulation and determine potential data exclusion.

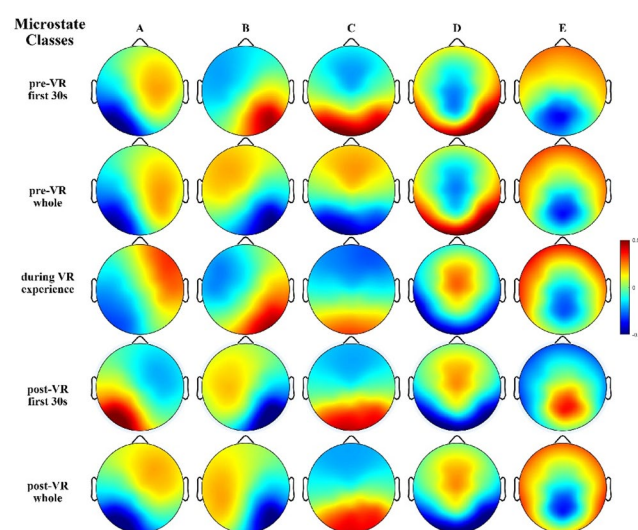


Fig. 3 Topographical maps of five microstate categories across five time periods

Second, the impact of resting-state duration selection on microstate indices (occurrence, duration, coverage, and GEV) was analyzed to determine appropriate data period for subsequent analyses. Differences were compared between the first 30 s of pre-VR and full pre-VR resting-state data, as well as between the first 30 s of post-VR and full post-VR resting-state data. Repeated-measures 2×5 ANOVAs were performed with time (the first 30 s and full data) and microstate classes (A, B, C, D, and E) as within-participant factors. If significant main effects of time or interactions was found, which suggesting that significant differences between the two periods existed, the first 30 s data were then selected; otherwise, full datasets were selected. And in subsequent descriptions, the selected data was referred to as pre-VR/post-VR data.

Third, repeated-measures 3×5 ANOVA was performed to analyze temporal effects on microstate indices, with time (pre-VR, 120 s VR experience, and post-VR) and microstate classes (A, B, C, D, and E) as within-subjects factors. Mauchly's test of sphericity was conducted prior to each repeated-measure ANOVA, and Greenhouse-Geisser correction was adopted.

Questionnaires

None of the participants reported that they had experienced with VR games as used in the experiment before. The mean score of the VRSQ was 10.33 (SD=1.65). The highest score obtained by participants in this experiment was 15, indicating that none of the participants exhibited significant symptoms of motion sickness, thus no participants was excluded. The IEQ showed a mean score of 119.76 (SD=10.82). The MPS showed a mean score of 36.64 (SD=5.51). The lowest scores of IEQ and MPS were 115.8 and 28.05, which were higher than reported in previous studies (Burns and Fairclough 2015; Grassini et al. 2021), suggesting that the VR experience in this experiment was effective in inducing immersion and presence of participants.

Microstate Topographies

Figure 3 shows the topographical maps of five microstate classes across five time periods in this study. Table 1 presents the Pearson spatial correlation coefficients between the microstate topographical maps in this study and one set of clusters reported in a large-sample normative study (Custo et al. 2017). And the complete table in Appendix 1 lists the spatial correlation coefficients between all microstate topographical maps. The microstate topographies obtained in each time period are consistent with the five typical microstate topographies reported in previous studies (Taralis et al. 2023). The topography of microstate A showed

Table 1 The correlation coefficients of microstate topographical maps between this study and Custo et al. (2017)

Time Periods	Microstate Category				
	A	B	C	D	E
first 30 s of pre-VR	-0.911	0.972	-0.951	-0.937	-0.944
full pre-VR	-0.891	-0.967	0.975	-0.965	-0.929
120 s VR experience	-0.931	0.937	-0.976	0.936	-0.833
first 30 s of post-VR	0.965	-0.861	-0.963	0.912	0.842
full post-VR	-0.951	-0.864	-0.949	0.916	-0.809

Note: All p-values are less than 0.001. Negative values indicate an inverted topographic polarity. A larger absolute value signifies greater similarity

a distribution from the right frontal-to-left posterior (Koenig et al. 1999), while microstate B exhibited a distribution structure from the left frontal-to-right posterior (Koenig et al. 2002). The topography with a symmetric anterior-to-posterior configuration was labeled as microstate C (Koenig et al. 2002). Microstate D showed extremums in fronto-central regions (Koenig et al. 1999). In addition to these four classic microstate topographical maps, we also obtained topography with an extremum at centro-parietal region, which has been labeled differently across various studies (Tarailis et al. 2023). In accordance with Tarailis et al. (2023), this topography was labelled microstate E. We also used the relabeling results in Tarailis et al. (2023) for other cited topographies, such as Brechet et al. (2019), Custo et al. (2017), and Tomescu et al. (2022), in current study. And then we used the *Microstate Template Editor and Explorer* (Koenig et al. 2024) to verify that our labelled topographies can be clustered into the same meta-microstate map class as corresponding classes in those above mention studies. The output, provided in Appendix 4, shows close correspondence between our maps and those already stored in the database. The GFP time curves for pre- and post-VR first 30 s, as well as during the 120 s VR experience, are shown in Appendix 2.

Microstate Indices and resting-state Duration Selection

A repeated-measures ANOVA showed significant differences in microstate temporal indices between the first 30 s and the full duration for both the pre-VR and post-VR conditions. When comparing the first 30 s of the pre-VR with the full pre-VR period regarding microstate temporal indices, repeated-measures 2 (first 30 s vs. full period) $\times$ 5 (A, B, C, D, and E) ANOVA revealed a significant interaction between time and microstate classes for occurrence, with $F(2.885, 92.310)=2.959$, $p=0.038$, $\eta_p^2=0.085$; for coverage, with $F(2.773, 88.738)=2.522$; $p=0.008$; $\eta_p^2=0.073$; and for GEV, with $F(2.095, 67.054)=7.517$; $p<0.001$; $\eta_p^2=0.190$). For the comparison between the first 30 s of

post-VR and the corresponding full duration, a repeated-measures 2 (first 30 s vs. full period) $\times$ 5 (A, B, C, D, and E) ANOVA indicated a significant interaction between time and microstate classes for occurrence, with $F(3.673, 117.544)=3.30$, $p=0.016$, $\eta_p^2=0.094$; and GEV, with $F(2.330, 74.576)=3.029$, $p=0.047$, $\eta_p^2=0.086$.

From the results, we can see that the microstates in the first 30 s of both pre-VR and post-VR were distinct from their corresponding states for the overall pre-VR rest periods. It thus possible that participants' resting-state neural activity changed during the measurement period, for example due to sleepiness or boredom. Also considering that the effects of VR experiences may quickly fade in tens of seconds as indicated in previous findings (Reinhard et al. 2020), the first 30 s of pre- and post-VR data were selected for later time-series analysis, thus to ensure that participants' microstates were matched as much as possible. As previous researches showed, 30 s period is enough for microstate analysis to reflect participants' neural activities (Seitzman et al. 2017; Brechet et al. 2019).

Time-Series Analysis of Microstate Indices

We ran a repeated-measures 3(pre-VR, 120 s VR experience, and post-VR) $\times$ 5(A, B, C, D, and E) ANOVA, and presented temporal index differences of each microstate class across different time stages in Fig. 4.

For occurrence (Fig. 4a), there was a significant main effect of time, with $F(1.647, 47.764)=11.216$, $p<0.001$, $\eta_p^2=0.279$. There was also a significant main effect of microstate class, with $F(3.139, 91.021)=3.982$, $p=0.009$, $\eta_p^2=0.121$. Additionally, there was a significant interaction between time and microstate class, with $F(4.766, 138.202)=2.369$, $p=0.045$, $\eta_p^2=0.076$. Simple effects analysis revealed that the occurrence of microstate A was significantly higher during the VR experience compared to both the pre-VR, with $t(29)=2.159$, $p=0.039$, $d=0.394$, and the post-VR, with $t(29)=2.764$, $p=0.010$, $d=0.505$. Similarly, the occurrence of microstate B was significantly elevated during the VR experience relative to the pre-VR, with $t(29)=2.376$, $p=0.024$, $d=0.434$; and the post-VR, with $t(29)=2.064$, $p=0.048$, $d=0.377$. The occurrence of microstate C was significantly higher during the pre-VR compared to the post-VR, with $t(29)=2.087$, $p=0.046$, $d=0.381$. Additionally, the occurrence of microstate E demonstrated a significant increase during the VR experience when compared to the post-VR, with $t(29)=3.481$, $p=0.002$, $d=0.636$.

For duration (Fig. 4b.), there was a significant main effect of time, with $F(1.939, 56.233)=11.034$, $p<0.001$, $\eta_p^2=0.276$. There was also a significant main effect of microstate classes, with $F(1.779, 51.597)=6.452$, $p=0.004$,

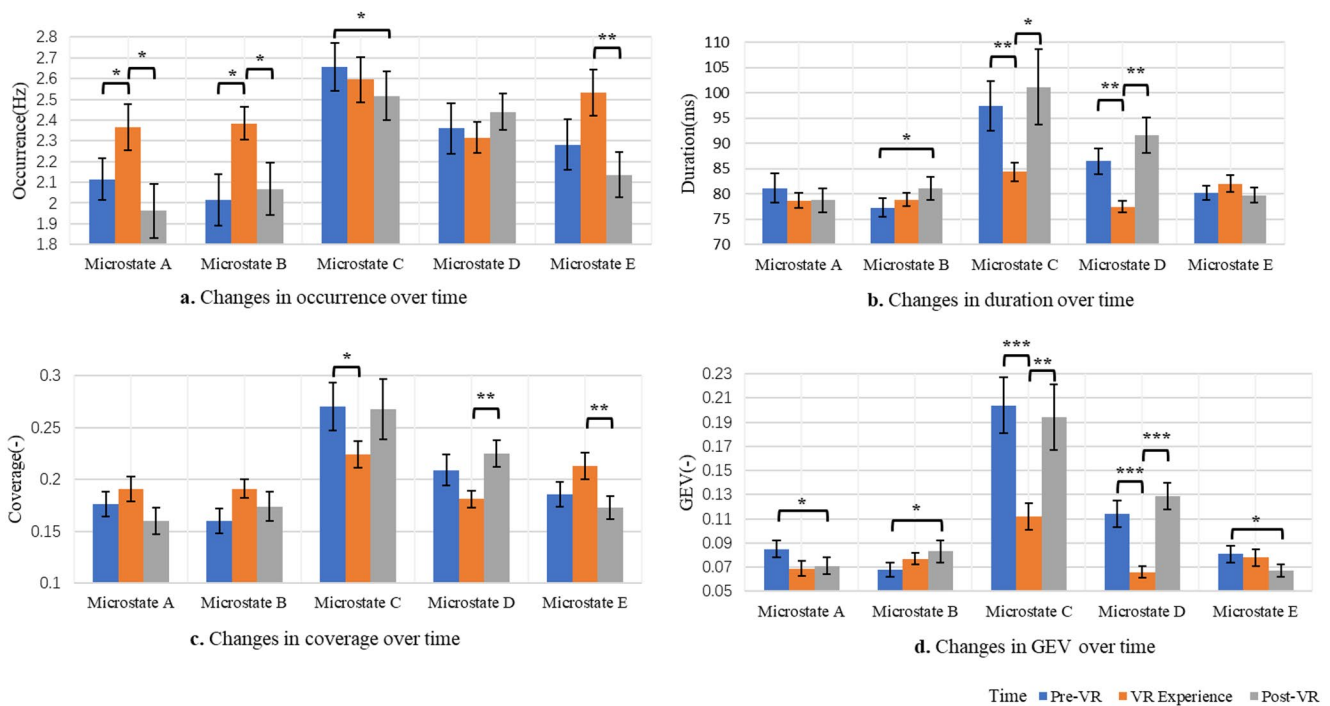


Fig. 4 Microstate temporal indices changes over time. Note: *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$

$\eta^2_p = 0.182$. And there was a significant interaction between time and microstate classes, with $F(3.158, 91.579) = 3.966$, $p = 0.009$, $\eta^2_p = 0.120$. Simple effects analysis indicated that the duration of microstate B was significantly longer during the post-VR compared to the pre-VR, with $t(29) = 2.306$, $p = 0.028$, $d = 0.421$. The duration of microstate C was significantly shorter during the VR experience than both the pre-VR, with $t(29) = 3.147$, $p = 0.004$, $d = 0.575$; and the post-VR, with $t(29) = 2.572$, $p = 0.015$, $d = 0.470$. Furthermore, the duration of microstate D showed a significant decrease during the VR experience relative to the pre-VR, with $t(29) = 3.381$, $p = 0.002$, $d = 0.617$ and the post-VR, with $t(29) = 3.860$, $p = 0.001$, $d = 0.705$.

For coverage (Fig. 4c.), since the sum of contribution rates across all microstate classes equals 100% under each time condition, the main effect of time could not be observed. A significant main effect of microstate classes was observed, with $F(2.154, 62.462) = 5.734$, $p = 0.004$, $\eta^2_p = 0.165$. And there was a significant interaction between time and microstate classes, with $F(3.999, 115.976) = 3.751$, $p = 0.007$, $\eta^2_p = 0.115$. Simple effects analysis demonstrated that the coverage of microstate C was significantly higher during the pre-VR compared to the VR experience, with $t(29) = 2.212$, $p = 0.035$, $d = 0.404$. The coverage of microstate D was significantly higher during the post-VR relative to the VR experience, with $t(29) = 3.406$, $p = 0.002$, $d = 0.622$. Additionally, the coverage of microstate E was significantly lower in the post-VR than in the VR experience, with $t(29) = 3.148$, $p = 0.004$, $d = 0.575$.

For GEV (Fig. 4d.), there was a significant main effect of time, with $F(1.403, 40.697) = 89.498$, $p < 0.001$, $\eta^2_p = 0.755$. There also a significant main effect of microstate class, with $F(1.718, 49.808) = 14.691$, $p < 0.001$, $\eta^2_p = 0.336$. And there was a significant interaction between time and microstate classes, with $F(3.135, 90.910) = 8.223$, $p < 0.001$, $\eta^2_p = 0.221$. Simple effects analysis revealed that the GEV of microstate A was significantly higher during the pre-VR compared to the post-VR, with $t(29) = 2.267$, $p = 0.031$, $d = 0.414$. The GEV of microstate B was significantly elevated during the post-VR relative to the pre-VR, with $t(29) = 2.724$, $p = 0.011$, $d = 0.497$. The GEV of microstate C was significantly reduced during the VR experience compared to both the pre-VR, with $t(29) = 4.659$, $p < 0.001$, $d = 0.851$, and the post-VR, with $t(29) = 3.598$, $p = 0.001$, $d = 0.657$. Furthermore, the GEV of microstate D showed a significant decrease during the VR experience relative to the pre-VR, with $t(29) = 4.334$, $p < 0.001$, $d = 0.791$; and the post-VR, with $t(29) = 6.227$, $p < 0.001$, $d = 1.137$. Finally, the GEV of microstate E was significantly higher in the pre-VR than in the post-VR, with $t(29) = 2.269$, $p = 0.031$, $d = 0.414$.

Discussion

We collected EEG data during pre-VR (baseline), VR experience, and post-VR stages to investigate dynamic brain changes using microstate analysis. To validate the

procedural efficacy, participants completed the IEQ, MPS, and VRSQ questionnaires after the VR experience. Five microstate topographies were identified in this study. We verified our hypothesis that microstates significantly change over time. The experimental hypotheses were empirically supported, with significant variations observed in temporal indices across all microstates among experimental stages. Although these variations did not fully match our hypotheses, they can be taken to reflect cognitive processing associated with the VR experience.

The Effect of VR Exposure on Microstates

The analysis of VR-induced electrophysiological changes includes two dimensions. First, VR experience induces significant differences in microstate indices between the VR experience and the pre-VR baseline stages. Second, certain electrophysiological effects of VR do not last to the post-VR stage, showing significant differences between the VR experience and post-VR stages. In other words, several microstate indices during the VR experience are significantly different from both pre-VR and post-VR. In our results, this pattern was observed in the occurrence of microstate A and B; duration and GEV of microstate C; duration and GEV of microstate D.

Source localization studies indicate that the occurrence of microstate A is associated with activation of the temporal cortex and auditory network, which suggests its role in speech processing and auditory network activity (Custo et al. 2017). A study using background music paradigm had found that the occurrence, duration, and coverage of microstate A in the experimental group, which were exposed to music-accompanied videos, were significantly higher during pre-test viewing, compared to post-test resting states; whereas no differences were observed in the control group, which were exposed to silent videos. This was interpreted as fatigue or adaptation of the auditory network after auditory distraction (Korn et al. 2021). Additionally, microstate A was revealed to be related to verbal thought during resting states (Tarailis et al. 2021). Microstate A also be reported increased during visual tasks and be thought of its associations with visual processing (Antonova et al. 2022). However, some conflicting evidence challenges both auditory- and visual-related claims (D'croz-Baron et al. 2021; Jabes et al. 2021; Tomescu et al. 2022). Overall, considering the presence of microstate A are positively correlated with subjective ratings of alertness (Antonova et al. 2022), researchers have suggested that, the association of microstate A with auditory and visual processing may be due to its relationship with the state of arousal (Tarailis et al. 2023).

Neuroimaging evidence indicates that microstate B primarily originates in the occipital cortex, overlapping with

visual regions (Custo et al. 2017). Several studies reported that occurrence of microstate B increased after visual stimuli or when eyes-open as compared to resting states or eyes-closed (Seitzman et al. 2017; D'croz-Baron et al. 2021; Jabes et al. 2021; Antonova et al. 2022). Furthermore, researchers observed higher occurrence of microstate B during autobiographical memory tasks compared to resting or arithmetic conditions (Brechet et al. 2019). Tarailis and colleagues (2021) identified a positive correlation between microstate B occurrence and the "self" domain of the Amsterdam Resting-State Questionnaire (ARSQ), thus microstate B possibly relates to self-visualization.

It thus seems that microstates A and B are broadly associated with visual and auditory processing. Their increased occurrence during the VR experiences compared to pre- and post-VR may reflect participants' intensive processing of audio-visual stimuli during the VR experience. In VR experience, visual signals presentation is advantageous compared with other stimulus presentation methods. However, in some VR experiments without auditory components (Burin et al. 2020), minimal activation of auditory-related brain regions would be expected, and related microstate indices (primarily microstate A) may not show significant increase.

Microstate C is believed to be primarily active in the precuneus and posterior cingulate cortex (PCC), as well as activity in the left angular gyrus (Croce et al. 2018). Microstate E demonstrates strong activation in the dorsal anterior cingulate cortex (ACC; BA32), extending to the superior frontal gyrus, with bilateral activations in the middle frontal gyrus and insula. Its source has been localized to the medial prefrontal cortex (Custo et al. 2017; Brechet et al. 2019). Numerous studies have reported positive correlations between microstate C indices and rest/non-task/comfort conditions, and negative correlations with task conditions (Seitzman et al. 2017; Brechet et al. 2019; Tomescu et al. 2022). Although microstate C shows reduced occurrence and duration during computational tasks, no significant differences were observed between autobiographical memory tasks and no-task rest (Brechet et al. 2019). Considering that source regions of microstate C relate to experiential self-processing in fMRI findings (Brechet et al. 2019) and studies on bipolar disorder patients (Vellante et al. 2020), microstate C may relate to internal mentation of personal information processing, self-reflection, and self-referential (Tarailis et al. 2023). We consider that the reductions in both duration and GEV of microstate C during the VR experience reflect participants' cognitive activities when they were playing VR games.

Microstate D originates from the frontoparietal network and is associated with cognitive executive processes (Custo et al. 2017; Brechet et al. 2019). Studies have reported

increase of microstate D during meditation, and decrease during mind-wandering (Faber et al. 2017). Also studies demonstrate increase of microstate D during arithmetic tasks compared to resting states and/or autobiographical retrieval tasks (Brechet et al. 2019). Microstate D is involved in cognitive control and attention (Tarailis et al. 2023). Furthermore, microstate D relates to internal processing, reduced microstate D correlates with greater dissociation from external environments and enhanced internal mentation (Tarailis et al. 2021). And during rest after oxytocin administration, a shift from internal to external oriented processing was observed, accompanied by a significant increase in the temporal coverage of Microstate D (Schiller et al. 2019).

Thus, we propose that the reduced duration and GEV of microstate D during the VR experience may indicate attentional dispersion in complex virtual environments and/or a reduced need for conscious cognitive processing during gameplay. However, rather than interpreting these changes from the perspective of executive control, we are more inclined to believe that during the VR experience, participants are indeed immersed and present (Shin 2018) in the virtual environment and disconnected from the real world. However, the decrease of microstates C and D during the VR experience did not last into post-VR, and both rapidly returned to pre-VR levels after the VR experience ended. This contradicts previous findings that VR effects may last after exposure (Reinhard et al. 2020). Therefore, we argue that the reduced microstate D during the VR experience should not be attributed to simply immersion and presence. Besides the cognitive processes associated with reduced microstates C/D during the VR experience, there may be another explanation. That is, the presence of a variety of cognitive and psychological activities during the VR experience. For example, participants were required to comprehend the instructions, to explore the virtual objects, and determine their subsequent actions. These activities are less frequent or even absent in resting states and cannot be categorized into the five microstates identified in this study, which may have led the reduction of microstates C and D.

In studies on group differences among gamers, Cui et al. (2021) found that, when auditory information is crucial information source, expert game players showed higher occurrence and coverage of microstate A, compared with non-expert players. When auditory information merely enriches the gaming experience, such difference was not observed, but experts exhibited higher occurrence and coverage of microstate B, alongside reduced occurrence, durations, and coverage of microstate C, relative to non-experts. These findings generally align with our results, suggesting that the increased microstate A/B occurrence and decreased microstate C duration/GEV during VR experience are general brain neural activity patterns during VR experience.

The Lasting Effects of VR Experience

The electrophysiological impact of VR experience may outlive the VR experience and continue to influence participants, even after they return to the real environment (Reinhard et al. 2020). This lasting effect will prevent post-VR microstate indices to show differences from those during the VR experience, but implies significant differences from pre-VR baseline levels. However, in this study, none microstate indices fit with this assumption. While some microstate indices showed difference between the pre-VR or post-VR, but no difference between pre-VR and VR experience, neither between post-VR and VR experience, including GEV of microstate A, duration and GEV of microstate B, occurrence of microstate C, and GEV of microstate E.

Microstate A exhibited lower GEV in the post-VR than pre-VR. Although Microstate A's GEV during VR experience showed none significant difference from both pre-VR and post-VR, its mean was numerically even lower than post-VR. The reduction of GEV during the VR experience than pre-VR, may be due to similar reasons as with our previous speculation regarding the decrease of microstate C/D during the VR experience: other psychological processes, which were unrelated to the five microstates, occupied more cognitive resources and processing time when experiencing VR than resting-state. Thus, the significant reduction of GEV of microstate A in post-VR compared to pre-VR baseline likely reflects residual effects of VR experience. Previous research suggests that occurrence, duration, and coverage of microstate A in the resting state after watching videos with songs were significantly lower than baseline and control conditions, and authors attributed this to fatigue or adaptation following auditory distraction (Korn et al. 2021). The significantly decreased GEV of microstate A in post-VR observed in our study fits with these findings, and may reflect participants' fatigue following VR experience.

The sustained increases in duration and GEV of microstate B, which did not return to pre-VR level even after the VR experience and were even higher than during the VR experience, may indicate an accumulation given the close association of microstate B with visual processing and visualization. If this is the case, it suggests that the immersion or presence sense in VR experience demands sustained visual processing. While the duration, coverage, and GEV of microstate C were lowest during the VR experience and returned to pre-VR levels in the post-VR, its occurrence continued to decrease and was significantly lower in the post-VR than in the pre-VR. Thus, we are more inclined to attribute this to fatigue, like the GEV of microstate A.

Microstate E has been found to be negatively correlated with somatic consciousness scores (Custo et al. 2017; Tarailis et al. 2021; Tomescu et al. 2022). A study using VR to

investigate the relationship between realistic versus fantastic experiences found that, as the coverage of microstate E increased, reality experience scores decreased and suspension of disbelief scores increased. The authors interpreted their findings as that, participants needed to suppress their skepticism about implausible phenomena and believe in the reality of the VR (Denzer et al. 2024). Thus, in our study, the observed continuous decrease in microstate E likely corresponds to participants' belief of the VR's realness. It is possible that in our study, participants firstly underwent a lengthy EEG preparation period before the pre-VR, during which they needed to remain as still as possible, and thus lacked interaction with the real world. While during the VR experience, they have had a relatively more real and enriched interaction in virtual environment, and maintained adequate somatic awareness. And later, the immersive and presence sense induced by VR did not immediately dissipate after the experience ended.

Further Discussion

Note that one may argue that the lack of a control group represents a limitation of our study. However, there were two reasons why we did not include such a group. First, designing a video game task for a control group would likely involve a comparison between VR experience and video game experience acquired through a computer screen. This would make it very hard to afford participants with the same degree of control over the screen content, to equate operational actions, and so forth (Bohil et al. 2011), rendering a true comparison very questionable. Second, we assume that, to verify the VR advantages in ecological validity, the most appropriate comparison is to compare VR with the real experience. Consequently, we recorded participants' pre-VR state as the baseline. The results of this study indicate that there are differences between VR experiences and reality at the microstate level, possibly because the process by which participants perceiving the virtual environment as real and developing presence is an active psychological activity (Shin 2018). In future research, if VR is used as a presentation method, researchers should therefore consider the differences between VR and reality, because results may stem not from specific experimental manipulations embedded in the VR environment, but from the mere act of entering VR.

Another limitation and future research possibility is that, the present study did not investigate the influence of different levels of presence or immersion. We note that some previous researches differentiated high- and low-scoring groups for both presence and immersion with questionnaires (Burns and Fairclough 2015; Terkildsen and Makransky 2019; Grassini et al. 2021). However, in the present study, all participants felt higher level sense of presence

and immersion than in previous researches. This precludes the detection of between-group differences. Future research may consider modulating presence or immersion levels and elucidating the underlying psychological mechanisms. For example, in the VR-related research field, virtual avatar may be a key to affect immersion and presence levels. Researchers have induced the Proteus effect (Yee and Bailenson 2007) or body ownership (Ma et al. 2019) to explain the psychological impact from virtual avatars. Even different virtual hand models can elicit behavioral changes in participants: human-like hand models could enhance stronger body ownership and elicit more naturalistic responses (Shin et al. 2021). In the present study, this critical variable was not manipulated: across both VR procedures, participants were embodied by the same pair of semi-transparent, light-blue virtual hands illustrated in Fig. 1. Fortunately, this limitation does not appear to lower participants' presence or immersion. Collectively, in future researches, deeper investigation on the neural mechanisms of the VR environment and also avatars on human cognition and affect would be valuable.

Conclusion

This study combined VR and EEG technologies and employed microstate analysis to compare the electrophysiological changes in participants before, during, and after the VR experience. During the VR experience, there was a significant increase in the occurrence of microstates A and B, and a significant decrease in the duration and GEV of microstates C and D. Compared with the post-VR, the GEV of microstate A was higher during the pre-VR, while the duration and GEV of microstate B increased continuously during the VR experience. The occurrence of microstate C and the GEV of microstate E exhibited a continuous decrease. Based on previous studies of the electrophysiological functions represented by microstates, microstates A, B, C, and D likely reflect the general cognitive activities that occur during the VR experience. And microstate E may reflect the psychological impacts of immersion and presence associated by VR experience, which even last after VR experience to some extent. Our study provides an empirical basis for future psychological experiments using VR, and provides methodological references for researchers who plan to conduct research with combination of VR with EEG technology.

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Author Contributions H.M. designed the overall research, conducted the experiments, organized data, analysed data, and wrote the main manuscript text. J.Z. provided guidance on experimental design, operation of EEG equipment, and analysis of EEG data. B.H. revised the manuscript. K.M. supervised and managed the experimental implementation, guided data analysis, and revised the manuscript.

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Data Availability The data that we collected and support the findings of this study are openly available in <https://osf.io/7bkeq/>. For more, please contact the corresponding author.

Declarations

Competing Interests The authors declare no competing interests.

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