

Neural function desynchronization in left and right dorsolateral prefrontal cortices during virtual reality earthquake video viewing

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Abstract: During natural disasters such as earthquakes, individuals are required to evacuate calmly amidst significant emotional distress, presenting a considerable challenge. Very few studies have measured emotional responses during disasters, and the emotional responses and brain activity during natural disasters are poorly understood. Therefore, this study aimed to investigate emotional responses during an earthquake using immersive virtual reality (VR), focusing on changes in neural connectivity in the left and right dorsolateral prefrontal cortices (DLPFCs). We measured changes in total hemoglobin concentration ($\Delta\text{total-Hb}$) using 2-channel near infrared spectroscopy (NIRS) while 24 healthy young adults viewed earthquake and neutral videos through a head-mounted display (HMD). Spearman's correlation analysis was applied to the time variation in $\Delta\text{total-Hb}$ in the left and right DLPFCs, independently for seismic or neutral video conditions. The findings revealed a negative correlation between the left and right total hemoglobin concentration changes during the earthquake video ($\rho = -0.53$). Conversely, individuals exposed to the neutral video exhibited a positive correlation ($\rho = 0.75$). The present steady-state analysis suggests that emotional changes induced by virtual earthquake videos disturbed steady-state neural synchronization between the left and right DLPFCs.

1 Introduction

Japan has recently experienced numerous earthquakes with magnitude scores exceeding 5 according on the Japan Meteorological Agency (JMA) seismic scale [1], spanning from Hokkaido to Kyushu. During natural disasters such as earthquakes, individuals are required to evacuate calmly, despite experiencing

heightened emotional turmoil. While several studies have investigated the left-right asymmetry or synchrony of brain activity during emotion induction [2,3], there remains a lack of research focusing on measuring emotional responses during disasters. Consequently, our understanding of emotional responses and brain activity during natural disasters remains incomplete.

This study aimed to investigate emotional responses during earthquakes using immersive virtual reality (VR), focusing on synchronizing cerebral hemodynamics in the left and right dorsolateral prefrontal cortices (DLPFCs). To the best of our knowledge, this is the first study to observe synchronization between the left and right DLPFCs during VR earthquake video viewing.

2 Methods

2.1 Subjects

Twenty-four healthy young adults (12 males, 12 females, 21.4 ± 0.2 years) participated in the study. The eligibility criteria included the absence of visual, auditory, or verbal comprehension impairments, as well as no history of mental disorders that could affect task performance. Participants were also required to have history of experiencing VR sickness prior to this experiment. Moreover, the Impact of Event Scale-Revised (IES-R) was administered to confirm the absence of prior trauma from the earthquake, and participants with a cutoff score of 24 were accepted. The Kyoto University Medical Ethics Committee approved this study. All participants were fully informed before the start of the experiment and informed consent was obtained through verbal and written consent.

2.2 Materials and Procedure

Two types of video were used: three earthquake simulations and two neutral scenes. The earthquake simulations were created using a 3D reconstruction system to provide an immersive VR experience in three different environments [4,5]: a living room, a conference room, and a laboratory office. The two neutral video clips were generated by overlaying pink noise to images of natural landscapes (rivers and grassland) [6]. A block design comprising earthquake and neutral video viewing conditions for each 100 s duration was employed.

First, the participants provided personal information, such as age, sex, education level, work history, dominant hand, and visual acuity. Next, they viewed the VR images while wearing a head-mounted display (HMD) with near-infrared

spectroscopy (NIRS) and verbally responded to a subjective evaluation after viewing each video. For subjective evaluation, we used the Self-Assessment Manikin on a 9-point scale from 1 to 9 for valence, arousal, and dominance, and a 7-point Likert scale from 1 to 7 for fear, astonishment, anxiety, and panic. Each experiment lasted approximately 90 min and included an explanation.

2.3 NIRS data acquisition and data analysis

We used 2-channel NIRS (HOT-2000-VR, NeU, Japan) for change of total hemoglobin concentration. The sampling rate for the measurement was 0.1 s. It consists of a light-emitting diode (LED) with a wavelength of 810 nm, one on each side of the headset, and two sensor units (located approximately 1 and 3 cm from the LED). The NIRS probes were bilaterally positioned in the DLPFCs (left Fp1-F7 and right Fp2-F8), with the NIRS probe and the top of the face cushion of the HMD overlapping at a distance of approximately 3 cm above the nasion. Changes in total hemoglobin concentration ($\Delta\text{total-Hb}$) were calculated according to the method described by Kiguchi and Funane [7]. The NIRS signal processing was performed according to a previous report [8]. Initially, a 3-s moving average (30 points) was employed to mitigate high-frequency noise in the $\Delta\text{total-Hb}$ (measured values). Next, trends and periodic fluctuations were removed, and the data were processed using a moving median filter in College Analysis (CA) Ver. 8.4 [9], and derived the following equation:

$$t(n) = [\Delta\text{Hb}_{\text{total}}(n) - \{V_{\text{trend}}(n) + V_{\text{period}}(n)\}]_{\text{median filter}=200} \quad (1)$$

where $t(n)$ is the parameter obtained after applying the median filter (200) in [Eq.(1)], where $V_{\text{trend}}(n)$ and $V_{\text{period}}(n)$ denote the trend and periodic variations in the NIRS signal, respectively.

The left and right $t(n)$ values are called $\Delta\text{total-Hb(L)}$ and $\Delta\text{total-Hb(R)}$, respectively. The units for $\Delta\text{total-Hb(L)}$ and $\Delta\text{total-Hb(R)}$ are expressed as arbitrary units (a.u.).

All results are presented as means $\pm$ standard error. Initially, the mean of the time-series data for $\Delta\text{total-Hb(L)}$ and $\Delta\text{total-Hb(R)}$ over a duration of 60 s, specifically from 20 to 80 s after the onset of each video-viewing session within 100 s, was calculated. This mean was determined either from the three earthquake videos or from the two neutral videos. Subsequently, after confirming the normality of the data using the Shapiro-Wilk test, Spearman's correlation coefficient (ρ) between $\Delta\text{total-Hb(L)}$ and $\Delta\text{total-Hb(R)}$ for both seismic and neutral videos was calculated. Wilcoxon signed-rank tests were performed for the subjective evaluations (valence, arousal, dominance, fear, astonishment, anxiety, and panic) of both earthquake and neutral videos. The analysis was performed using IBM SPSS Statistics Ver. 29 and CA Ver. 8.4 [9], with a significance level set at 5%.

3 Results

Three of the twenty-four participants were excluded from the analysis because they had difficulty viewing the videos continuously due to their physical condition or failure of data measurement. Twenty-one participants exhibited right-handedness, had a visual acuity of at least 0.7 in both eyes, and possessed an average education duration of 14.8 ± 0.2 years. The IES-R was 1.4 ± 0.8 points, and no subjects were excluded due to seismic trauma.

Comparisons of subjective ratings between the earthquake and neutral conditions showed that valence, arousal, dominance, fear, astonishment, anxiety, and panic were significantly higher in the earthquake condition than in the neutral condition ($p < 0.001$).

The time series data of $\Delta\text{total-Hb(L)}$ and $\Delta\text{total-Hb(R)}$ during the earthquake video showed a significant negative correlation ($\rho = -0.53$, $p < 0.001$) (Fig.1-a, c), while those during the neutral video showed a significant positive correlation ($\rho = 0.75$, $p < 0.001$). (Fig.1-b, d)

4 Discussion

Previous studies that evaluated left-right hemispheric asymmetry related to emotion have reported that brain activity in the left hemisphere is generally predominant for positive stimuli. In contrast, the right hemisphere is activated by negative stimuli [2]. In addition, the right amygdala is associated with rapid processing of emotional stimuli, whereas the left amygdala is related to the maintenance of emotion [10]. In this study, temporal changes of total hemoglobin concentration (Fig.1-a) during the earthquake showed that the right hemisphere was dominant in the first half of the time, while the left hemisphere was dominant in the second half. This may be because negative emotions were rapidly evoked in the first half and maintained in the second half. In the neutral images, the right hemisphere was consistently dominant throughout (Fig.1-b), suggesting that the participants' feelings of boredom and tiredness were influenced by viewing natural scenery. However, the subjective evaluation showed that the earthquake evoked significantly more negative emotions than the neutral video and that the neutral video did not induce a reversal of the dominance of the left and right $\Delta\text{total-Hb}$, suggesting that the asynchrony between the left and right total hemoglobin concentration changes may reflect different emotional reactions. Emotional responses encompass alterations in heart rate and respiration, potentially influencing variations in brain hemoglobin concentration [11,12]. Further research, incorporating additional biological signals, is warranted to elucidate the desynchronization of left and right brain activity in response to emotional changes.

Tyagi et al. investigated the functional connectivity of brain regions during a VR disaster. They reported that the correlation between the left and right DLPFCs

was higher during environmental experiences with a high cognitive stress load in emergencies [3], a result opposite to that of the present study. Our results may have been influenced by the difference in the task used in the present study, which did not require cognitive performance but only viewed video images. A previous study reported that reduced synchronization strength in the left and right hemispheres is associated with reduced cognitive performance [13]. Therefore, further investigations, such as measurements under experimental conditions that require cognitive control, such as having participants think about simulated evacuation behavior, are needed. The dynamic interactions of brain networks have also been reported to change over time when various emotions are continuously experienced [14]. Therefore, further investigations focusing on a wider range of dynamic neural networks are required.

In conclusion, this study investigated the synchronization of total hemoglobin concentration changes in the l- and r-DLPFCs during a virtual earthquake. While the l- and r-DLPFC showed significant positive correlations during neutral video viewing, they showed significant negative correlations during earthquakes. This result suggests that negative emotional arousal from the VR earthquake experience may interfere with the synchronization of the left and right concentration change of total hemoglobin in the DLPFCs. The present results clarify human emotional reactions to disasters, such as earthquakes.

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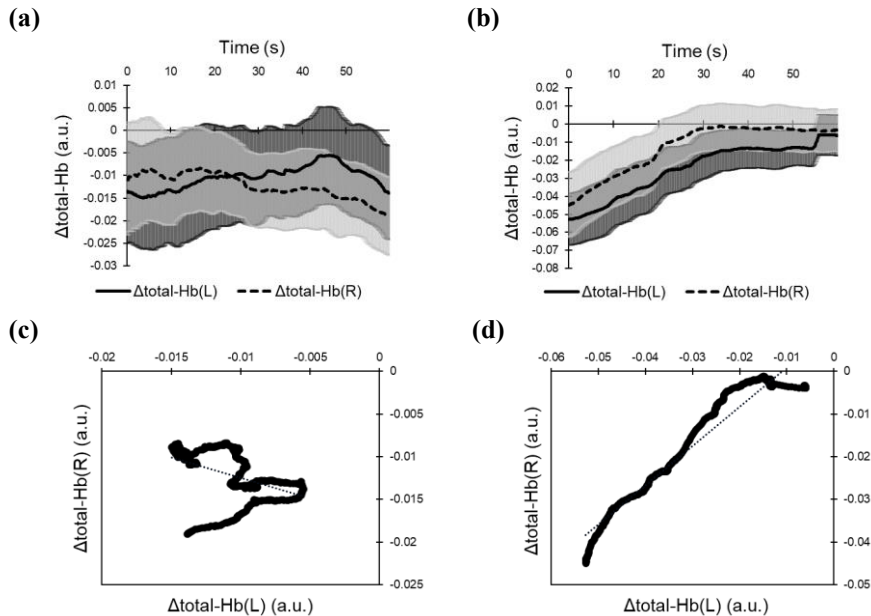


Fig. 1 $\Delta\text{total-Hb}$ time series data and relationships between both DLPFCs
 (a) and (b) show mean and standard error of time-series data for the $\Delta\text{total-Hb(L)}$ and $\Delta\text{total-Hb(R)}$ ($n=21$). The dark gray zone shows the standard error of $\Delta\text{total-Hb(L)}$ and the light gray zone shows $\Delta\text{total-Hb(R)}$. (a) Earthquake and (b) neutral videos. (c) and (d) Scatter plots of the correlation between $\Delta\text{total-Hb(L)}$ and $\Delta\text{total-Hb(R)}$ during each video viewing.