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Electroencephalography Signal Analysis for Virtual Reality Sickness: Head-mounted Display and Screen-based

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***Abstract*— The use of virtual reality (VR) technology is growing in the current era of the COVID-19 pandemic. However, the use of VR is causing problems for its users. Some symptoms, such as nausea, headache, and eye strain, are felt after using VR. These symptoms are called VR sickness. This study used electroencephalography (EEG) to record participants' brain activity changes when experiencing VR sickness. Participants are given VR impressions via screens and head-mounted displays (HMD). In addition, the subject also filled out a simulator sickness questionnaire (SSQ) before and after being given a VR. Brain waves in the alpha frequency range (8 Hz-13 Hz) and low beta frequency (13 Hz-21 Hz) were analyzed through the power spectral density (PSD). From the SSQ results, participants who saw VR through the screen experienced increased nausea symptoms. On the other hand, participants who saw VR through HMD experienced an increase in nausea and oculomotor symptoms ($p<0.05$). Based on power spectral analysis, changes in alpha wave PSD were obtained in the frontal, central, and parietal brain regions. There was also a shift in the value of the alpha peak frequency from before and after the participants were given VR. The average value of the alpha peak frequency shifts to a significant value. Therefore, it is concluded that the VR sickness from HMD viewing is more significant than through screens in the form of PSD results.**

***Keywords*— Alpha frequency; electroencephalography; low beta frequency; power spectral density; sickness; virtual reality.**

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I. INTRODUCTION

Life activities have changed a lot due to the COVID-19 pandemic. One is using electronic devices to replace activities usually carried out directly. Various activities are generally done offline, instantly turned online, or through technology and electronic devices. One of the emerging technologies in this pandemic era is virtual reality (VR). VR use scope is extensive, from entertainment to education. In entertainment, VR can be used for playing games, watching movies, 3D theater, and more [1], [2]. While in the world of education, VR is widely used for medical education, such as assisting the operation process, virtual lab, and laboratory work [3], [4].

With VR and personal headsets becoming more accessible to the public, like other technological advances, VR is starting to harm health, regardless of the impact size. It is pretty common for users of VR technology to experience certain types of nausea, eye strain, sweating, and dizziness to some extent [5]–[7].

The simulation environment affects the user's spatial and time awareness. The brain will panic when the eyes see a scene that says the user is moving but not moving. Research studies named this phenomenon VR sickness [8]–[10]. During long periods of staring at a TV or computer screen, the muscles responsible for eye movement become tense [11], [12].

The problem of VR sickness has become a significant obstacle to VR's widespread acceptance [13]. The appearance of the symptoms of VR sickness is tried to be eliminated by various methods. Various things were done to avoid the possibility of VR sickness symptoms, such as setting the airflow, the smell of the room, and the use of background music [14]. However, this cannot be confirmed with certainty because no studies explain its impact quantitatively. An instrument is needed to measure the

emergence of VR sickness symptoms when using VR so that these efforts can be confirmed.

One method is often used to measure the appearance of VR sickness symptoms. The technique is in the form of a simulator sickness questionnaire (SSQ) [15]. SSQ is subjectively used to see if a person experiences VR sickness symptoms after using VR. Various studies on SSQ-based VR sickness have been carried out. The level of VR sickness in using VR based on monoscopic and stereoscopic conditions was compared [16]–[18]. In other studies, information was obtained on how the effect of the duration of stimulation and the type of simulator on the level of VR sickness [19], a comparison of the level of VR sickness in the use of VR based on 2D and 3D stereoscopy [20], and a comparison of the VR shows provided in the form of two types of movement of a point pattern [21].

SSQ is given just before and after someone uses VR. This is a distinct disadvantage of the SSQ because it cannot describe the appearance of VR sickness symptoms in real-time [13]. In addition, the SSQ has several limitations reported in various studies. For example, there is a bias with cognitive and psychological factors, and there is no correlation between the results of the questionnaire and the desired variable, making it difficult to interpret [22]

Methods based on physiological signal parameters were developed to overcome the limitations of using SSQ. Some examples of techniques that have been carried out include electrogastrography (EGG) [23], electrocardiography (ECG) [24], salivary cortisol levels [25], measurement of blood pressure and pulse [26], [27], electrooculography (EOG) [28], and electroencephalography (EEG) [29]–[31].

There are two types of VR based on their complexity, static and dynamic. The kinds of VR based on the device vary, ranging from driving simulators and on-screen video (2D and 3D) to head-mounted displays (HMD). VR sickness arising from driving simulators has been investigated by various researchers [32]–[35]. The stimulation using a driving simulator is dynamic, where the subject experiences motion in real time, while the stimulus in the video is static. In the case of a driving simulator, there is one problem when concluding the measurement results via EEG. This is because the measured EEG physical parameters change cannot determine whether the cause comes only from VR sickness or the subject's interaction with the simulator machine [36]. Therefore, providing static VR-based stimuli is expected to describe VR sickness more precisely. Therefore, this research will focus on screen-based and HMD-based static VR.

Static VR content can be delivered through various devices like screens and HMDs. Users will feel different things between the two types of devices. This study will compare the EEG signal generated from measurement when participants view VR through a screen and HMD. The signal will be analyzed and compared with the symptoms of VR sickness experienced by the subject.

The measured EEG signals have various ranges, ranging from gamma wave (γ) (> 30 Hz), beta wave (β) (13 Hz – 30 Hz), alpha wave (α) (8 Hz – 13 Hz), theta wave (θ) (4 Hz – 8 Hz), and delta wave (δ) (0.5 Hz – 4 Hz). Each brain wave frequency corresponds to a person's mental state [37], [38]. All EEG frequency bands were analyzed in a related study, resulting in various conclusions regarding the relationship between EEG signals and VR sickness [39]. Alpha (8-13 Hz) and low beta (13-21 Hz) waves are interesting to be explicitly analyzed because of the various frequency bands of these brain waves. Alpha waves occur in a conscious and relaxed person with closed eyes. Alpha waves are blocked or reduced by attention (mainly visual) and mental or psychic effort. In comparison, beta waves occur when a person experiences mental activity that is fully awake or in a thinking state associated with an active cortex [40]–[42]. This study's EEG signal analysis will focus on the alpha and low-beta wave frequency bands.

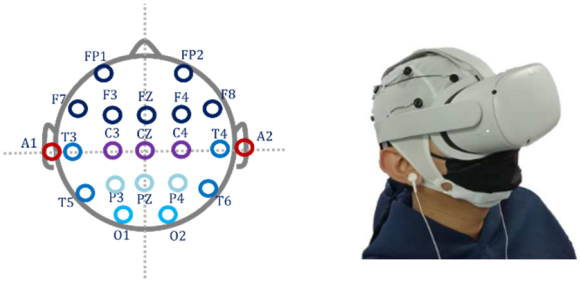
II. Materials and Method

A. Participants

A total of 22 males aged 20-24 years participated as volunteers in this study. Participants' background related to a history of motion sickness was obtained through the motion sickness susceptibility questionnaire (MSSQ) [43]. In addition, experience using VR devices is one of the factors for recruiting participants. Participants who are accustomed to using VR devices or have used VR devices in the past three months will be excluded from the experiment. Based on the questionnaire, participants with no history of nervous and vestibular disorders were selected. They are also not on medication or under the influence of drugs. All participants were also confirmed to never or rarely use VR devices, especially in the last six months.

B. Experimental Devices and VR Environment

1) EEG Device: This study uses Neuron-Spectrum-63 (Neurosoft), which had 19+2 EEG electrodes with Ag/AgCl electrodes (A1, A2 as reference, and 19 head electrodes). The arrangement of these electrodes follows international standards, as shown in Fig.1. The naming of the electrodes was made based on the position of the electrodes on the head representing each lobe. Electrodes Fp1, Fp2, F7, F3, Fz, F4, and F8 are in the frontal lobes. Electrodes T3, T4, T5, and T6 are in the temporal lobes. Electrodes P3, Pz, and P4 are in the parietal lobes. Electrodes O1 and O2 are in the occipital lobes. Electrode C3, Cz, and C4 are in the central region of the brain. The reference electrode (A1 and A2) is on the earlobe. The sampling rate of data acquisition for this EEG is 500 Hz.



(a) (b)

Fig. 1 EEG electrode placement configuration (a) Referential montage (b) A participant wearing a cap with EEG electrodes and HMD

2) VR Environment: We used a screen and HMD as the VR environment. In screen-based VR, we used a 50-inch flat-screen resolution of 3840 x 2160. As for HMD-based

VR, we used the Oculus Quest 2 (Oculus) device with a single fast-switch LCD panel type, 1832 x 1920 pixels in each eye. This device has a supported refresh rate of 72 Hz. The VR impressions are in the form of a roller coaster game in which there are various types of motion (translation and rotation), changes in altitude, and speed changes.

C. Data Acquisition

Data is acquired in the laboratory with specific settings to minimize noise and artifacts from external electromagnetic fields. The arrangement and testing of the room for data acquisition have been obtained in previous studies [44], [45].

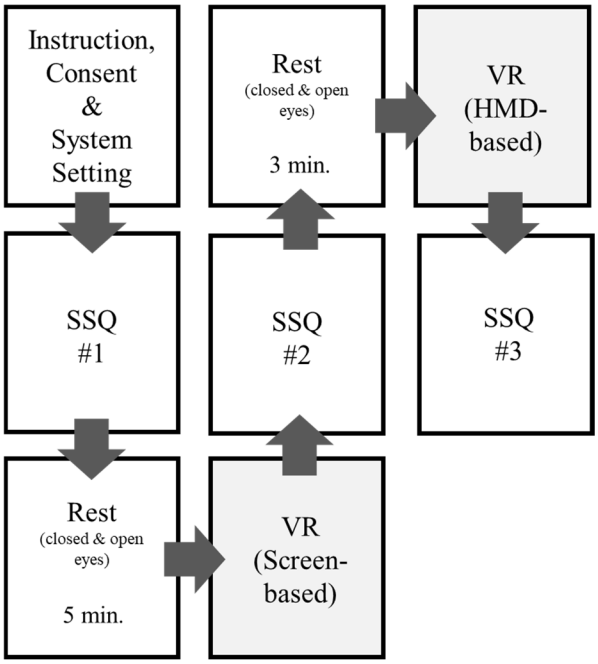


Fig. 2 Experimental protocol design for data acquisition

Fig. 2 shows the experimental protocol at the time of data acquisition. Before starting the EEG measurement, participants were instructed on the technical data collection and asked to fill out informed consent forms. After that, the EEG electrode was placed on the subject's head. Then participants fill in the first SSQ, which will be the background value.

Before data recording begins, notch filters with 60 Hz and 120 Hz stop bands are applied to eliminate interference from electronic devices. The contact between the electrodes and the scalp is also ensured in good condition through an impedance value below 5 kΩ.

Participants entered the rest session by closing their eyes and opening them for 1 minute and 30 seconds each. At this stage, the EEG begins to collect data. Next, the on-screen VR display starts. Participants were asked to watch the VR video. The video lasts 3 minutes and 45 seconds. After the video ends, participants fill in the second SSQ, which shows the effects of VR through the screen.

The HMD is mounted on the participant's head in the last stage. Then the VR video is shown through the HMD. The video lasts 2 minutes and 50 seconds. During the measurement, participants were asked not to move to avoid noise and artifacts from physiological signals other than EEG signals.

D. Data Analysis

In this study, there are two kinds of data. The first is subjective data derived from questionnaires, and the second is objective data derived from EEG measurements.

1) Subjective data: The SSQ consists of 16 types of symptoms related to VR sickness: dizziness (eyes open), the fullness of the head, dizzy (eyes closed), fatigue, sweating, stomach awareness, nausea, eye strain, increased salivation, burping, headache, vertigo, general discomfort, eye strain, difficulty concentrating, and blurred vision. The sixteen symptoms were divided into oculomotor, nausea, and disorientation. All symptom questions in the SSQ are filled with a choice of symptom levels: none (score 0), little (score 1), moderate (score 2), and severe (score 3) [46].

2) Objective data: The obtained EEG signal will be processed and analyzed through re-processing, feature extraction, and classification [47], [48]. Fig. 3 shows the steps to process the obtained EEG signal for further analysis.

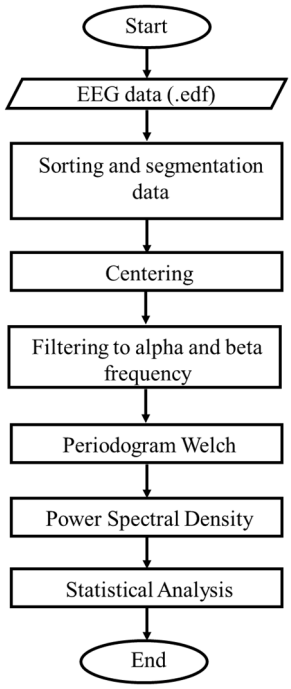


Fig. 3 EEG signal processing flowchart

The EEG data (.edf) is converted into (.set) to be sorted and cut to obtain the desired data. After receiving the EEG data (.set), the position of the electrodes is loaded following the EEG placement system used. Furthermore, the centering process, which aims to eliminate DC offset, uses averaging all data and then reducing each data by that average. Filtering is done to obtain the desired frequency range. Bandpass filters only pass signals in the frequency ranges of alpha wave (8 Hz -13 Hz) and low beta wave or beta-1 (13 Hz - 21 Hz). With this method, noise and artifacts can be removed.

Power Spectral Density (PSD) is the power of a signal as a function of frequency. This PSD was obtained using the Welch Periodogram [48], [49]. The obtained PSD can be determined for peak frequency and peak PSD. If the PSD in

a frequency range has more than one peak, the Center of Gravity (CoG) method is used [50], [51].

III. Results and Discussion

A. Simulator Sickness Questionnaire (SSQ)

SSQ data from all participants were processed. SSQ scores were obtained for each symptom category: nausea (N), oculomotor (O), and disorientation (D). The total score of the SSQ is also obtained, as shown in Fig. 4.

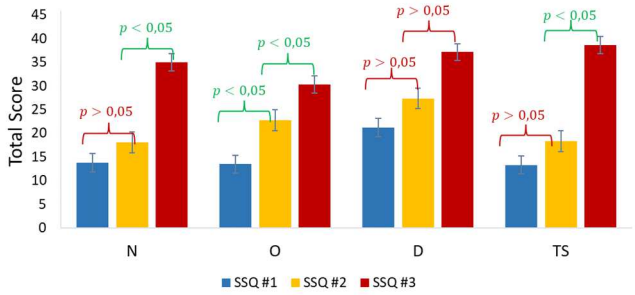


Fig. 4 Average SSQ score for three stages: baseline, after screen-based VR, and after HMD-based VR

Kennedy et al. [52] and Stanney et al. [53] stated that there is a threshold on the total SSQ score to indicate whether VR sickness is induced in a person. SSQ scoring results provide information about an increase in the subject's experience with VR sickness. The SSQ total score range (TS) can be categorized into several groups. The TS categories are no symptoms ($TS < 5$), minimum symptoms ($5 < TS < 10$), moderate symptoms ($10 < TS < 15$), high symptoms ($15 < TS < 20$), and bad symptoms ($TS > 20$). A person can be categorized as having VR sickness if he gets a total SSQ score above 20 [13].

In general, there was an increase in scores, both for each symptom category and in total, from SSQ#1 to SSQ#2, up to SSQ#3. No significant difference was found between the two sessions, SSQ#1 to SSQ#2 ($p > 0.05$), except in the category of oculomotor symptoms. In the category of oculomotor symptoms, there was a significant difference ($p < 0.05$) between SSQ#1 (13.47) and SSQ#2 (27.53). This oculomotor is associated with symptomsuch as general discomfort, fatigue, headache, eye strain, difficulty focusing and concentrating, and blurred vision [52].

From SSQ#2 to SSQ#3, there was a significant increase in scores ($p < 0.05$) in the nausea, oculomotor, and total score categories. Meanwhile, in the disorientation category, the increase was not significant ($p > 0.05$). The increased total score on SSQ#2 (18.28) to SSQ#3 (38.65) indicates that when VR playback via HMD, the subject experienced an increase in the severity of VR sickness during and after VR playback [54]. SSQ scores increased from screen-based VR to HMD-based VR. This indicates that HMD-based VR strongly influences the emergence of VR sickness.

B. Power Spectral Density

The peak PSD values obtained from all participants at each electrode point were averaged. Then, the mean peaks of the PSD were grouped by brain lobe and re-averaged. These steps received the average peak PSD for each lobe of the brain. Only PSD peaks in the alpha and low beta wave ranges were analyzed following the research objectives.

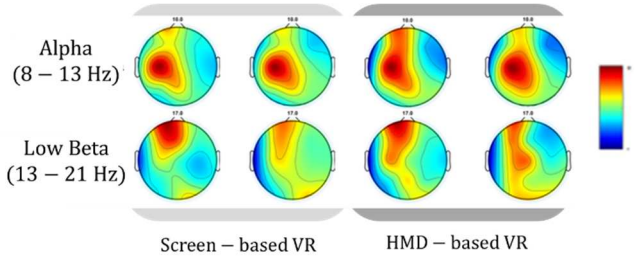


Fig. 5 Brain maps of a participant while viewing VR

Electrical activity in a person's brain can be seen through brain maps. These brain maps have a blue color indicating low PSD to a red color indicating high PSD. Based on Fig. 5, in the alpha wave frequency range, the area of the brain that is activated when participants view screen-based VR is in the parietal lobe. When the show becomes HMD-based VR, the activated brain area becomes increasingly up to the frontal. Likewise, in the low beta frequency range, it can be observed that there is a change in the distribution of activated brain areas, although not as large as the alpha range. This result aligns with previous studies, which showed that the PSD value only increased in specific lobes, especially in the frontal and parietal regions [10], [39].

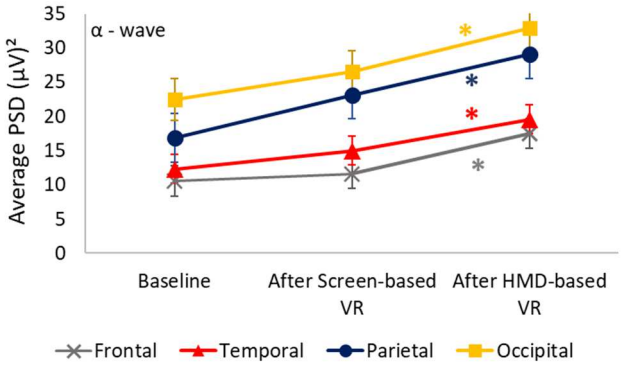


Fig. 6 The change in average PSD peak from the baseline condition-after screen-based VR-after HMD-based VR for the alpha wave frequency range (the * sign indicates that p<0.05)

Fig. 6 shows the change in the average value of the PSD peak for the alpha-wave frequency range (8-13 Hz). The average peak PSD value in all brain areas increased when participants were given a screen-based VR stimulus. Likewise, when the given VR is changed via HMD, it is seen that the average peak PSD value increases. However, when compared between the provision of VR via the screen and HMD, it is seen that the increase in the average peak value of PSD is significant only in the case of HMD-based VR ($p < 0.05$). This significant increase occurred in all areas of the brain.

Physiologically, an increase in the average peak value of this PSD describes increased activity in specific brain areas. In this case, the increase in electrical activity caused by HMD-based VR is more significant than screen-based VR. This increase in activity is related to the appearance of VR

sickness symptoms experienced by participants, as seen from the SSQ results [7], [10], [41], [42].

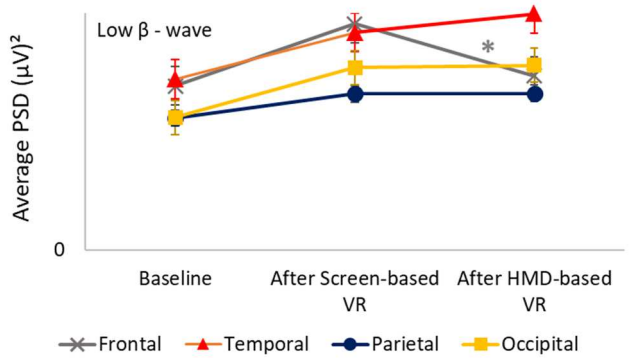


Fig. 7 The change in mean PSD from the baseline condition-after screen-based VR-after HMD-based VR for the beta-low wave frequency range (the * sign indicates that p<0.05)

Fig. 7 shows the average change of PSD peak in the low beta wave frequency range (13-21 Hz). The mean peak value of PSD at this low beta frequency increased in the temporal, parietal, and occipital areas. The provision of serial VR stimuli from the screen to the HMD was one of the factors that caused insignificant PSD changes ($p > 0.05$) to occur in the low beta wave range in the temporal, parietal, and occipital areas [39]. On the other hand, the change in the PSD value occurred significantly in the frontal area. In the frontal area, the mean peak PSD value grew from the baseline to screen-based VR, but the value decreased significantly at the change to the HMD-based VR condition ($p < 0.05$). This relates to the frontal lobe's function that controls key functions relating to consciousness and communication, memory, attention, and other roles [38], [55].

Generally, the peak PSD values for this low beta frequency range are below the alpha frequency range. This indicates that the brain's electrical activity is in the alpha frequency range [13], [19], [29], [40], [56]. This condition is contrary to several studies that have been conducted where the change in PSD in the alpha frequency range is not significant [11], [20], [28], [30]. This difference in results arose due to differences in the conditioning of the subjects when the VR stimulus and EEG measurements were to be carried out. In this study, the subject's initial conditioning was carried out in a relaxed state,a condition in the alpha frequency range [38], [55]. This can also be seen from the PSD value in the alpha frequency range ($10.56 - 32.92\ \mu V^2$), which is much higher than the low beta frequency range ($0.56 - 0.99\ \mu V^2$) and other frequencies ($< 0.50\ \mu V^2$).

C. Peak Frequency

A shift in the peak frequency value in a brain wave frequency range can indicate a change in a person's mental state. This shift in mental state is one of the things that can indicate the appearance of VR sickness symptoms in a person. [57]. The shift in the peak frequency value in the alpha range is shown in Fig.8. The alpha peak frequency shifted to smaller values for the frontal (10.17 – 10.11 Hz) and temporal areas (10.33 – 10.32 Hz). While in the parietal (10.34 – 10.35 Hz) and occipital (10.29 – 10.37 Hz), the shift appears towards a higher frequency. Even though there was a change, the value was not significant ($p > 0.05$). This is related to the subject is used to watching a broadcast from the screen. This condition causes the subject's mental state to not change much, except for the occipital area which works to process visual stimuli from the screen [20], [24], [31], [36], [58]

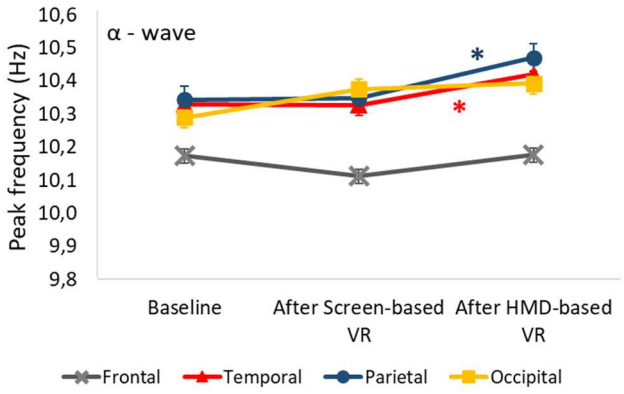


Fig. 8 Shift in the average value of the alpha peak frequency from the baseline condition-after screen-based VR-after HMD-based VR (the * sign indicates that p<0.05)

In changing VR from screen-based to HMD, the frontal, temporal, and parietal areas experienced a shift in the alpha peak frequency to a higher value. Distinguishable changes ($p < 0.05$) appeared in the temporal and the parietal regions, with the highest increase in the parietal of 0.12 Hz. In line with previous research, the effects of VR on HMD were more felt by the subjects, so their mental state changed to be more focused [10], [17]. Interestingly, the occipital area has shifted to a minor frequency. This is related to the process of receiving VR stimuli from the beginning so that no new experiences are received in this area [56].

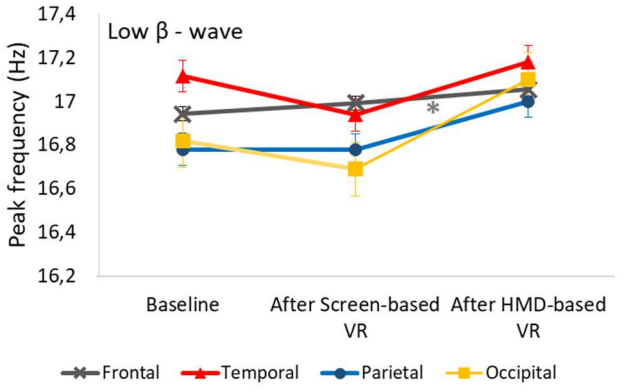


Fig. 9 Shift in the average value of the low beta peak frequency from the baseline condition-after screen-based VR-after HMD-based VR (the * sign indicates that p<0.05)

The shift in the low beta wave frequency range has a different pattern from the alpha wave frequency range, as shown in Fig. 9. The temporal, parietal, and occipital areas undergo similar shifts. From baseline to screen-based VR, frequency shifts to a smaller value (towards the alpha frequency range). Then from screen-based VR state to HMD, the shift towards higher values (towards high beta frequency

range). On the other hand, the frontal area experienced a change in beta frequency, which continued toward higher values ($p < 0.05$).

IV. Conclusion

An experiment was conducted to investigate how the symptoms of VR sickness appear based on the physical parameters of the electroencephalography signal. Virtual reality content is broadcast through the screen and the HMD. The mean PSD value increased for all brain regions in the alpha wave frequency range. This increase in mean PSD value is related to increased brain activity due to VR stimuli. When the rendered VR was changed from screen-based to HMD-based, the rise in PSD was significant, with the most prominent being in the frontal and parietal regions. On the other hand, in the low beta wave frequency range, the increase in the average PSD is not as significant as at the alpha frequency. In general, it can be said that there is no substantial increase in PSD.

The VR stimulus causes a shift in the peak frequency value, both alpha and low beta. This shift indicates a change in the participant's mental state related to the symptoms of VR sickness. The value of the peak frequency of the alpha wave shifts towards a higher value as the VR stimulus is given, while for the low beta, it tends to be the opposite.

This study can be developed further by creating more varied and characterized VR content. Variations in types of motion, speed, length of time, lighting, and position on VR content can be a reference to find out in more detail about VR sickness. This study aims to obtain a system that can predict what kind of VR content can potentially cause VR sickness in its users.

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