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SPECIAL ISSUE ARTICLE

EEG based time and frequency dynamics analysis of visually induced motion sickness (VIMS)

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Abstract 3D movies are attracting the viewers as they can see the objects flying out of the screen. However, many viewers have reported various problems which are usually faced after watching 3D movies. These problems include visual fatigue, eye strain, headaches, dizziness, blurred vision or collectively may be termed as visually induced motion sickness (VIMS). This research focuses on the comparison between 3D passive technology with a conventional 2D technology to find that whether 3D is causing trouble in the viewers or not. For this purpose, an experiment was designed in which participants were randomly assigned to watch 2D or a 3D movie. The movie was specially designed to induce VIMS. The movie was shown for the duration of 10 min to every participant. The electroencephalogram (EEG) data was recorded throughout the session. At the end of the session, participants rated their feelings using simulator sickness questionnaire (SSQ). The SSQ data was analyzed and the ratings of 2D and 3D participants were compared statistically by using a two tailed *t* test. From the SSQ results, it was found that participants watching 3D movies reported significantly higher symptoms of VIMS (p value <0.05). EEG data was analyzed by using MATLAB and topographic plots are created from the data. A significant difference has been observed in the frontal-theta power which increases with the passage of time in 2D condition while decreases with time in 3D condition. Also, a decrease in beta power has been found in the temporal lobe of 3D group. Therefore, it is concluded that there are negative effects of 3D movies causing significant changes in the brain activity in terms of band powers. This condition leads to produce symptoms of VIMS in the viewers.

Keywords Visually induced motion sickness (VIMS) · Stereoscopy · 3D movies · Electroencephalogram (EEG) · Simulator sickness questionnaire (SSQ) · Time–frequency analysis

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Introduction

Visually induced motion sickness (VIMS) is a major problem for viewers of 3D movies. Entertainment becomes a fatigue for those viewers who are affected by the symptoms of VIMS. Research in the field of VIMS is progressing significantly. A variety of physiological signals have been used for the characterization of VIMS such as pupillary responses, autonomic responses and responses from central nervous system [1]. Yano et al. used pupillary response as accommodation response to find visual fatigue and visual comfort caused by 3D movies [2]. In an experiment done by Daugherty et al. [3], vergence response was reported more active during stereoscopic 3D tasks. In some of the studies, eye blink counts have also been studied for measuring eye strain in 2D and 3D viewing [4]. Visual symptoms produced by viewing stereoscopic films are still under investigation. In a study the VIMS is reported to be significantly higher after watching motion

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images compared to still images [5]. Researchers are trying to create models for visual parameters, such as accommodation and vergence response, that are accepted as trouble makers for 3D viewers [6]. Autonomic responses such as, heart rate, blood pressure, pulse transmission time (PTT), photo-plethysmography (PPG) etc., have also been investigated in this aspect [6–8]. However a number of disadvantages have been reported in using such autonomic responses. A number of disadvantages have been reported in autonomic response. First of all they are dependent upon subjective conditions which include fear and excitement, and they can vary with physiological conditions. Secondly, PTT and PPG are less accurate as they are recorded using finger probes which are disturbed with finger movement. In a study by Naqvi et al. a comparison is made between visual induced motion sickness induced due to 2D and 3D visual stimuli [9].

A number of investigations have been done to analyze physiological aspects of motion sickness. VIMS is derived from motion sickness which is caused when human senses get conflicting inputs from the visual and vestibular system [10]. The processing center of visual and vestibular systems lies within the central nervous system. Thus, the conflict is actually occurring in the brain regions where information from the two regions is being processed. Therefore, neural correlates of VIMS can be studied using neuroimaging techniques. Electroencephalography (EEG) can be used to analyze brain signals because of its high temporal resolution and ease of use in experimental conditions. Experiments involving EEG mostly investigate motion sickness, not VIMS. Chen et al. investigated the EEG dynamics of motion sickness, they stimulated both visual and vestibular senses of subjects, who were asked to sit as a passenger of a car moving along a road. It was observed that an increase in alpha power correlating with subjective motion sickness level in parietal lobe and theta power also increased in motor areas of the brain [11]. Kim et al. used virtual reality experiment to induce "cybersickness" and found an increase in delta and decrease in beta power in frontal and temporal areas [12]. Min et al. evaluated simulator sickness in a car driving experiment and found that theta power declined as motion sickness increased while delta power increased in Fz and Cz electrodes [13]. Hu et al. used optokinetic drum to induce motion sickness, an increase in delta band power was found in C3–C4 electrodes compared to baseline power [14]. However, the findings obtained in the present work are different.

Objectively recorded parameters require a cross check which is done by subjective ratings. Researchers often conduct interviews or provide questionnaires to get the feedback of a participant. The most popular questionnaire adopted by many of the researchers is SSQ developed by [15]. It consists of 16 questions rated on a scale of none (0), slight (1), moderate (2) and severe (3). These questions are divided into three different symptoms categories which are nausea, oculomotor and disorientation. Final results are obtained by mathematically calculating the rating of each question which gives a numerical outcome of total score and for each of the three symptom categories. However, it is not advised to use SSQ in long duration experiments in which participants will be interrupted to ask the questions again and again which will cause loss of focus in the experiment.

This study highlights anatomical activations of the cortical areas of the brain found in a VIMS inducing environment.

Materials and methods

In this research work, a 128 channel EEG device was used to capture the brain signals from subjects watching a movie that induces motion sickness. The movie is designed to have specialized camera movements in pitch and roll directions. The subjective feedback of the viewers was taken in the form of SSQ. The experiment was designed to have minimum effects of vestibular activation so that symptoms induced are purely from visuals of the stimulus. The EEG signals are analyzed in time–frequency domain to find the possible correlates of brain physiology and development of VIMS symptoms over the time. The brain activations are visualized in topographic maps which provide better understanding of the cortical regions and their activation. Hence, two groups are compared with one watching 3D movie and another watching 2D movie. It is hypothesized that 3D viewing induces VIMS symptoms more than 2D viewing. Therefore, an independent study is selected with parallel architecture. Parallel study will make sure that subjects do not overlap, that is if one subject is selected for first case he/she cannot participate in second case. The reason behind this selection is that, same stimulus will be presented in both cases which can induce an effect of boredom in participants. There is also an effect of habituation which might reduce the VIMS symptoms when participants watch the movie second time. A randomized controlled trial (RCT) design was selected so that participants were allocated randomly to the two groups.

Experimental protocol

Sample size calculation was done by PS (power and sample size) software, using uncorrected Chi square test [16].

a is the significance level, 0.05; P is the power of the study, 80 %; P1 is the probability of motion sickness in 2D

case, 18.5 % fixed base simulators [17]; P2 is the probability of motion sickness in 3D case, 59.1 % [18]; N is the 21 participants for one group.

A written consent was taken from all the participants before participation and they were informed about the risks involved in the study. The study was approved by the ethics committee of Hospital Universiti Sains Malaysia (HUSM). All participants were compensated for the time consumed.

The experiment involved an eye open (EO) condition and a VIMS condition. In the EO condition subjects were asked to focus on a point on the screen while there EEG was recorded. EO condition lasted for 5 min. After EO recording the participants were asked to watch a movie and there EEG was recorded which is called as the VIMS condition. VIMS condition lasted for 10 min. At the end of VIMS condition participants were asked to fill SSQ, which will provide the motion sickness scores of the participants.

Participants

More than 60 students were recruited for this experiment from Universiti Teknologi PETRONAS, Perak, Malaysia for this study. However, after careful screening with no history of eye disease, eye surgery, neurological disease, head injury, systemic problems, ear problem or surgery etc. only 52 were selected to take part in experiment. It should also be noted that participants with refractive error i.e., myopia, hyperopia and presbyopia were excluded from the study. Before experiment, a complete eye assessment was performed by an ophthalmologist. This includes visual acuity, refraction and fundus examination. Finally, data from 46 students was used in the data analysis with 23 students in both groups as corrupt data was removed.

Stimulus

Visual stimulus was shown on a 42" 3D LCD TV. The TV uses polarized glasses technology to create 3D images. The stimulus was displayed through TOBII software. The TOBII software can be synchronized with E-prime therefore making it possible for the experimenter to start the stimulus and EEG recording at the same time. E-prime can also be used for stimulus display but it does not support 3D display. Hence, it was better to provide stimulus on TOBII. The stimulus was a view from a camera while it moves along the road. The camera was animated to have specialized movements along pitch and roll axes. The camera was rotated alternately on the two axes with 30° of amplitude and 0.167 Hz of temporal frequency. The stimulus was created in both 2D and 3D using 3D computer graphics software, (Omega Space, Solidray Inc.). It has already been reported that VIMS can be easily induced with camera rotations along pitch and roll axis [19]. The movie composed of 2 min. In the first minute camera was rotated along pitch axis and in the second minute camera was rotated along roll axis. The stimulus was repeated five times making the total viewing time to be 10 min. The stimulus was taken on request from [20].

Signal acquisition and pre processing

EEG recording was done using Electrical Geodesic Inc. (EGI) dense array EEG device. The recording net was HydroCel Geodesic Sensor Net with 128 channels. The net uses saline electrolyte for routine recordings. Sampling rate was set at 250 samples per second. Raw data was recorded and stored on the hard disk drive for later use. The data is first preprocessed on the NetStation software with a band pass filter of 0.3 –48 Hz to remove unwanted noise. After filtering, the data was checked for eye blink artifacts using NetStation built in algorithm based on [21] that marks the eye blinks. It creates an event file of the eye blink data that can be exported to MATLAB software. The data is exported to MATLAB along with its event log file of eye blinks. The remaining of the cleaning of the data is performed in MATLAB with EOG channel subtracting the eye blinks from the rest of the channels. Data from one participant was discard which was not cleaned leaving 22 participant for 3D and 23 for 2D group. The channels with corrupt data and covering an area irrelevant of the head were also removed from further analysis. The cleaned data was saved for further analysis.

Hardware configuration

The data recording and stimulus presentation was made synchronized using E–prime software. The synchronization of the NetStation and Tobii was done so that both have the same starting and ending time. E-prime was used as the master for initiating both the devices. E-prime, NetStation, and Tobii were connected to an Ethernet switch with user defined IP address [22]. Before starting E-prime, both NetStation and Tobii computers were set-up to the trigger point. When E-prime executes it sends trigger over the IP address of NetStation and Tobii, to start the recording and display the stimulus, respectively.

Time frequency analysis

A joint time frequency approach was chosen to analyze the data. Power of the EEG signal was computed in short time intervals of 2 s with an overlapping window of 50 %. The total duration of the signal was 10 min i.e., 600 s. For each participant, the absolute power was calculated for 128 electrodes, and decomposed into five bands. Frequency ranges were categorized into different bands which are

delta (1.0–3.5 Hz), theta (4–7.5 Hz), alpha (8–12 Hz), beta (12.5–25 Hz) and high beta (25.5–30 Hz). The power in every 1 min was averaged to get only ten values corresponding to 10 min of the data. This resulted in a matrix of electrodes (128) × minutes (10) × frequency bands (5) for one participant. This data was averaged over the participants of the two groups which are 2D-viewing group and 3D-viewing group. Two types of power were computed from the bands, absolute and relative power. The frequency transform gives absolute power which was then used to calculate relative power. Relative power is the ratio of a band power over the total power. Relative power gives an idea of actual contribution of a particular band in the overall EEG.

Topographic maps

A topographic map was generated from the average power of a minute using 128 electrodes. 10 topographic maps were generated in one frequency band. To find the significant changes in the brain regions, an independent sample *t* test was applied on the data. Every 1 min of the VIMS condition was compared with the EO condition in all electrodes. The significant electrode (having p value <0.05) was coded as 1 (orange), if mean value of EO condition was less than VIMS condition, while significant electrode (having p value < 0.05) was coded as -1 (blue), if mean value of EO condition was greater than VIMS condition. The insignificant electrodes ware marked with 0 (green). Thus, a topographic map was created for every 1 min and every single band in absolute power and relative power.

Results and discussion

The topographic maps are organized in a matrix form with frequency bands placed in rows while each column is 1 min of the recording compared to EO condition. The nose points towards the north in all the topographic maps. Maps for 2D and 3D groups are presented in separate figures within absolute power. The topographic maps are generated using freely available MATLAB toolbox, EEGLAB (http://sccn.ucsd.edu/eeglab).

SSQ analysis

The SSQ scores for 19 participants from 2D movie-viewing and 20 participants from 3D movie-viewing are compared. The average SSQ scores for the 2D and 3D groups are presented in Fig. 1. The figure shows sub scores for nausea (N), occulomotor (O) and disorientation (D) symptoms and also the total score (TS) for the SSQ. An independent

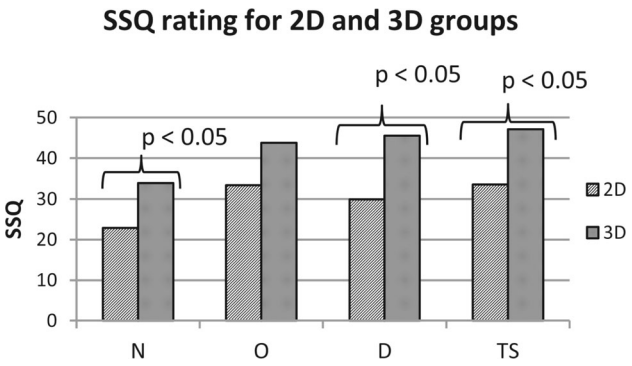

Fig. 1 Average SSQ score for 2D and 3D condition

sample *t* test was applied to find the difference between the 3D and 2D condition. The result shows that there is a significant difference in the mean score of nausea, disorientation and total score (p value <0.05). Thus, participants watching 3D reported higher symptoms of motion sickness. It is obvious from the result that occulomotor symptoms are common in both of the conditions due to similar camera motion; however, the rest of the symptoms are severe in 3D condition. Therefore, 2D and 3D groups are compared on the base of SSQ ratings.

Topographic maps

Figure 2 represents the topographic maps of absolute power in 2D condition while Fig. 3 represents the topographic maps of absolute power in 3D condition. To study the differences among the two conditions it is better to have a band wise comparison.

Delta band

From Figs. 2 and 3 it can be seen that delta band has a pattern throughout the VIMS condition. The movie is also changing in alternating minute from pitch axis to roll axis. When the participants are watching pitch movement the eye ball involuntarily moves with the images on the screen up and down. This phenomenon must have activated the frontal area of the brain. First minute shows a very high activity which shows a sudden change has occurred in the environment compared to baseline condition. Also every odd minute shows a higher activity in frontal region. Now let us consider the even minute of the movie in which the camera is moving in roll direction. The center of the screen is almost fixed at a point while the rest of the surrounding is moving. If the subject fixates at the center of the screen the condition becomes more like the baseline condition in which subject was asked to look at a particular point. There is a significant difference in the even minutes of the movie with mean value of the VIMS less than the mean value of

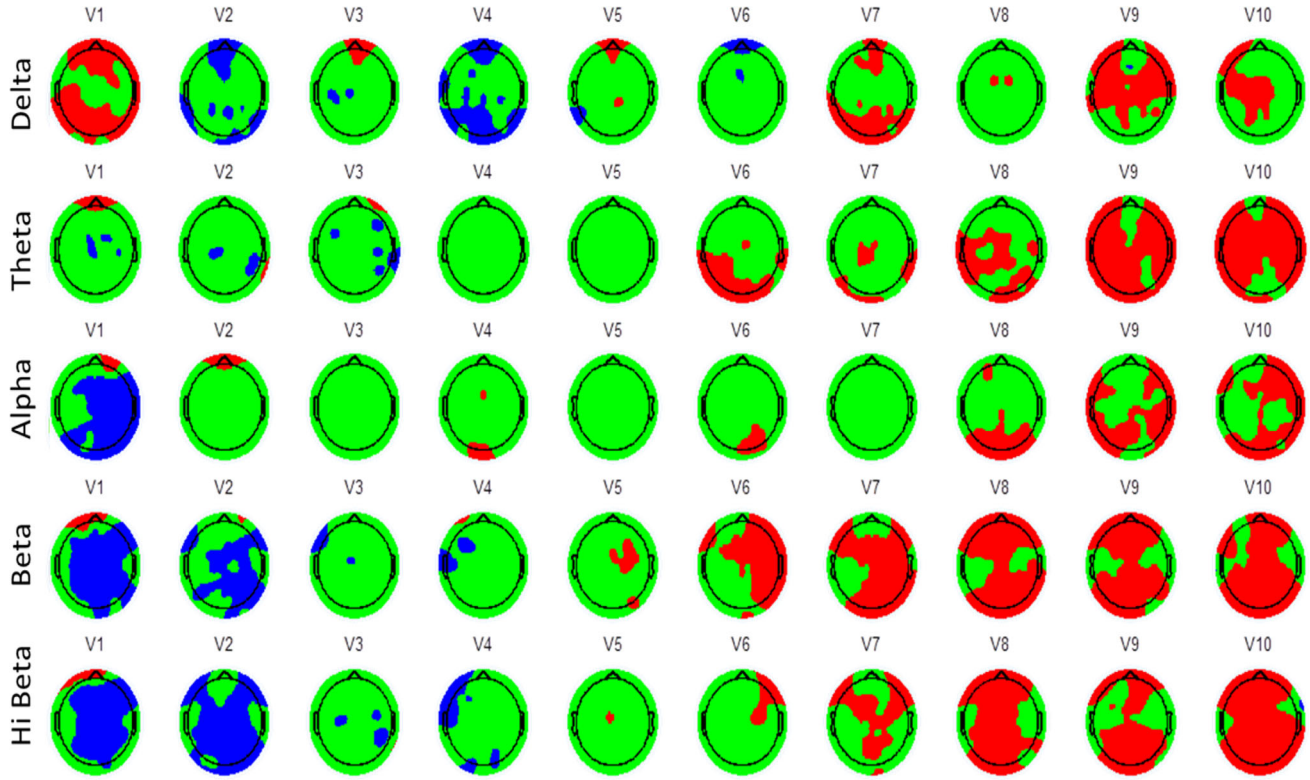

Fig. 2 Topographic maps of absolute power in different EEG bands for 2D condition

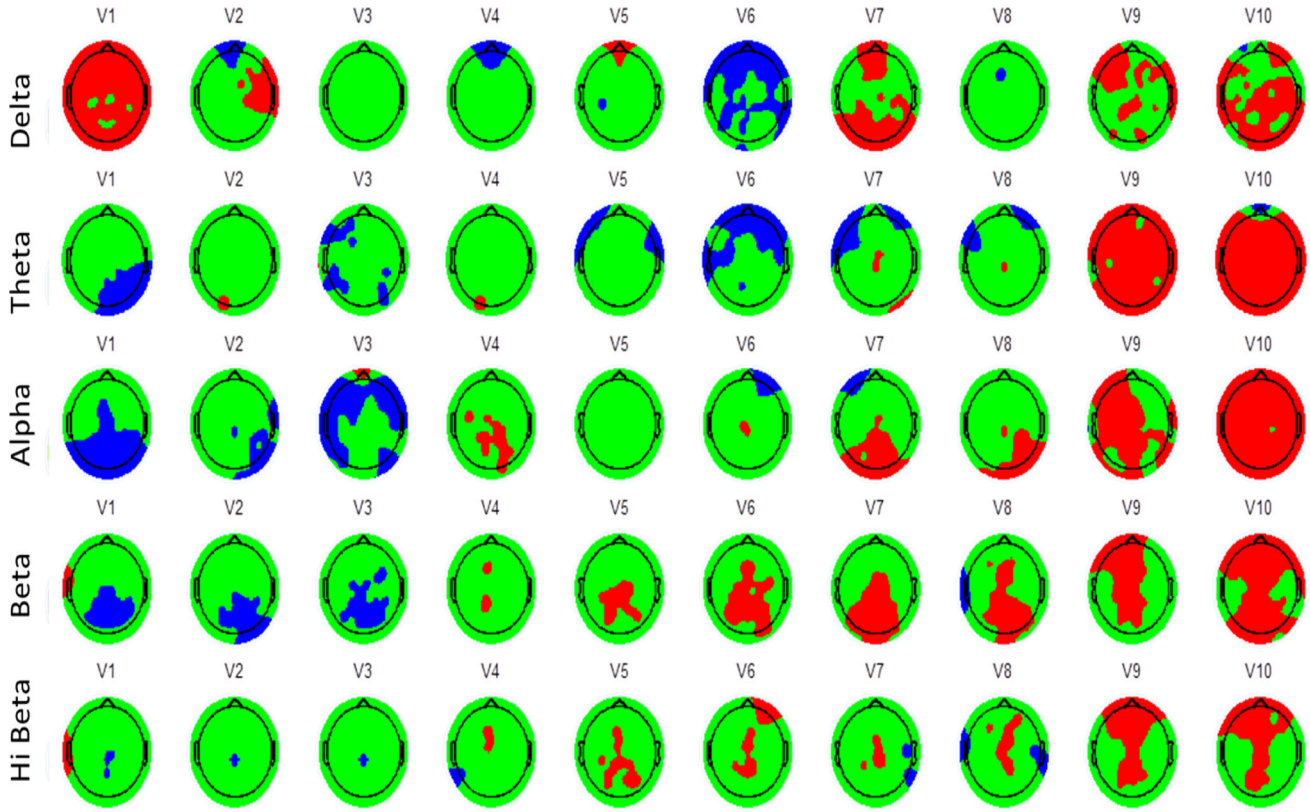

Fig. 3 Topographic maps of absolute power for various EEG bands for 3D condition

baseline condition. This shows that the brain encounters a problem when looking continuously to moving images in vertical direction and this increases the power of frontal region. While in the alternating minute when eyes do not move very much then the activity goes below the normal baseline condition to counterbalance the initial activity.

Theta band

In Fig. 2 topographic maps showed an increase in theta power compared to baseline condition in 6th, 7th, and 8th minute in posterior regions of the brain. Whereas in Fig. 3 participants showed decreased theta power in in 5th, 6th, 7th and 8th minute in fronto—temporal regions. In [11, 21–25] it is reported that theta power increases over baseline condition in frontal regions. While, [12] reports that theta power declined as motion sickness increased in electrode Fz. The increased power in 2D group cannot be reported as a motion sickness condition as all the researchers report an increase in frontal region. While the decreased power in theta is also reported in frontal region. These results are contradictory and have ambiguous outcome that whether an increase in theta causes motion sickness or decrease in theta power causes motion sickness. Comparing the results of theta power with results obtained from SSQ, 3D participants reported more symptoms of SSQ compared to 2D and this is in relation to results reported by [12] in which theta power decreased in Fz electrode while motion sickness rating increased.

Alpha band

In [11], it was reported that alpha power increase in parietal region with increase in subjective motion sickness level. In our study alpha power gradually increased in both 2D and 3D groups. Critically analyzing the significant areas of topographic map shows that from 4th minute onwards alpha power start to increase in posterior regions of the brain. In 4th, 6th, and 8th minute 2D alpha power increased in occipital region while in 3D group it increased in parietal and occipital regions in 4th, 7th, and 8th minute. If presence of alpha power in parietal region indicates the presence of VIMS, then 3D group is more likely to be motion sick.

Beta band

Beta power is not very common in the study of motion sickness as it is mostly related to complex task and brain activity in cognitive states. Changes in beta power are related to mental activity, cognition and awareness. Figures 2 and 3 show that beta power gradually increased with time in all the brain regions in 2D group, while in 3D it did not increased in frontal region.

High beta band

High beta shows a similar pattern as of beta in 2D group, while in 3D it is only significant in central region. The effects of high beta have not been studied in motion sickness studies so far. The result of 3D group shows that high beta does not remains consistent with the increase therefore the regions are not significant.

Relative power

Figures 4 and 5 show topographic maps for relative power for 2D and 3D condition, respectively. The relative delta power shows similar trend as it was in absolute delta power. An alternating change in power of frontal region is prominent in both 2D and 3D condition as visible by significant topographic maps. First minute of both conditions of 2D and 3D shows a high activity in delta band. This drastic change is justified as brain was previously experiencing a normal condition and suddenly the environments change ending up with an unusual visual stimulus. This might have caused an increase in the delta power of first minute. Comparing the relative power of other bands, it is found that there is a similar patter distribution like delta power but in opposite polarity. In 3D condition, starting from the first minute the trend follows in alternate change in almost every band until 7th minute. This shows the intensity of delta band in frontal region of 3D group was more than those in the 2D group. Now comparing the other regions of the brain in both groups' shows that most of the regions are not significant that is showing same power distribution as of baseline condition. Alpha band shows an increase in 2D group for the 2nd, 3rd, and 4th minute. This change is not giving us any idea that is it due to subjects getting adapted to the stimulus or is it due to motion sickness. Let's take a look on both of the cases, assume that subjects are having motion sickness as reported by [10] that increase in alpha power with subjective level of motion sickness. This doesn't hold true because after 4th minute the power of alpha band doesn't change significantly in any of the region. So looking at the second option that brain is adapting the stimulus it can be said that there is a steady change in alpha power for the first 3 min. This causes the brain to get stabilized and adapted to this stimulus because after this any changes in other regions or power bands of the EEG are not found. Comparing 3D group from the 2D group, there are no changes occurring in 3D group while the participants have reported higher symptoms of VIMS in 3D condition. Thus it is concluded that participants of 3D

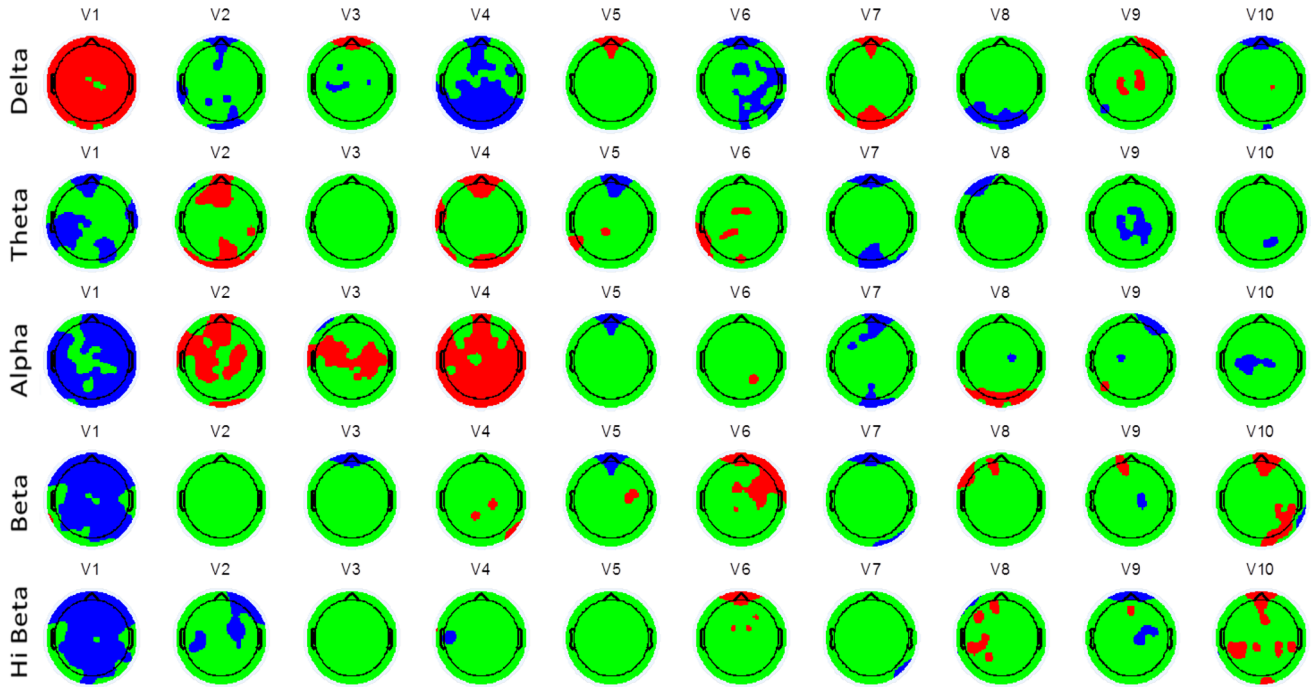

Fig. 4 Topographic maps of relative power of various EEG bands for 2D condition

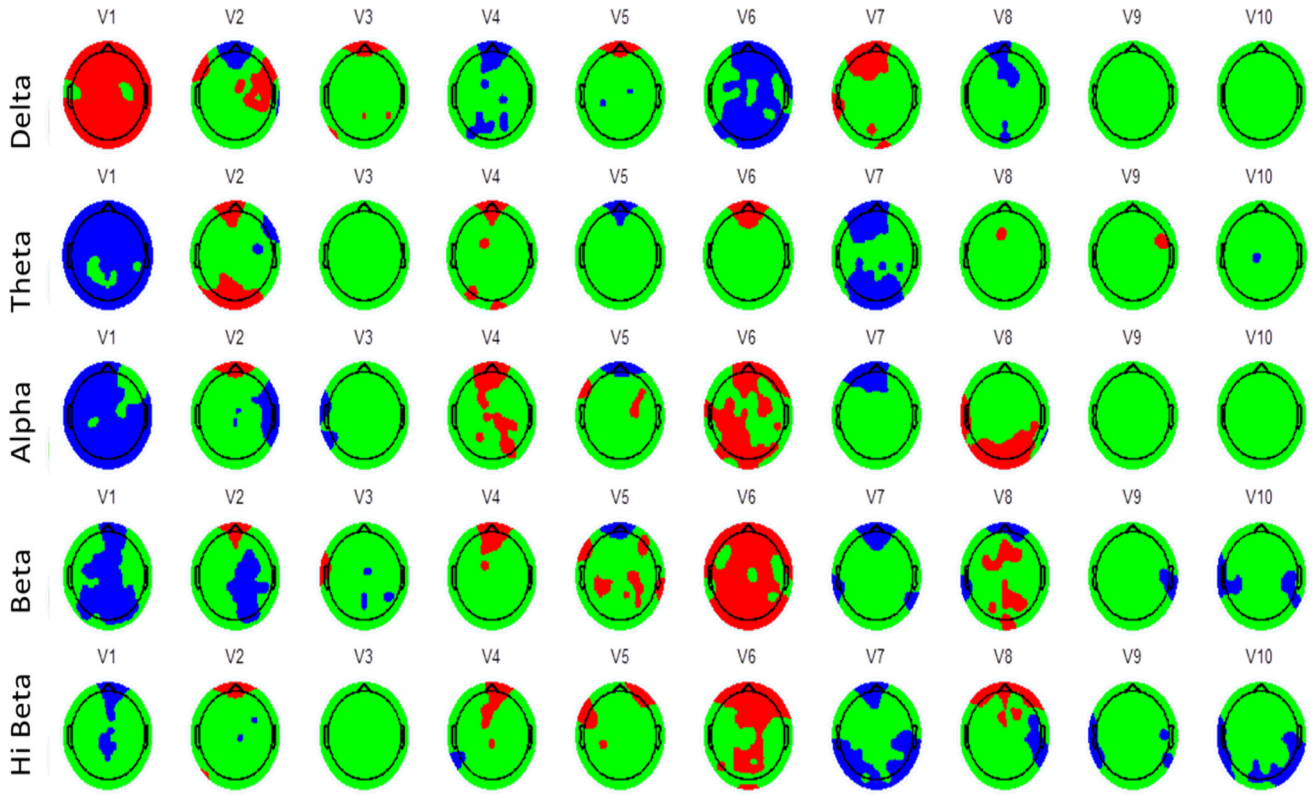

Fig. 5 Topographic maps of relative power of EEG bands for 3D condition

group are unable to adapt the stimulus that caused them to have higher symptoms of VIMS. Also, the 4th and 6th minute of the VIMS condition in 3D group shows a decrease in delta band. This change in delta is causing an increase in alpha, beta and high beta band. Since relative power is a percentage distribution the decrease in delta power might have caused an increase in other power bands.

The temporal region consists of a temporal vestibular cortex that deals with the body positioning [24]. This region provides information to the sensory vestibular cortex about orientation of the body posture. As beta waves are related to attention, cognition and awareness lower levels of beta and high beta bands in this region can reduce the sense of body positioning and introduce effects of disorientation or dizziness in the subjects. These lower levels of beta have been found in the last four minutes of the recording in 3D-viewing group (Fig. 5). The relative beta power have also been reported by [12] to be decreased in electrodes sites T3 and F3. These results coincide and thus problems faced by viewers of 3D movies show changes in the beta activity within the temporal lobe.

Conclusion

This study evaluates the EEG dynamics of a visually induced motion sickness in two different conditions i.e., 2D movie-viewing and 3D movie-viewing. The two conditions are compared to find the differences in EEG dynamics that arose due to watching a specially designed movie. The SSQ reports the level of motion sickness among the two conditions and EEG correlates the changes that occur in the brain. The participants experience the VIMS symptoms and report them through the SSQ. The topographic maps are generated in frequency domain having different band powers averaged into 1 min each, out of 10 min recording. The descriptive analysis of these maps shows that decrease in theta power in frontal region is similar to the study of [13]. On the other hand, decreased relative beta power in temporal region have been found which is similar to the study of [12].The extra pitch and roll motion of the stimulus is the main reason for the changes in the delta band. These changes in delta band are effective in both 2D and 3D movie-viewing hence they cannot be taken into account for VIMS. Instead, they can be assumed as initiation of VIMS due to specialized movements. This highlights that motion sickness can be induced by specialized movie if watched in 3D environment. Due to these special movements in the movie, the EEG rhythms of theta and beta bands get elevated. Therefore, it is concluded that, EEG rhythms of theta and beta bands should be analyzed in certain physiological conditions like VIMS. This work can be extended to visualize the activation of certain parts of brain during visual stimuli by using various localization techniques such as LORETA, sLORETA, eLORETA, MUSIC etc. [26, 27].

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