Estimating the Level of Motion Sickness Based on EEG Spectra

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Abstract. Motion sickness (MS) is a normal response to real, perceived, or even anticipated movement. People tend to get motion sickness on a moving boat, train, airplane, car, or amusement park rides. Although many motion sickness-related biomarkers have been identified, but how to estimate human's motion sickness level (MSL) is a big challenge in the operational environment. Traditionally, questionnaire and physical check are the common ways to passively evaluate subject's sickness level. Our past studies had investigated the EEG activities correlated with motion sickness in a virtual-reality based driving simulator. The driving simulator comprised an actual automobile mounted on a Stewart motion platform with six degrees of freedom, providing both visual and vestibular stimulations to induce motion-sickness in a manner that is close to that in daily life. EEG data were acquired at a sampling rate of 500 Hz using a 32-channel EEG system. The acquired EEG signals were analyzed using independent component analysis (ICA) and time-frequency analysis to assess EEG correlates of motion sickness. Subject's degree of motion-sickness was simultaneously and continuously reported using an onsite joystick, providing non-stop psychophysical references to the recorded EEG changes. We found that the parietal, motor, occipital brain regions exhibited significant EEG power changes in response to vestibular and visual stimuli. Based on these findings and experimental results, this study aims to develop an EEG-based system to estimate subject's motion sickness level upon the EEG power spectra from motion-sickness related brain areas. The MS evaluation system can be applied to early detection of the subject's motion sickness and prevent its uncomfortable syndromes in our daily life. Furthermore, the experiment results could also lead to a practical human-machine interface for noninvasive monitoring of motion sickness of drivers or passengers in real-world environments.

Keywords: EEG, ICA, motion-sickness, estimation, time-frequency, driving cognition.

1 Introduction

Motion-sickness is a common experience to everybody, and it has provoked a great deal of attentiveness in plenty of studies. The sensory conflict theory that came about

D.D. Schmorrow and C.M. Fidopiastis (Eds.): FAC 2011, HCII 2011, LNAI 6780, pp. 169–176, 2011.

in the 1970's has become the most widely accepted theorem of motion-sickness among scientists [1]. The theory proposed that the conflict between the incoming sensory inputs could induce motion-sickness. Accordingly, new research studies have appeared to tackle the issue of the vestibular function in central nervous system (CNS). In the previous human subject studies, researchers attempt to confirm the brain areas involved in the conflict in multi-modal sensory systems by means of clinical or anatomical methods. Brandt et al. demonstrated that the posterior insula in human brain was homologous to PIVC in the monkey by evaluating vestibular functions in patients with vestibular cortex lesions [2]. In agreement with previous clinical studies, the cortical activations during caloric [3] and galvanic vestibular stimulation [4] had been studied by functional imaging technologies such as positron emission tomography (PET) and functional magnetic resonance imaging (fMRI). To overcome the temporal limitation of the two imaging modalities, some studies have investigated the vestibular information transmission in time domain. Monitoring the brain dynamics induced by motion-sickness because of its high temporal resolution and portability De Waele et al., for example, applied current pulse stimulation to patients' vestibular nerve to generate vestibular evoked potentials [5].

The EEG studies related to motion-sickness can be divided into two groups according to the types of stimuli: vestibular and visual. Vestibular stimuli were normally provided to the subjects with rotating chair [6-7], parallel swing [8], and cross-coupled angular stimulation [9] to induce motion-sickness. Theta power increases in the frontal and central areas were reported to be associated with motion-sickness induced by parallel swing [8] and rotating drum [6-7]. Chelen et al. [9] employed cross-coupled angular stimulation to induce motion-sickness symptoms and found increased delta- and theta-band power during sickness but no significant change in alpha power. Visually induced motion-sickness is also commonly studied in previous studies. Visually induced sickness can be provoked with an optokinetic drum rotating around the yaw axis. This situation can cause a compelling sense of self-motion (called vection). Vestibular cues indicate that the body is stationary, whereas visual cues report the body is moving. Hu et al. investigated MS triggered by the viewing of an optokinetic rotating drum and found a higher net percentage increase in EEG power in the 0.5-4 Hz band at electrode sites C3 and C4 than in the baseline spectra. [10]. This study employees ahe driving simulator comprised an actual automobile mounted on a Stewart motion platform with six degrees of freedom, providing both visual and vestibular stimulations to induce motion-sickness and accompanied EEG dynamics.

Our past studies [11-13] had investigated the EEG activities correlated with motion sickness in a virtual-reality based driving simulator. We found that the parietal and motor brain regions exhibited significant alpha power suppression in response to vestibular stimuli, while the occipital area exhibited motion sickness related power augmentation in mainly theta and delta bands; the occipital midline region exhibited a broad band power increase. Based on these results, we think that both visual and vestibular stimulations should be used to induce motion sickness in brain dynamic research. Hence, we attempt to implement an EEG-based evaluation system to estimate subject's motion sickness level (MSL) upon the major EEG power spectra from these motion sickness related brain area in this study. The evaluation system can be applied to early detect the subject's MSL and prevent the uncomfortable syndromes occurred in advance in our daily life.

2 Materials and Methods

2.1 Experimental Paradigm

Unlike the previous studies, we provided both visual and vestibular stimuli to participant through a compelling VR environment consisting of 360° projection of VR scene and a motion platform with six degree-of-freedom to induce motion-sickness. With such a setup, we expected to create motion-sickness in a manner that is close to that in daily life.. During the experiment, the subjects were asked to sit inside an actual vehicle mounted on a motion platform, with their hands holding a joystick to report their sickness level continuously. The VR scenes simulating driving in a tunnel were programmed to eliminate any possible visual distracter and shorten the depth of visual field such that motion-sickness could be easily induced. A three-section experimental protocol (shown in Fig. 1) was designed to induce motion-sickness.

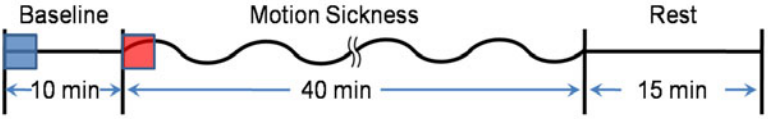

Fig. 1. Experimental design of motion-sickness experiments

First, the baseline section contained a 10-minute straight road to record the subjects' baseline state. Then, a 40-minute motion-sickness section, which consisted of a long winding road, was presented to the subjects to induce motion-sickness. Finally a 15-minute rest section with a straight-road condition was displayed for the subjects to recover from their sickness. The level of sickness was continuously reported by the subjects using a joystick with continuous scale on its side. The experimental setting successfully induced motion sickness to more than 80% of subjects in this study.

2.2 Subjects

Sixteen healthy, right-handed volunteers with no history of gastrointestinal, cardiovascular or vestibular disorders or of drug or alcohol abuse, taking no medication and with normal or corrected-to-normal vision participated in this experiment. EEG signals were recorded with 500 Hz sampling rate by 32-channel NuAmps (BioLink Ltd., Australia). Simultaneously, during EEG recording, the level of sickness was continuously reported by each subject using a joystick with a continuous scale ranging 0 – 5. The subjects were asked to raise/lower the scale to a higher/lower level if they felt more motion sick comparing to the last condition. This continuous sickness level was reported in real time without interrupting the experiment rather than the traditional motion-sickness questionnaire (MSQ).

2.3 EEG Data Acquisition and Signal Processing

EEG signals were recorded with 500 Hz sampling rate by 32-channel NuAmps (BioLink Ltd., Australia). Simultaneously during EEG recording, the level of sickness was continuously reported by each subject using a joystick with a continuous scale ranging 0 – 5. The subjects were asked to raise the scale to a higher level if they felt more sick comparing to the last condition. This continuous sickness level was reported in real time without interrupting the experiment rather than the traditional motion-sickness questionnaire (MSQ).

The acquired EEG signals were first inspected to remove bad EEG channels and then down-sampled to 250 Hz. A high-pass filter with cut-off frequency at 1 Hz and transition band width 0.2 Hz was used to remove baseline-drifting artifacts, and a low-pass filter with cut-off frequency at 60 Hz and transition band width 7 Hz was to remove muscular artifacts and line noise. After the preprocessing procedures, the clean EEG signals will feed into the proposed evaluation system for further analysis.

3 Proposed MS Level Estimation System

The proposed evaluation system to estimate subject's motion sickness level can be divided into five parts: independent component analysis (ICA), component clustering, time-frequency analysis, Feature Extraction by Principle Component Analysis (PCA), and Estimation part by applying linear regression, RBF Neural Network and Support Vector Regression with leave one out (LOO) cross validation. Figure 2 shows the system flowchart of the proposed motion sickness evaluation system.

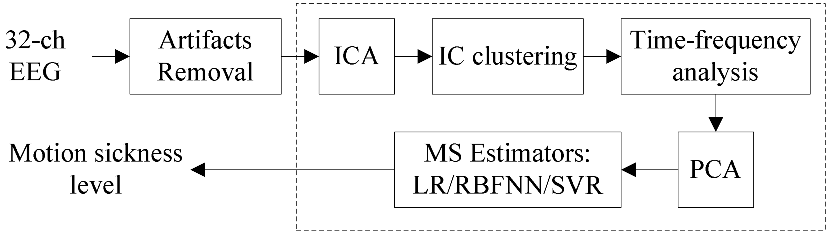

Fig. 2. System flowchart of the proposed motion sickness evaluation system

Independent Component Analysis (ICA) was applied to EEG recordings to remove various kinds of artifacts, including blink artifact and indoor power-line noise, and to extract features of human's cognition. Among components from all subjects, those with similar scalp topographies, dipole locations and power spectra were grouped using *k*-means clustering.

After doing ICA process, component clustering was analyzed using DIPFIT2 routines, a plug-in in EEGLAB, to find the 3D location of an equivalent dipole or dipoles based on a four-shell spherical head model. Among components from all subjects, those with similar scalp topographies, dipole locations and power spectra were clustered. Ten component clusters recruited more than 10 components from multiple subjects with similar topographic maps were regarded as robust component clusters. In component clustering results, we find that not all subjects have every motion sickness related components because the level of motion sickness induced by vestibular and visual stimuli to each subject had the significant individual difference. According to MSQ results and subject's self-response of motion sickness, we can confirm that each subject indeed felt sickness during the whole experiment session. Consequently, these extracted components are correlated with motion sickness. Then we can feed the ICA signals into the system and do time-frequency analysis.

Time-frequency analysis was used to investigate the dynamics of the ICA power spectra. In order to provide a temporal resolution of 30 seconds, the spectra of ICA activations were calculated using 7500-point non-overlapping window, and subdivided into several 125-point sub-windows with 25-point overlaps. Each 125-point sub-window was zero-padded to 512 points for using 512-point fast Fourier transform (FFT) with 1 Hz resolution in frequency. The linear power spectrum density (PSD) was then converted into a logarithmic scale (dB power).

The data set of each subject was combined with all the PSD of the subject's desired component. Since each subject provided 2 – 5 components for MS level estimation and each PSD was in 50 dimensions (from 1-50 Hz), the data set of each subject was between 100 – 250 dimensions.

PCA was then used to summarize the variances and extract first few principal components of the components' PSD's. In this study, the number of eigenvectors/components to retain was set to the number of first principal components that are necessary to explain 80% of the variances in the data. In addition, the EEG-based motion sickness evaluation system proposed in this study is including three different estimators: 1) Linear regression (LR), 2) Radial basis function neural network (RBFNN), and 3) Support vector regression (SVR). The MS level of the subject was estimated with leave-one-out cross-validation (LOOCV), where each observation was took as the validation data while the remaining as the training data.

4 Experimental Results and Discussion

In this study, we totally selected 16 subjects that were analyzed and applied to the modeling the estimation of our proposed MS level evaluation system. Figures 3 and 4 were shown the correlation coefficients (CC) results and root mean square errors (RMSE) in comparison with the actual MS level and the estimation performance of our proposed system. To summary the all estimation performance from 16 subjects, the average correlation coefficients were about 0.6467, 0.6738, and 0.7123 in corresponding to linear regression (LR), RBF neural networks (RBFNN), and support vector regression (SVR), respectively. As for the RMSE performance, the average estimation results were 0.2256, 0.2134, and 0.2199 in corresponding to LR, RBFNN, and SVR, respectively. According to the estimation results in Figure 3, we can see that the proposed MS level estimation system using SVR is better than using RBFNN or LR models. Subject 11's performance is an outlier subject because he/she reported not feel sickness during the experiment period according the self-reported MSQ.

We then select two subjects (S1 & S13) to show their comparison results between the actual MS level and estimation results from LR, RBFNN and SVR in Figure 5.

The black line shows the subject's actual (self-response) MS level and the black, blue and red dotted lines plot the estimation level from LR, RBFNN, and SVR evaluation systems, respectively. We can clearly see that the estimated performance followed the trend of the actual MS level, especially at the MS level increasing in the curving road.

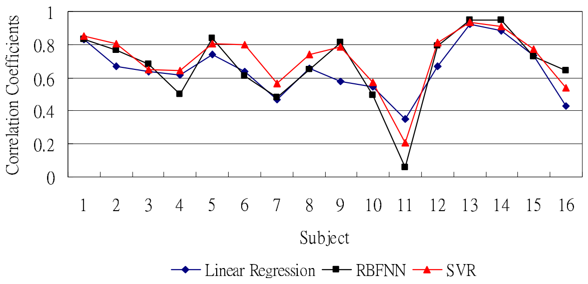

Fig. 3. Motion sickness estimation via using correlation coefficients results

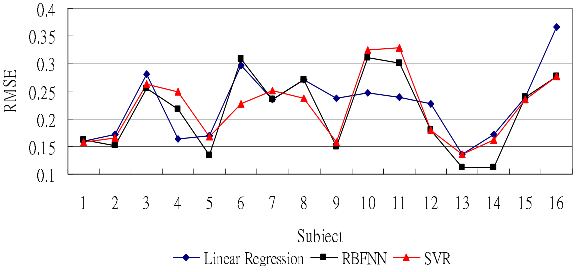

Fig. 4. Motion sickness estimation results via using correlation coefficients

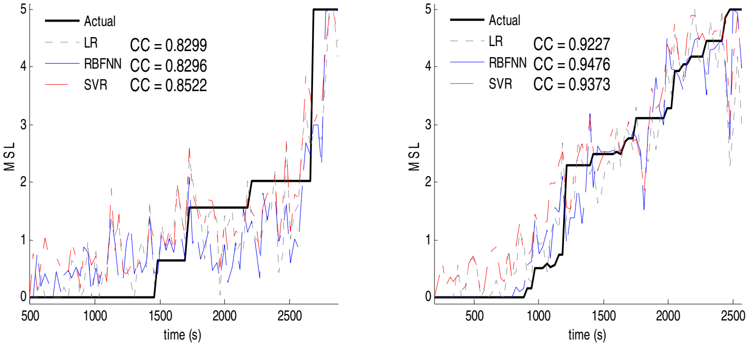

Fig. 5. Subjects 1's (left) and 13's (right) motion sickness estimation performance via using LR, RBFNN and SVR

Through the experimental results on the system performance under different conditions, we find that 9 subjects out of 15 subjects except subject 11 had the better CC estimation result via using SVR, and 6 subjects had better performance via using RBFNN. In conclusion, this study demonstrated that our proposed EEG-based evaluation system could successfully estimate the motion sickness level reported by individual subject, we suggest that SVR model can be utilized to estimate the motion sickness level in the operational environment. Since the potential of real-time application is emerging and desired, nevertheless, we need to consider more about the complexity, instantaneity, and robustness of the system. These results let us open an emerging sight on the potential of real-time application. Nevertheless, the complexity, instantaneity, and robustness of the system still have to be considered for the implementation.

Acknowledgment. This work was supported in part by the National Science Council, Taiwan, on Establishing "International Research-Intensive Centers of Excellence in Taiwan" (I-RiCE Project) under Contract NSC 99-2911-I-010-101, in part by the Aiming for the Top University Plan of National Chiao Tung University, the Ministry of Education, Taiwan, under Contract 99W906, and supported in part supported by the National Science Council, Taiwan, under Contracts NSC 99-3114-E-009-167 and NSC 99-2628-E-009-091. Doctors Li-Wei Ko and Chin-Teng Lin are sponsored in part by grants from the US Army Research Laboratory (W911NF-10-2-0022).

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