Study of Relationship between Electroencephalogram Dynamics and Motion Sickness of Drivers in a Virtual Reality Dynamic Driving Environment

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Abstract

The nausea-related Electroencephalogram (EEG) dynamics corresponding to motion sickness inclining tasks is studied in this thesis with the virtual-reality based dynamic driving environment. The VR-based dynamic driving environment provides the advantages of safety, low cost, and the realistic stimuli to the subjects. The Motion Sickness Questionnaire (MSQ) is designed and the physiological responses (including Electrocardiogram (EKG), Electrogastrography (EGG) and galvanic skin response) are recorded to assess the motion sickness. The EEG changes correlated to motion sickness will not only refer to the MSQ score, but the objective indices should also be involved for systematic evaluation. It was found from the result that the EGG signal is an efficient index, which is suitable for most of the subjects with excellent response time. The independent component analysis (ICA) combined with power spectral analysis is applied to investigate the EEG dynamics during the motion sickness. The experiment results demonstrated that the subjects have the power-suppressions in some specific frequency bands (10 Hz and/or 20 Hz) in the parietal lobe region. The nausea-related region and the nausea-influenced power spectrum suppression can be successfully obtained with our experimental results.

Chapter 1 Introduction

Several researches have been made on symptoms of motion sickness. A study of R. S. Kellog et al. (1980) described that the malaise of sickness may last more than one hour, and D. W. Gower et al. (1989) further proved that the duration of sickness can even last for one day. Many previous studies have indicated that the malaise of sickness can sometimes induce decline of thinking and response ability. The physiological signal analysis of the motion sickness research was first started in 1970s. Some signals, such as heart rate, body temperature were first used at the initial stage of the research; some researches were then focused on breathe, electrogastrography (EGG), galvanic skin response (GSR) signals (Graybiel, 1980; Stern, 1985; Cowings, 1990; Miller, 1993; Hirohisa, 1996). Some works in recent years were focused on the analysis of electroencephalogram (EEG) (Min, 2004).

However, the stimuli of the previous researches are not realistic to the subjects. The Stewart platform and the VR technology can provide a realistic environment in our application. And also, the symptoms of motion sickness are investigated with multi-stream physiological signals and the motion sickness questionnaire (MSQ). The assessment of both physiological responses and subjective evaluation guarantees the objectivity of motion sickness.

Chapter 2 Design of Experiments

The induce factors of motion sickness are going to be introduced in this chapter, by means of a simple introduction to the vestibular system in human barin and inner ear. The experimental setup and environment are also given in this chapter, including design of the experiment scheme, Stewart platform, VR technology and physiological signal collection

2.1 Introduction of Motion Sickness

Motion sickness begins when the brain receives visual and sensory clues that contradict each other. There are a number of symptoms that can occur due to motion sickness including eye strain, headache, pallor, sweating, dryness of mouth, fullness of stomach, disorientation, vertigo, ataxia, nausea and vomiting (Joseph, 2000). Some researches (Kolasinski, 1995; Magellan's Travel Advice) reveal that the individual difference between different subjects is large even in the same environment or stimuli condition.

2.2 Experimental protocol

For the reason of safety and reality, the virtual reality (VR) technology is used in our experiments to induce motion sickness. It takes the advantages of low cost, reality and time saving. The VR scene combined with the Stewart dynamic platform can provide the visual and kinesthetic stimuli to subjects. The subjects can interact directly with the environment and perceive more realistic driving conditions during the experiments.

A three-stage driving task is designed for this study. A ten minutes practice session was hold before each experiment which allowed the subjects to get used to the situation and the control methods. It consists of a 5-minute session of straight road driving at the beginning of the experiment, a 20-minute consecutive-curve road driving to induce motion sickness, and a 10-minute straight road for rest. The experimental scheme is shown in Fig. 2-1.

The first 5-min session of each experiment, was regarded as the baseline. It is assumed that the subjects will fall into motion sickness after the

20-min curve road driving session. The physiological signals collected during the "Motion-Sickness" session are then compared with those in the "Baseline" session. We assume that the differences of signals between the two sessions may be induced by motion sickness. The assumption is more impregnable if the differences of signals are vanished in the 10-min "Rest session".
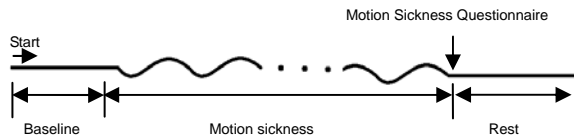

Fig. 2-1. The experimental scheme.

2.3 VR-based Dynamic Driving Environment

The developed VR dynamical simulation system mainly consists of three elements: (1) a six-degree-of-freedom motion platform, (2) a real car, and (3) an interactive VR scene. The subjects are asked to sit inside the car on the platform with their hands holding the steering wheel to control the car in the VR scene. Seven projectors are used in the experiment to construct a 360-degree 3D scene as shown in Fig. 2-2. The movements of the platform are according to the operation of the subject and the condition of the road surface.

Fig. 2-2. A 360-degree 3D VR dynamic driving environment.

A typical Stewart platform has a lower base platform and an upper payload platform connected by six extensible legs with ball joints at both ends. A Stewart platform is also called a six-degree-of-freedom motion platform, which means the payload platform of the system has 6-dimension of freedom. Excellent possibility of high-speed platform application can be provided because a singular solution of the inverse kinematics can be evaluated by simple formulae.

A real car is placed on the Stewart platform. Many high-sensitivity sensors and equipments are set up inside the car to accomplish the experiment. A video camera was placed beside the steering wheel to capture the movements and facial expression of subjects during the experiments. Two physiological signal amplifiers, NuAmps and GSR100C are also fixed on the car for the purpose of data acquisitions. An EEG electrode cap was mounted the on the subject's head to record the EEG signals. Four

Ag-AgCl electrodes were placed on the chest of subjects to record EKG and EGG signals respectively. The 32-channel EEG, 2-channel EKG and 2-channel EGG signals were collected and enhanced by NuAmps amplifier. The galvanic skin response (GSR) signal was collected at the back of the neck of the subject with two Ag-AgCl electrodes and the recordings were enhanced with the GSR amplifier, GSR100C.

For the development of the VR driving scene, the 3DS-max software is used to create the three-dimensional models and the WorldToolKit (WTK) library is used to program the VR scenes. The 3DS-man software is a popular graphic software to create a three-dimensional model. The WTK library is an advanced cross-platform development environment for high-performance, real-time and three-dimensional graphics applications.

The development flow of the VR sense is shown in Fig. 2-3. Firstly, the 3DS-max is used to build three-dimensional models accurately for a true system (such as the road) and to define the parameters of each model (such as the width of the road). Then, the C program including the WTK library is used and its library function is called up to move the three-dimensional models.
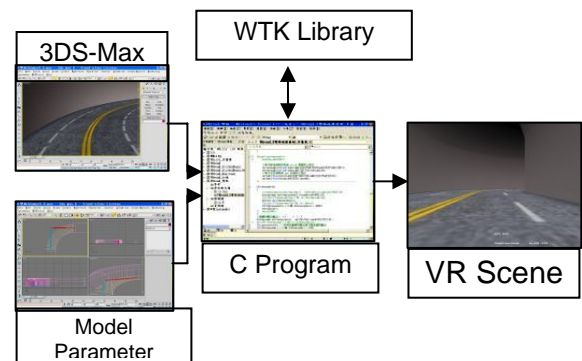

Fig. 2-3. Development flow of the VR scene.

2.4 Data Acquisition

Ten healthy volunteers (including five males and five females) with no history of gastrointestinal, cardiovascular, or vestibular disorders participated in the experiments of the motion sickness study. The ages of these subjects are from 18 to 26 years with a average of 22 years. They were requested not to smoke, drink caffeine, use drugs, or drink alcohol for a week prior to the main experiment to avoid influencing the central and autonomic nervous system.

An electrode cap is mounted on the subject's head for signal acquisitions on the scalp. The 10-20 International System of Electrode Placement standard to place the EEG electrodes proposed by Jasper in 1958 [1], was used in this study. An illustration of the 10-20 system is shown in Fig. 2-4.

The NuAmps, manufactured by NeuroScan Company, is a high-quality 40-channel digital EEG

amplifier that is capable of 22 bit sampling at 500 Hz, measuring signals from DC to 260Hz. The heart electrical activity and tomach electrical activity of subjects is simultaneous recorded with the EEG signal through the NuAmps amplifier with sampling rate 500 Hz. The GSR100C sensor and amplifier manufactured by BIOPAC Systems Instruments was used to detect galvanic skin response with sampling rate 30 Hz.
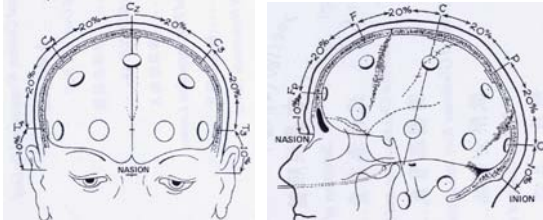

Fig. 2-4. The 10-20 international electrode placement system [1].

Chapter 3 Assessment of Motion Sickness Symptoms

The symptoms of motion sickness are investigated with the motion sickness questionnaire (MSQ) and multi-stream physiological signals in this chapter. The assessment of both subjective evaluation and physiological responses guarantees the objectivity of motion sickness.

3.1 Subjective Evaluation of Motion Sickness: Motion Sickness Questionnaire (MSQ) Design

The famous motion sickness questionnaire (MSQ) developed by Kennedy et al. [2] in 1993 is a commonly used MSQ in the related research field of study. We also designed a MSQ according to several references for subjective evaluation of motion sickness. Our MSQ composes of 10 items, and each of which has six score levels (0-'not at all', 5-'very much'). The total motion sickness score was the aggregate score of these 10 items. The full range of total motion sickness score was within 0-50 points.

Two subjects (subject 2 and 4) terminated the experiments because of the severe symptoms of motion sickness. Two subjects (subject 6 and 8) claimed they did not feel any symptom of motion sickness. The MSQ score served as a subjective method to appraise various states of motion sickness (high or low) in the experiments.

3.2 Physiological Responses induced by Motion Sickness

The EEG changes correlated to motion sickness will not only refer to the MSQ score, but the objective indices should also be involved for systematic evaluation. The physiological signals recorded for objective motion sickness assessment included EKG, EGG and GSR.

3.2.1 EKG changes during Motion Sickness

The EKG is simply a voltmeter that uses up to two electrode wires with gel patches placed on designated areas of the body. The EKG dominant frequency of a normal adult is around 1 to 1.6 Hz in a relax situation. However, we can expect that the EKG dominant frequency will increase in some special conditions, such as motion sickness. A typical spectral changes of EKG dominant frequency during our experiment are shown in Fig. 3-1.
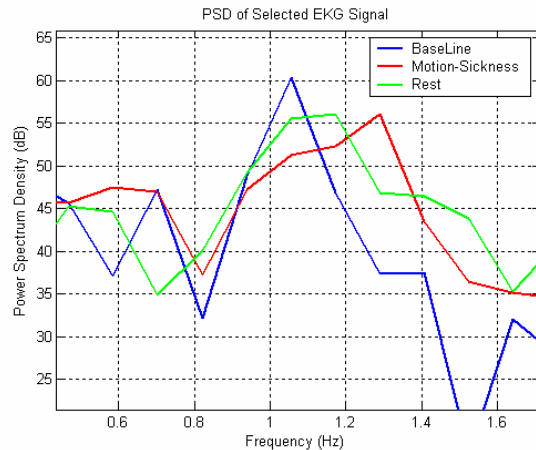

Fig. 3-1. A typical spectral changes of EKG dominant frequency during our experiment (subject 1).

The results indicate that the subject's heart rate may change when they are in motion sickness. The variations of the EKG dominant frequency of all subjects during the three sessions: "Baseline", "Motion-Sickness" and "Rest" in the experiments are summarized in Fig. 3-2.
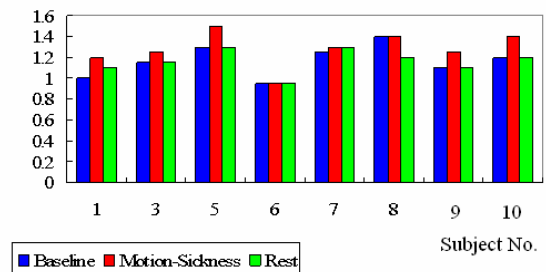

Fig.3-2.Variations of the EKG dominant frequency.

3.2.2 EGG Changes during Motion Sickness

The EGG-activity in a normal condition is 3 to 6 cpm of a healthy adult which means 0.05 Hz to 0.1 Hz. The increased activities of EGG will be induced by the symptoms of nausea or vomiting. The variations of the EGG dominant frequency for different subjects in the three sessions: "Baseline", "Motion-Sickness" and "Rest" are summarized in Fig. 3-3.

The EGG analysis results show distinguish able differences between the "Baseline" and "Motion-Sickness" sessions, which indicate the increase gastric activities. The increase of gastric activities is sometimes the direct reason of gastralgia, and highly related to the symptoms of motion

sickness. Some of these subjects could be proved that they could recover from the symptoms of motion sickness after the 10-min "Rest" session by the evidence that the EGG dominant frequency shifted back to the state as "Baseline" session.
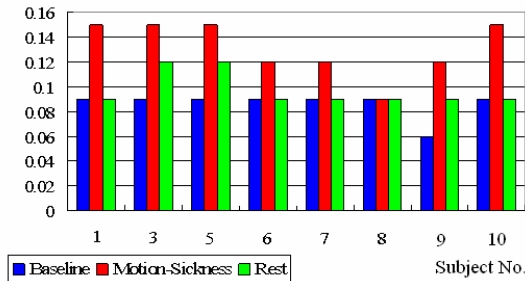

Fig. 3-3 Variations of the EGG dominant frequency.

3.2.3 GSR Changes during Motion Sickness

The GSR will increase when the subject is sweating. Sweating is one of the important symptoms of motion sickness, so one can expect some distinguish changes in the GSR signal. A typical changes of GSR during our experiments are given in Fig.3-4.
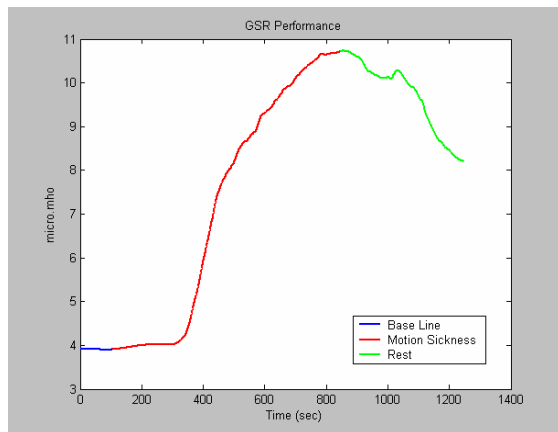

Fig. 3-4. The GSR of subject 7.

GSR changes can be regarded as a good index of motion sickness only for subject 7 and 10. The analysis of the GSR signals is that a moving average filter in time domain is used for analysis of motion sickness. So, it is an instantaneous physiological index for the real-time experimental monitoring.

3.3 Assessment of Motion Sickness Symptoms with Subjective Evaluation and Physiological Responses

The MSQ has served as a subjective index of motion sickness in many previous researches. However, it is an arbitrary assessment method which can be too subjective for scientific studies. Both subjective and objective evaluations are used in our study for the systematic motion sickness estimation. The MSQ scores of subject 3 and subject 9 are 28 and 34, respectively, which indicate severe sickness in the subjective assessment. By contrast, the MSQ score of

subject 6 and subject 8 are only 8 and 5, respectively. The MSQ score lower than 10 ponits in our experiment is considered as indistinct-sickness in the subjective assessment. For objective indices, EKG, EGG and GSR, if more than two of the three indices have significant changes, the subject is considered as a subject with motion sickness in the experiment.

The normalized scores of subjective and objective indices of different subjects are shown in Fig. 3-5. It shows strong evidence to the validity of the indices such that we can study the EEG changes related to motion sickness base on these results.
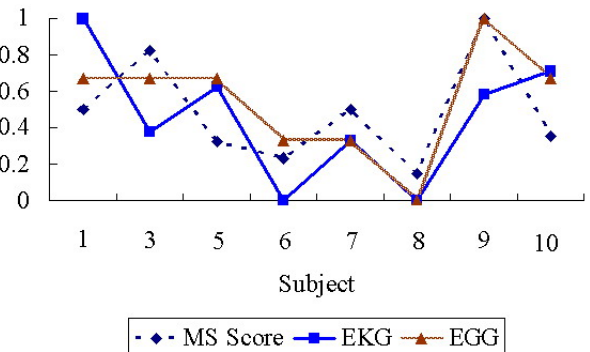

Fig. 3-7. The comparison results of both subjective evaluation and physiological responses.

Chapter 4 Analysis Results of EEG Response during Motion Sickness

The EEG data analysis is based on the cross-demonstrations of subjective evaluation and physiological responses to ensure the objectivity of sickness assessment.

4.1 EEG Signal Analysis Procedure

Flowchart of the EEG signal processing procedure is show in Fig. 4-1. The 32-ch EEG data was collected through an electrode cap and amplified by the NuAmps. The sampling rate of the EEG data is 500Hz. It consists of artifacts removal, independent component analysis, useless component rejection, spectral analysis, nausea-related components selection and dynamic spectral analysis.
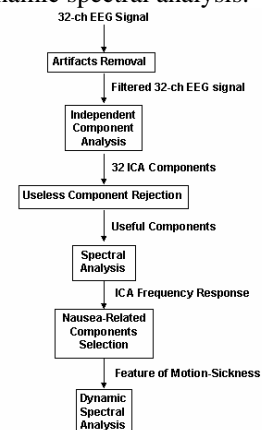

Fig. 4-1. Flowchart of the EEG signal analysis procedure.

4.2 Relationship between the Power Spectrum of ICA components and Motion Sickness

Figure 4-2 shows the EEG Power Spectrum Density (PSD) analysis result of subject 10. The blue, red, and green line in Fig. 4-2 represents the power spectrums in the "Baseline", "Motion-Sickness", and "Rest" sessions, respectively. According to Fig. 4-5, distinguish able changes magnitude at 12Hz can be obseved in the central parietal lobe area. The suppression of ICA power at 12 Hz during the "Motion-Sickness" session can be a good demonstration for the nausea-related feature of EEG signals. Power spectrum of ICA components of subjects 3 and 7 also give the same phenomenon.
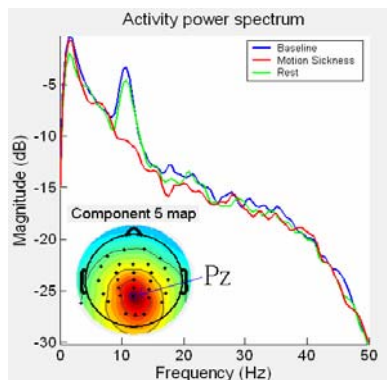

Fig. 4-2. Spectral analysis results of subject 10.

The spectral analysis result of subject 5 shown in Fig. 4-3. It is different from the result of subject 10. The nausea-related regions of subject 5 are in the right parietal and left parietal lobe. The magnitude of power spectrum at near 13 Hz was suppressed from "Baseline" session to "Motion-Sickness" session. The 13 Hz peak raise again after a 10-mim rest. Power spectrum of ICA components of subjects 7, 9 and 10 also showed the same phenomenon.
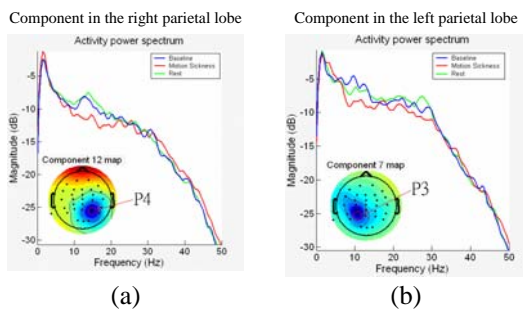

Fig. 4-3. Spectral analysis results of subject 5

According to our experimental results, power suppression in some specific frequency bands of ICA components are proved to be a common phenomenon when most of subjects in nausea and the suppressions will release when the subjects recovered from nausea after rest. In addition, EEG sources related to motion sickness are located at the central parietal lobe, right parietal lobe and left parietal lobe.

4.3 Spectral Dynamic Changes of ICA Components

According to the results discussed in subsection 4.2, the ICA power spectrum suppressed at some specific frequency band when the subject feels nausea. The dynamic changes of the ICA spectrum along the time course is discussed in this subsection. The relationship between the spectral ICA components and the transition of the road-type (straight / curve) will also be investigated. The continuous changes of ICA component spectrum at 23 Hz in the region of the left central parietal lobe of subject 10 is shown in Fig.4-4. The blue, red, and green line in Fig. 4-4 represents the power spectrums in the "Baseline", "Motion-Sickness", and "Rest" sessions, respectively. The x-axis here represents the time steps, and the y-axis is the magnitude of ICA spectrum in dB. A significant drop of spectral magnitude of 23 Hz can be found at the transition point between the "Baseline" session and the "Motion-Sickness" session. The spectral magnitude rises again after the subject drived in the "Rest" session.
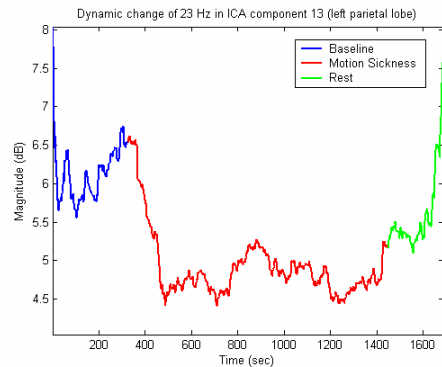

Fig. 4-4. Subject 10's spectral dynamic variations of ICA component 13 (left parietal lobe) at 23 Hz.

The experimental results shown in this subsection demonstrates that the correlation between the feeling of motion sickness and the spectral suppression of ICA components is high. In addition, the EEG signal variations induced by motion sickness can be monitored by using analyzing the spectral dynamic changes of ICA components change immediately with the variations of road-typ.
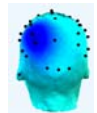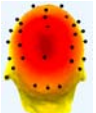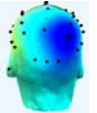
Chapter 5 Discussions

Some specific phenomena of motion sickness in the physiological signals are discovered in chapter 3 and 4. We are going to further emphasize the discussion of cross-subject specific phenomena in this chapter.

5.1 Motion Sickness Influence Region on Human Cortex

The influence regions of motion sickness on human cortex are discussed in this section. Three different phenomena are found in this study including the 20Hz suppression in left and right parietal region, the 10 Hz suppression in left and right parietal region

and of 10/20 Hz power suppression in the central parietal region. Table 5-1 is a comparison of the nausea-related regions in different subjects. All the subjects have the power-suppressions near 10 Hz or 20 Hz in the parietal lobe. In general, the parietal lobe plays important roles in integrating sensory information from various senses and in the manipulation of objects. This area of the cortex is responsible for somatosensation. This cortical region receives inputs from the somatosensory relays of the thalamus.

Table 5-1: Comparison of nausea-related regions

Component Region / Subject	Left Parietal Lobe	Central Parietal Lobe	Right Parietal Lobe
Subject 1	10 ~ 20 Hz		17 ~ 20 Hz
Subject 3		10 ~ 13 Hz 18 ~ 21 Hz	
Subject 5	8 ~ 18 Hz		10 ~ 22 Hz
Subject 7	8 ~ 13 Hz	10 ~ 13 Hz 18 ~ 19 Hz	
Subject 9	8 ~ 16 Hz		
Subject 10	10 ~ 12 Hz 22 ~ 24 Hz	10 ~ 15 Hz 18 ~ 20 Hz	10 ~ 15 Hz

5.2 Power Spectrum Suppression Induced by Motion Sickness

The frequency band of power-suppression differs from subjects, but inside the range between 8 and 22 Hz. The range of the power-suppression frequency band is sometimes wide for subject 1 and 5, which is about 10 to 20 Hz. And the range for subject 3, 7, and 10 may be narrow with the range about 18 to 19 Hz and 10 to 13 Hz in the central parietal lobe. All the subjects have the power-suppressions in the range from 10 to 13 Hz and more than 80 % of the subjects have the power-suppressions in the range from 18 to 19 Hz.

5.3 Reliability of Different Physiological Responses

The influence factors to the EKG signal is varied. And also, the variation rates of EKG are not as significant as GSR or EGG. It was found from the result that the EGG signal is the most efficient physiological signal, which is suitable for most of subjects and provides excellent response time. Although the GSR signal is useless for most of subjects, but it is a good physiological index for the subjects who feel sweating during motion sickness with significant changes and fast response time.

Chapter 6 Conclusions and Future Work

The nausea-related EEG dynamics corresponding to motion sickness inclining tasks is studied in this thesis with the virtual-reality based dynamic driving environment. The VR-based dynamic driving environment provides the advantages of safety, low cost, and the realistic stimuli to the subjects. The MSQ is designed and the physiological responses (including EKG, EGG and galvanic skin response) are recorded to assess the motion sickness. The EEG data analysis is based on the cross-demonstrations of subjective evaluation and physiological responses to ensure the objectivity of sickness assessment. In other words, the EEG changes correlated to motion sickness will not only refer to the MSQ score, but the objective indices should also be involved for systematic evaluation. It was found from the result that the EGG signal is an efficient index, which is suitable for most of the subjects with excellent response time.

Using ICA and PSD analysis technology, the power suppression in some specific frequency bands (such as 10 Hz or 20 Hz) of ICA components are proved to be a common phenomenon when most of subjects during motion sickness and the suppressions will release when the subjects recovered from motion sickness after rest. All of subjects indicate that the influence regions of motion sickness on human cortex are in the parietal lobe area. The phenomenon is obviously, and is considered as an important discovery in our study.

The future directions of this study are: (1) assessment of nausea degree, (2) a motion sickness estimator can be developed based on the findings in this thesis, and (3) the comparison study between the drivers and the passengers.

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