Analysis of Motion Sickness Associated Brain Activity Using fNIRS: A Driving Simulator Study

CHENYANG ZHANG¹,², SHUGUANG LI³,⁴, YAOHUA LI³, SHENGBO EBEN LI⁴, (Senior Member, IEEE), AND BINGBING NIE⁴, (Member, IEEE)

¹School of Automation Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China
²School of Mechanical Engineering, Sichuan University, Chengdu 610065, China
³Chengdu First People’s Hospital, Chengdu 610000, China
⁴State Key Laboratory of Automotive Safety and Energy, Tsinghua University, Beijing 100084, China

Corresponding author: Shuguang Li (lisg@uestc.edu.cn)

This work was supported in part by the Open Fund of the State Key Laboratory of Automotive Safety and Energy under Project KF1802, in part by the Sichuan Science and Technology Program under Grant 2019YG0412, in part by the School of Mechanical Engineering, Sichuan University, and in part by the NIRx Medical Technology Company.

ABSTRACT Motion sickness is a common disease encountered in traditional vehicles as well as autonomous vehicles, which will negatively affect user acceptance. To make clear the pathogenesis of motion sickness, this study focused on drivers’ brain activity changes before and after motion sickness happens. Based on the six-degree-of-freedom driving simulator and noninvasive functional near-infrared spectroscopy (fNIRS), a database containing driving operation data synchronized with drivers’ brain activity record from 52 participants was collected under straight and curved driving conditions. The correlation analysis between motion sickness and changes of cerebral oxyhemoglobin concentration in the cerebral cortex was carried out based on this database. Results suggest that brain activity associated with motion sickness may differ under different driving conditions. However, the emergence of motion sickness responses is related to the occipital lobe under both driving conditions. Experimental results corroborate with several theoretical hypothesis about motion sickness in neuroscience. Consequently, this study proposes a new approach to research the mechanism of the correlation between motion sickness and cerebral cortex activity, which will contribute to developing the driving assistance system for preventing or alleviating motion sickness in autonomous vehicles.

INDEX TERMS Noninvasive functional near-infrared spectroscopy (fNIRS), motion sickness, driving simulator, brain activity.

I. INTRODUCTION

Autonomous vehicles are expected to replace conventional vehicles in the coming decades by providing various potential benefits [1], [2]. However, autonomous vehicles enable drivers to focus on tasks other than vehicle navigation and increase the possibility of motion sickness [3]. Sivak and Schoettle’s study found that 6% to 12% of American adults suffered from moderate or severe motion sickness in autonomous vehicles based on the assumption that the cabin of self-driving vehicles would be similar to that of conventional vehicles, possibly resulting from some activities that have negative effects on motion sickness in autonomous vehicles (texting, reading and so on) [4]. Motion sickness may impact the comfort of driving, and it can negatively affect user acceptance and, in turn, limit the potential socioeconomic benefits that this emerging technology may provide. Therefore, it has been argued comprehensively that the critical challenge to the acceptance of autonomous vehicle’s will be motion sickness [5]. Studies on the pathogenesis of motion sickness by physiological signals will find out main factors that lead to motion sickness, contributing that the autonomous driving vehicle can be improved to minimize the effect of these factors on people.

Motion sickness is a syndrome characterized by dizziness, upper abdominal discomfort, nausea, vomiting, cold sweating and other nervous reactions caused by exposing the body to inappropriate stimulation from the movement environment [6]. Based on different movement environments, motion sickness is divided into car sickness, air sickness, sea sickness, space motion sickness and simulator motion sickness. In daily life, motion sickness may adversely affect people’s
physical state or even survival. Smyth et al. proposed that motion sickness has a significant impact on body and cognitive performance [7]. For some people, motion sickness reduces the amplitude of the normal gastric rhythm and increases its frequency [8]. In the case of floating on the sea and needing rescue, motion sickness may reduce the will to survive and increase the risk of hypothermia [9].

In exploring the pathogenesis of motion sickness over many years, research has found that abnormal motor stimulation produces sensory conflict in the central nervous system, resulting in motion sickness [10]. At present, theories about the pathogenesis of motion sickness can be divided into several categories [11]: sensory conflict theory, neurotransmitter theory, vestibular organ hypersensitivity theory, hemodynamic change theory, otolith weightlessness theory, genetic inheritance theory, neural mismatch theory and other theories.

Based on the above-identified theories, since the 1970s, people began to study motion sickness by analyzing physiological signals, such as heart rate data, electromyogram (EMG) signals and galvanic skin response (GSR) signals. Cowings et al. induced the symptoms of motion sickness with rotating-chair tests and studied self-regulation of the autonomic nervous system by measuring heart rate, finger pulse volume, and skin conductance [12]. Miller et al. studied simulator motion sickness using a rotorcraft simulator [13], and the data suggested that heart period, tachygastria and skin conductance level were more sensitive to simulator sickness than vagal tone and normal myoelectrical gastric activity. Hirohisa et al. performed an experiment on a boat in Tokyo Bay to study HRV and EGG in severe or mild motion sickness [14], and the results showed that the 0.05 Hz rhythm of the EGG was slightly enhanced during mild motion sickness, whereas HRV spectra showed no significant difference.

With the development of technologies that aid in the visualization of brain function, some researchers have focused on the analysis of physiological signals from the brain related to motion sickness for the past few years. Min et al. projected a virtual reality scene on a liquid crystal display monitor to induce motion sickness, and analyzed subjective evaluation and EEG signals to evaluate motion sickness [15]. Li et al. measured the changes in the EEG to study how EEG dynamics related to motion sickness in the virtual-reality-based dynamic driving environment [16]. EGG is a relatively traditional measurement method, and it has high temporal resolution, which is proved by Lin et al. [17]; however, due to its vulnerability to environmental electromagnetic fields, the accuracy of EEG for locating the positions of brain functional areas is not high, which is supported by Zhu [18].

To study the relationship between brain functional areas and driving behaviors, some researchers have investigated fMRI, which has higher accuracy. Toschi et al. used fMRI to find that vection-induced nausea increases connectivity between nausea-processing regions and those activated by the nauseogenic stimulus [19]. Nevertheless, the experimental environment of using fMRI is harsh. Participants are required to lie in a recumbent position, which lowers motion sensitivity and worsens time resolution. Therefore, this study uses fNIRS to collect physiological signals of the brain to satisfy both high accuracy and better spatial mobility.

Compared with EEG and fMRI, fNIRS has unique characteristics. Zhu et al. found that fNIRS had high spatial resolution after analyzing the braking intention of drivers based on fNIRS in driving simulation experiments [20]. Because the main purpose of this paper is to explore brain regions related to motion sickness, we believe that the spatial resolution may be more important than the temporal resolution in this paper. In addition to high spatial resolution, fNIRS has more flexible operating conditions, so drivers can be in a normal driving attitude to complete the experiment. Leff et al. systematically reviewed studies about brain activity in driving tasks based on fNIRS and showed that fNIRS is beneficial in exploring the internal mechanisms of skill learning, motion controlling and neurological diseases [21]. To date, few studies have examined the relationship between changes of blood oxygen concentration in cerebral cortex and motion sickness. Consequently, this study used fNIRS for measurement and analyzed the change of oxyhemoglobin concentration ($\Delta COE$) in drivers with motion sickness.

Chen et al. certified that the driving simulator could be used to study driving safety [22]. Oka et al. invited 15 healthy participants to take an experiment using a driving simulator and fNIRS for studying differences in brain activity of drivers [23], and they found that there were differences in brain response between left and right curve driving. Based on these, we utilized the six-degree-of-freedom driving simulator platform to research the pathogenesis of motion sickness, which included the simulator sickness, designed a simulated road consisting of straight and curved segments, and invited 52 volunteers with qualified Chinese driving licenses to participate. Over the course of the experiment, the driving simulator recorded driving data, while fNIRS recorded data from the cerebral cortex. After the experiment, the relationship between the driver’s motion sickness state and brain activity under different driving conditions was obtained by analyzing the data from straight and curved driving extracted from the experimental data. Combined with knowledge of neuroscience, this study used oxygen concentration changes in the cerebral cortex to analyze the brain activity when the driver was in a state of motion sickness, thereby further exploring the pathogenesis of motion sickness and providing physiological reference values for its prevention.

II. EXPERIMENTAL METHODS

This study recruited 52 healthy volunteers, 10 women and 42 men aged from 19 to 38 who have the legitimate motor vehicle driving license of the People’s Republic of China without knowing propensity for motion sickness, to participate in the experiment using a driving simulator (DS) and an fNIRS device. All of them were recruited from the Sichuan University. Before the experiment, all participants signed the Informed consent, and all experimental protocols were
carried out in accordance with the relevant guidelines and regulations. At the beginning of the experiment, participants were required to close their eyes and rest on the driving simulator for approximately two minutes. After the ΔCOE became stable, participants began to operate the driving simulator. During the entire experiment, participants were required to remain quiet, sit in the seat, look straight ahead with eyes horizontal, and forbid them from operating other than driving. Besides, the driving speed of each participant was controlled to about 50 km/h and could not exceed 70 km/h. The driving simulator recorded driving-related data, such as speed, the pressure of the brake pedal and the accelerator pedal, the rotation angle of the front wheel and the steering wheel, and the fNIRS recorded data from the cortical activity of the participant’s brain. If the participant was unable to continue driving due to dizziness, chest tightness, nausea or other symptoms during the experiment, the experiment would be immediately stopped. If the participant was in good physical condition, the experiment would proceed normally until symptoms of motion sickness made it impossible to continue driving or the driving task was over. We used the motion sickness questionnaire (MSQ) to investigate the symptoms of motion sickness on each participant. The diagram of experimental data sampling is shown in Fig.1.

A. DRIVING SIMULATOR
The six-degree-of-freedom driving simulator platform used in the experiment is shown in Fig.2, it is composed of vehicle motion sensation simulation, visual environment simulation, audio environment simulation, driving sensation simulation and a central control platform for coordinated control of each subsystem. The driving simulator has the ability to simulate the closed-loop response of the human-vehicle-road-environment system in real time and reproduces various typical road conditions. In addition, the driving simulator can provide six-degree-of-freedom dynamic feedback for drivers in the process of driving, which makes driving in the simulator similar to real driving.

B. fNIRS
This study used the functional near-infrared spectroscopy imaging instrument (fNIRS) produced by the NIRx Medical Technologies LLC, and the model of it was the NIRScout. Near-infrared light can penetrate tissue at a certain depth with the range of 700-900 nm, and the wavelengths emitted by the emission point of the light source are 760 nm and 850 nm respectively. The absorption coefficients to light of oxyhemoglobin (HbO) and deoxyhemoglobin (Hb) are different; therefore, fNIRS can record changes in the saturation of oxygen concentration in the human brain. The fNIRS used in this experiment is shown in Fig.3, with a sampling frequency of 7.8 Hz, which transmits light source signal by timesharing, so that the light detector point can only receive the signal from one light source transmitting point at a certain time, thus ensuring that the signal of one channel does not receive the interference of other channels.
C. EXPERIMENTAL ROAD

The experimental road is a regular hexagonal circular road (as shown in Fig.5), which contains two kinds of sections: straight and curved. The length of each straight section is 1000 meters, and the length of the central line of each curved section is approximately 890 meters. Each circular road includes six straight sections and six curved sections. In the experiment, every driver was required to drive clock-wise around the circular road following the lane line for up to two laps. To better distinguish the straight driving condition from the curved driving condition, a green pile landmark was located at the boundary between the straight section and the curved section. When the driver passed the green pile landmark, the driving simulator automatically recorded the position. At the same time, the driver was requested to immediately press the “F3” key on the keyboard of the computer for marking the data collected by the fNIRS.

D. MOTION SICKNESS QUESTIONNAIRE

The motion sickness questionnaire (MSQ) score served as a subjective method to appraise various states of motion sickness (high or low) in the experiments. The famous MSQ developed by Kennedy et al. [25] in 1993 is a commonly used MSQ in the related research field of study. According to several references for subjective evaluation of motion sickness, we also designed a MSQ, which is shown in Fig.6. Our MSQ composes of 10 items, and each of which has two score levels (0-'No', 1-'Yes'). The total motion sickness score was the aggregate score of these 10 items. The full range of total motion sickness score was within 0-10 points. The higher scores, the more serious symptom of motion sickness. In the experiment, we investigated symptoms of motion sickness twice for participants by reading the contents of MSQ and making participants answer orally. The first investigation is at the end of the first lap, and the second one is at the end of the whole task (it may be at the end of the second lap or before that).

III. DATA ANALYSIS

Previous studies have indicated that cerebral oxygen exchange ($\Delta COE$) is an effective regional index of brain activity [26]–[28]. We assessed the brain activity of the driver in the state of motion sickness by the $\Delta COE$ calculated by using Eq.1. Besides, $\Delta OxyHb$ means changes in the saturation of oxyhemoglobin, and $\Delta DeoxyHb$ means changes in the saturation of deoxyhemoglobin.

$$\Delta COE = \frac{\Delta DeoxyHb - \Delta OxyHb}{\sqrt{2}}$$

The $\Delta COE$ value indicates brain activity. A positive $\Delta COE$ (starting from $\Delta COE = 0$) means that the capillaries undergo deoxygenation due to the oxygen consumption of nerve cells, which indicates hypoxia of blood vessels; A negative $\Delta COE$ means that oxygen-containing red blood cells are provided in arteries, indicating a high level of oxygenation in blood vessels. Studies have shown that the main reason for the fluctuation of visual signals is a 0.1 Hz oscillation caused by regional cerebral blood flow [29]. Because of this, we subjected the original $\Delta OxyHb$ and $\Delta DeoxyHb$ data to a 0.1 Hz low-pass filter to remove high-frequency components. To further study the relationship between driver motion sickness state and brain activity under different driving conditions, the fNIRS data of each participant was divided into two groups, a straight driving condition group and a curved driving condition group, by setting landmarks at...
the boundary between straight sections and curved sections. In each group, we chose the ΔCOE data of the first and the last section for comparing the data before the onset of motion sickness with the data after the onset of motion sickness. Specifically, we analyzed the ΔCOE data of the first straight section and the last straight section to study the differences of the 41 channels related to brain activity under the straight driving condition. Meanwhile, we analyzed the ΔCOE data of the first curved section and the last curved section to study the differences of the 41 channels related to brain activity under the curved driving condition. The flow chart of data processing is shown in Fig.7.

Figure 7. The flow chart of data processing.

We calculated the average values of the ΔCOE data under the first straight section, the first curved section, the last straight section and the last curved section for each participant to improve precision. Then, we obtained four matrices: \( Z_f \) (the first straight section), \( W_f \) (the first curved section), \( Z_a \) (the last straight section) and \( W_a \) (the last curved section). The rows of the matrix represent the number of participants, and the columns of the matrix represent the 41 fNIRS channels.

Based on these four matrices, we can analyze the significant differences between the samples before and after the onset of motion sickness. Within the existing research, the \( t \) test and Mann-Whitney U test are two common methods for high accuracy difference analysis. After using a \( t \) test, Li et al. found that the power of the \( \theta \) band in the prefrontal cortex increased more dramatically than that in the central lobe and parietal lobe with an increase in memory load [30], and Naqvi et al. utilized a \( t \) test to analyze the time-frequency dynamics of motion sickness [31]. In long-term EEG research, Freire et al. used the Mann-Whitney U test to explore EEG signals associated with epilepsy syndrome [32]. Hence, it can be seen that the results obtained by these two methods are reliable. According to the requirements of the central limit theorem, if the sample size is not large enough for analysis by using the two-sample \( t \) test, it is necessary to ensure that the single sample data obeys normal distribution. For those single sample data that do not obey normal distribution, the Mann-Whitney U test can be used for analysis. Therefore, to determine whether the single sample data of each fNIRS channel under straight or curved driving conditions obeyed a normal distribution, this study selected the Jarque-Bera test to analyze the first section and the last section under the same driving conditions and chose \( \alpha \) as 0.05 to improve accuracy. In statistics, the Jarque-Bera test is a goodness-of-fit test of whether sample data have skewness and kurtosis matching a normal distribution [33]. The test statistic \( JB \) is defined by using Eq.2.

\[
JB = \frac{n - k + 1}{6} \left[ S^2 + \frac{1}{4} (C - 3)^2 \right]
\]

In the Jarque-Bera test, if the \( H \) value of a single sample is equal to 0, the single sample data obeys a normal distribution, whereas if the \( H \) value of a single sample equals 1, the single sample data does not obey a normal distribution. After the Jarque-Bera test, samples of the 41 channels were divided into two categories: samples that obeyed a normal distribution and samples that did not. Under the same driving condition, for the same channel, if samples of both the first section and the last section obeyed normal distributions, we used the \( t \) test (\( \alpha = 0.01 \) and 0.05) to analyze the difference of related channels, whereas we used the Mann-Whitney U test (\( \alpha = 0.01 \) and 0.05) to analyze the difference of the remaining channels. The function of the \( t \) test is to deduce the probability of the difference and test whether the difference between two averages is significant. It is mainly used for normal distributions with small sample sizes and unknown population standard deviation (\( \sigma \)) [34]. Furthermore, the \( t \) test can be divided into one-sample and two-sample \( t \) tests, which can be further divided into unpaired and paired two-sample \( t \) test, while each fNIRS channel is independent. Thus, this paper selected the unpaired two-sample \( t \) test, and its statistic is calculated by using Eq.3.

\[
t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\frac{(n_1-1)s_1^2 + (n_2-1)s_2^2}{n_1+n_2-2} \left(\frac{1}{n_1} + \frac{1}{n_2}\right)}}
\]

The Mann-Whitney U test assumes that two samples come from two populations, which are identical except for the population mean, and its purpose is to test whether there is a significant difference between the mean values of these two populations [35]. The statistic is calculated by using Eq.4 and Eq.5.

\[
U_1 = R_1 - \frac{n_1(n_1 + 1)}{2}
\]

\[
U_2 = R_2 - \frac{n_2(n_2 + 1)}{2}
\]

In particular, \( n_1 \) is the sample size for sample 1, \( n_2 \) is the sample size for sample 2, \( R_1 \) is the sum of the ranks in sample 1 and \( R_2 \) is the sum of the ranks in sample 2. The sum
of $U_1$ and $U_2$ is calculated by using Eq.6 and Eq.7.

$$U_1 + U_2 = R_1 - \frac{n_1(n_1 + 1)}{2} + R_2 - \frac{n_2(n_2 + 1)}{2}$$  \tag{6}

$$U_1 + U_2 = n_1n_2$$  \tag{7}

After the difference analysis of each channel, channels with differences were extracted. To characterize the degree of difference, this paper used Euclidean distance and cosine similarity to quantify the differences of each channel that had the difference. When $\alpha$ equals 0.01, the $p$ value of the channel with difference is less than 0.01, which also meets the requirement of the difference analysis when $\alpha$ equals 0.05, so quantitative objects of this study are channels with difference when $\alpha$ equals 0.01. Euclidean distance is a common definition of distance, which refers to the real distance between two points in n-dimensional space or the natural vector length (namely, the distance from the point to the origin) [36]. Specifically, the Euclidean distance in n-dimensional space is calculated by using Eq.8.

$$d(x, y) := \sqrt{(x_1 - y_1)^2 + \cdots + (x_n - y_n)^2}$$  \tag{8}

Cosine similarity is used to evaluate the similarity of two vectors by calculating the cosine of the angle between them [37]. It is usually used in positive space, resulting in a value between 0 and 1. It is independent of the length of the vector and only related to the direction of the vector; hence, cosine similarity is calculated by using Eq.9.

$$\text{similarity} = \cos \theta = \frac{A \cdot B}{||A|| \cdot ||B||} = \frac{\sum_{i=1}^{n} A_i B_i}{\sqrt{\sum_{i=1}^{n} A_i^2 \cdot \sum_{i=1}^{n} B_i^2}}$$  \tag{9}

IV. RESULT

Participants exhibited a driving time of 17 ± 7 mins in completing the designated two-lap driving task using the driving simulator. The results of driving time of participants are shown in Table 1.

**TABLE 1. Results of driving time of participants.**

| Driving Time | The number of participants |
|--------------|--------------------------|
| > 17 mins    | 38                       |
| ≤ 17 mins    | 14                       |

Among the 52 participants, everyone has completed the first lap driving, but not everyone has completed the second lap driving. The symptoms of motion sickness on the participants at the first MSQ investigation were light, which may be not enough for participants to judge whether they should give up driving, so we focused the results of the last MSQ investigation. We have summarized the results of the last MSQ investigation, shown in the Table 2.

**TABLE 2. Results of the last MSQ investigation.**

| MSQ Score | The number of participants |
|-----------|---------------------------|
| 0         | 5                         |
| 1~5       | 0                         |
| 6~10      | 47                        |

According to the results of the last MSQ investigation, five participants claimed they did not feel any symptoms of motion sickness after completing the two-lap driving task, while the remaining participants terminated the experiments because of the severe symptoms of motion sickness and were unable to complete the whole driving task. Therefore, this study selected data from those 47 participants with symptoms of motion sickness.

To explore whether there are differences in the brain regions related to motion sickness under two different driving conditions, we divided the results into two parts.

A. STRAIGHT DRIVING CONDITION

In the straight driving condition group, we determined whether the sample of each channel obeyed normal distributions in the first and the last straight sections by analyzing the matrix $Z_f$ and $Z_l$ using the Jarque-Bera test. According to the results, when the samples obtained from the first and last straight sections of a certain channel obey the normal distribution, we select the $t$ test ($\alpha = 0.01$ and $\alpha = 0.05$) to analyze samples of that channel. Otherwise, we use the Mann-Whitney U test ($\alpha = 0.01$ and $\alpha = 0.05$) on the samples. The results of difference analysis in the straight driving condition are shown in Table 3.

**TABLE 3. Results of the difference analysis under the straight driving condition.**

| Channel | p value | Channel | p value | Channel | p value |
|---------|---------|---------|---------|---------|---------|
| 1       | 0.031*  | 15      | 0.286   | 29      | 0.982   |
| 2       | 0.187   | 16      | 0.487   | 30      | 0.300   |
| 3       | 0.314   | 17      | 0.517   | 31      | 0.432   |
| 4       | 0.356   | 18      | 0.127   | 32      | 0.739   |
| 5       | 0.257   | 19      | 0.410   | 33      | 0.445   |
| 6       | 0.982   | 20      | 0.482   | 34      | 0.506   |
| 7       | 0.525   | 21      | 0.042*  | 35      | 0.322   |
| 8       | 0.116   | 22      | 0.068   | 36      | 0.501   |
| 9       | 0.024*  | 23      | 0.602   | 37      | 0.001** |
| 10      | 0.286   | 24      | 0.491   | 38      | 0.009** |
| 11      | 0.535   | 25      | 0.290   | 39      | 0.002** |
| 12      | 0.008** | 26      | 0.364   | 40      | 0.124   |
| 13      | 0.005** | 27      | 0.910   | 41      | 0.065   |
| 14      | 0.002** | 28      | 0.482   |         |         |

* corresponds to value below 0.05.
* corresponds to value below 0.01.

The results above showed that the cortex of the left hemisphere was more active in the process of motion sickness under the straight driving condition, which were consistent with the findings of Caplan et al. [38].
To show the degree of difference, the quantitative results of the difference under the straight driving condition are shown in Fig. 8. Overall, the degrees of difference of channels 37, 38 and 39 are greater than those of channels 12, 13 and 14. In the quantitative results of the Euclidean distance, the value of channel 12 is the largest and the value of channel 14 is the smallest. Meanwhile, in the quantitative results of cosine similarity, the value of channel 39 is the largest and the value of channel 13 is the smallest.

**B. CURVED DRIVING CONDITION**

In the curved driving condition group, we determined whether the sample of each channel obeyed the normal distribution in the first and the last curved section by analyzing the matrix $W_f$ and $W_a$ using the Jarque-Bera test.

According to the results, when the samples obtained from the first and last curved sections of a certain channel obey the normal distribution, we select the $t$ test ($\alpha = 0.01$ and $\alpha = 0.05$) to analyze samples of that channel. Otherwise, we use the Mann-Whitney U test ($\alpha = 0.01$ and $\alpha = 0.05$) on the samples. The results of difference analysis in the curved driving condition are shown in Table 4.

The results showed that the cortex of the left hemisphere was more active in the process of motion sickness under the curved driving condition.

| Channel | $p$ value | Channel | $p$ value | Channel | $p$ value |
|---------|-----------|---------|-----------|---------|-----------|
| 1       | 0.008**   | 15      | 0.715     | 29      | 0.946     |
| 2       | 0.004***  | 16      | 0.356     | 30      | 0.432     |
| 3       | 0.068     | 17      | 0.138     | 31      | 0.645     |
| 4       | 0.037*    | 18      | 0.029*    | 32      | 0.571     |
| 5       | 0.511     | 19      | 0.618     | 33      | 0.515     |
| 6       | 0.160     | 20      | 0.898     | 34      | 0.341     |
| 7       | 0.147     | 21      | 0.125     | 35      | 0.892     |
| 8       | 0.006***  | 22      | 0.109     | 36      | 0.868     |
| 9       | 0.006***  | 23      | 0.791     | 37      | 0.001***  |
| 10      | 0.661     | 24      | 0.376     | 38      | 0.014*    |
| 11      | 0.560     | 25      | 0.785     | 39      | 0.002***  |
| 12      | 0.670     | 26      | 0.389     | 40      | 0.722     |
| 13      | 0.038*    | 27      | 0.623     | 41      | 0.327     |
| 14      | 0.023*    | 28      | 0.832     |

* corresponds to value below 0.05.  
** corresponds to value below 0.01.
the smallest. Meanwhile, in the quantitative results of cosine similarity, the value of channel 39 is the largest and the value of channel 8 is the smallest.

V. DISCUSSION
Based on the 10-20 system, we can determine which functional part of the brain each channel is located in Fig.10. We identify brain areas that affect the data of certain channels; thus, we can obtain brain areas that are active when the driver is in the state of motion sickness.

Therefore, the findings suggest that the occurrence of motion sickness during long driving may be related to the visual cortex (BA17 and BA18). In recent studies, Gupta et al. believed that stimulation of the trigeminal nerve in the anterior part of the eye might be involved in the formation of motion sickness [39]. Farmer et al. found that the incidence of motion sickness was positively correlated with activity of the middle occipital lobe [40], and a study by Wada and Yoshida found vision is the predominant factor affecting carsickness [41]. Besides, Li et al. believed that vision was one of factors to evaluate drivers’ distraction [42]. Consequently, this study validates the preceding results by using physiological signal measurement methods with higher accuracy. Furthermore, we gain different results by comparing the data of two different driving conditions.

In the straight driving condition, except for channels 37 and 39, the occurrence of motion sickness may be related to the channel whose p value is less than 0.01 when driving long, straight sections of road.

Channel 12 is located on the left side of the frontal lobe (between F1 and Fz), corresponding to BA6. Channel 13 is located on the precentral gyri (between C1 and FC1), corresponding to BA4. Channel 14 is located on the postcentral gyri (between C1 and CP1), corresponding to the first somatosensory area, which include BA1, BA2 and BA3. Channel 38 is located on the occipital lobe, corresponding to BA17. BA6 is composed of the premotor cortex and the supplementary motor area (SMA), and it is thought to play an important role in complex and coordinated motor planning. BA4 is the primary motor cortex of the human brain, located at the rear of the frontal lobe. The function of BA4 is not only motion execution but also motion planning and motion control, which also demonstrates that the information interaction between different sensorimotor systems in the sensory conflict theory of motion sickness is related to the processing of motion information by BA4. Stippich et al. subdivided the primary motor cortex (BA4) into two parts [43]. The part close to the premotor cortex and the SMA (BA6) is the BA4a area, which is the main location activated by motor association. Another part is the BA4p area, which is closely related to pure movement execution. In addition, Naqvi et al. found that motion sickness was related to the activity of the cerebral motor cortex [31]. BA1, BA2 and BA3 constitute the primary somatosensory cortex of the human brain, which has basic somatosensory function and can receive incoming sensory signals from the opposite limb. Stoffregen et al. hypothesized that motion sickness was caused by instability in the control of body position [44]. In this study, the active state of BA1, BA2 and BA3 denotes that the primary somatosensory cortex receives somatosensory signals during the occurrence of motion sickness, and these somatosensory signals participate in the process of motion sickness. Hence, this study verifies its hypothesis to some extent. Similar to channel 39, channel 37 also corresponds to BA17, so it can be concluded that channel 37 and channel 39 have stronger significant differences than channel 38 in the occurrence of motion sickness.
sickness. In the quantitative result under the straight driving condition, we find that, in both the Euclidean distance and cosine similarity, the values of channels 13 and 14 are less than the values of the other four channels, and it can be inferred that the visual cortex of the occipital lobe (BA17 and BA18) and the frontal cortex (BA6) are more active than the posterior frontal cortex (BA4) and the postcentral gyri (BA1, BA2 and BA3).

In the curved driving condition, the occurrence of motion sickness may be related to the channel whose p value is less than 0.01 when driving long, curved sections of road except for channels 37 and 39.

Channels 1 and 2 are located at the prefrontal cortex (between Fp1 and Fp2), corresponding to BA10. Channel 8 is located on the frontal lobe of the brain (between AF3 and AFZ), corresponding to BA9. Channel 9 is located on the frontal lobe of the brain (between F1 and AF3), corresponding to BA8. BA10 is the largest cytoarchitectonic area in the human brain. In present research, BA10 has been shown to be involved in memory, as well as in strategic processes for various executive functions [45]. Some scholars have proposed that BA10 can play a major role in the highest level integration of information from visual, auditory and somatosensory systems, thus achieving a modeless, abstract and conceptual interpretation of the environment [46]. At the same time, Napadow et al. used fMRI to study motion sickness and found that the occurrence of motion sickness is related to the middle prefrontal cortex of the brain [47]. As a result, based on the six-degree-of-freedom driving simulator platform, drivers need to simultaneously perceive visual, tactile and somatosensory information during driving. In the process of integrating this information, BA10 is in an active state, which indicates that the occurrence of motion sickness is related to BA10. BA9 is part of the cerebral cortex. In previous studies, left hemisphere BA9 was responsible for processing some emotional scenes [48]. In the process of driving with the aggravation of motion sickness, the driver’s emotion will become more negative, making them unable to continue to perform driving tasks. However, the change in emotion is related to BA9. BA8 is located on the frontal lobe of the brain, which constitutes the premotor cortex with BA6, and BA8 plays an important role in controlling eye movement. When motion sickness occurs, the driver’s attention decreases. At this point, the decrease in attention will largely affect eye movement, which indicates that the occurrence of motion sickness related to BA10. In addition, some studies have shown that BA8 is active when subjects experience uncertainty, and BA8 is going to be more active with increasing uncertainty [49]. In this study, the activity of BA8 may also be associated with the uncertainty of when motion sickness will occur. In the quantitative results under the curved driving condition, we find that, in both the Euclidean distance and cosine similarity, the values of channels 8 and 9 are less than the values of the other four channels, and it can be inferred that the visual cortex of the occipital lobe (BA17 and BA18) and the prefrontal cortex (BA10) are more active than the posterior prefrontal cortex (BA8 and BA9).

Besides, p values of channels 1, 9, 13, 14 and 38 are all less than 0.05 in both driving conditions, which indicates that the occurrence of driver motion sickness may be related to these five channels when driving long sections of road. Consequently, this study suggests that the occurrence of motion sickness is directly related to the activity of the occipital cortex and the frontal cortex, to some extent, which confirms the hypothesis in Farmer’s research that motion sickness is caused by the combined action of occipital cortex and frontal cortex [40], and it also conforms to the sensory conflict theory [3]. Moreover, this study also finds that channels 37 and 39 are more active than these five channels under both driving conditions, suggesting that driver visual cortex (BA17 and BA18) is more active than the frontal lobe (BA4, BA8 and BA10), which is consistent with the finding of Chen et al. [50]. We can get more results by studying data of two driving conditions separately.

In the straight driving condition, the p values of channels 1, 9 and 21 also are less than 0.05, which means that the occurrence of driver motion sickness may be related to these three channels, while channels whose p value are less than 0.01 are more active than these three channels when driving long, straight sections of road. Channel 21 is located on the lower part of the central sulcus of the left hemisphere (between C5 and C3), corresponding to BA40, and BA40 is located on the supramarginal gyri of the lower part of the parietal lobe, which is related to spatial localization and supervises coordination of motion. When the driver has symptoms of motion sickness, BA40 is relatively active, indicating that the driver needs to coordinate motion for accomplishing driving tasks. Consequently, the visual cortex (BA17 and BA18), the posterior frontal cortex (BA4 and BA6) and the postcentral gyri (BA1, BA2 and BA3) are more active than the anterior frontal cortex (BA8 and BA10) and the lower parietal cortex (BA40) in the straight driving condition.

In the curved driving condition, the p values of channels 4, 13, 14, 18 and 38 also are less than 0.05, which means that the occurrence of driver motion sickness may be related to these five channels, while channels whose p value are less than 0.01 are more active than these five channels when driving long, curved sections of road. Like channel 8, channel 4 is located at the frontal lobe (between AF3 and AFZ), which corresponds to BA9. Like channel 13, channel 18 is located at the precentral gyri, at the junction of the frontal lobe and the central sulcus (between FC5 and FC3), which corresponds to BA4. In result, the visual cortex (BA17 and BA18) and the anterior frontal cortex (BA8 and BA10) are more active than the posterior frontal cortex (BA4) and the postcentral gyri (BA1, BA2 and BA3) in the curved driving condition.

In general, this study successfully finds brain areas that are active when the driver is in the state of motion sickness. However, this experiment lacks the monitoring of quantitative parameters of motion sickness self-evaluated by volunteers, which limits the use of statistical methods to a certain extent.
Thus, we will use the questionnaire in future work to further promote the identification accuracy of active brain areas for better studying the relationship between motion sickness and brain activity.

VI. CONCLUSION

To study the relationship between motion sickness and the brain activity, this study used a six-degree-of-freedom driving simulator platform for the experiment, and measured the changes of oxyhemoglobin concentration in the brain using fNIRS. It has been found that the activity of the visual cortex in the occipital lobe is associated with motion sickness during long driving periods. In the straight driving condition, the visual cortex of the occipital lobe (BA17 and BA18) and the frontal cortex (BA6) have the highest degree of activity, followed in decreasing order by the posterior frontal cortex (BA4) and the postcentral gyrus (BA1, BA2 and BA3), and the anterior frontal cortex (BA10 and BA8) and the lower parietal cortex (BA40). In the curved driving condition, the visual cortex of the occipital lobe (BA17 and BA18) and the prefrontal cortex (BA10) have the highest degree of activity, followed in decreasing order by the posterior prefrontal cortex (BA8 and BA9), and the posterior frontal cortex (BA4) and the postcentral gyrus (BA1, BA2 and BA3).

This study will help people better understand the pathogenesis of motion sickness to improve the comfort of driving, and contribute to developing the driving assistance system for preventing or alleviating motion sickness in autonomous vehicles.

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YAOHUA LI received the bachelor’s degree from the West China School of Medicine, Sichuan University, in 2009, and the M.D. degree from Sichuan University, in 2014. She is currently working with the Neurology Department, Chengdu First People’s Hospital. She is an expert at electroencephalogram analysis, diagnosis and treatment of epilepsy, and behavioral neuroscience. Her main research interest includes pathogenesis of epilepsy.

SHENGBO EBEN LI (Senior Member, IEEE) received the M.S. and Ph.D. degrees from Tsinghua University, in 2006 and 2009, respectively. He has worked with Stanford University, University of Michigan, and UC Berkeley. He is currently leading the Intelligent Driving Laboratory (iLab), Tsinghua University. His research interests include intelligent vehicles and driver assistance, reinforcement learning and optimal control, distributed control and estimation, and so on. He is the author of over 100 peer-reviewed journal/conference papers. He is the co-inventor of over 30 patents. He was a recipient of the Best Paper Award in 2014 IEEE ITS Symposium, the Best Paper Award in 14th ITS Asia Pacific Forum, the National Award for Technological Invention of China, in 2013, the Excellent Young Scholar of NSF China, in 2016, the Young Professorship of Changjiang Scholar Program, in 2016, the Tsinghua University Excellent Professorship Award, in 2017, the National Award for Progress in Science and Technology of China, in 2018, the Distinguished Young Scholar of Beijing NSF, in 2018, and so on. He also serves as the Board of Governor of the IEEE ITS Society. He serves as an Associate Editor for the IEEE Intelligent Transportation Systems Magazine, the IEEE Transactions on Intelligent Transportation Systems, the Indian Journal of Chemical Technology, and Vehicles.

BINGBING NIE (Member, IEEE) received the B.Sc. degree from Tsinghua University, in 2007, the M.Sc. degree from RWTH-Aachen, Germany, in 2009, and the Ph.D. degree from Tsinghua University, in 2013. She worked as a Visiting Scholar with General Motors Research and Development, from 2012 to 2013, and as a Research Associate with the University of Virginia, from 2013 to 2016. She is currently an Associate Professor with the School of Vehicle and Mobility, Tsinghua University, China. She has authored/coauthored more than 40 technical articles and three patents related to automotive safety. Her research interests include applied biomechanics, vehicle safety, protection of occupants and vulnerable road users, and human body modeling. She has also served as an Organizer of the Pedestrian and Cyclist Safety Session of SAE World Congress, the IRCOBI Scientific Review Committee Member, and the AAAA Scientific Program Committee Member.

CHENYANG ZHANG received the B.S. degree in flight vehicle propulsion engineering from the Civil Aviation University of China, in 2015. He is currently pursuing the M.S. degree in industrial engineering with Sichuan University. His research interests include man–machine interaction and driver behavior.