Physiological signals responses to normal and abnormal brake events in simulated autonomous car

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***Abstract*—An autonomous driving technology brings a new challenge of communication between human and autonomous car. The development of this new technology has been devoted to safety, but comfortability for drivers has not been interested. The safety is necessary, but the comfortability should be considered to achieve a reliable technology. Thus we investigated how the mental state appears in physiological signals during autonomous driving. To this end, we explored the responses of physiological signals to normal and abnormal brake situation in a simulated autonomous car. It was assumed that a brake timing of drivers is different from each other. Thus, we created normal and abnormal brake scenes in autonomous driving simulation. Then, we recorded EEG and ECG signals during the normal and abnormal brake situations of autonomous driving. In the abnormal brake situation, after brake, an event-related desynchronization (ERD) of the frequency band of 8 to 13 Hz observed in some subjects. Those subjects showed higher tension by analysis RR interval of ECG: the ratio of LF power to HF power during abnormal brake situation was higher than normal brake situation.**

I. INTRODUCTION

Autonomous driving technology might change people's daily life. Consumers all around the world are enthusiastic about the advent of autonomous car for public. However, as human back out of the driving task, the autonomous driving technology brings a new challenge of communication between human and autonomous car. The enthusiastic of consumes has accelerated the development of various autonomous driving technology. However the development of this new technology has been devoted to safety [1] [2], comfortability for drivers has not been interested. The safety is necessary, but the comfortability should be considered to achieve a reliable technology.

Vibrations in the vertical direction and velocity fluctuations in the travelling direction are raised as factors leading to discomfort of ride, especially emergency braking is the main cause of discomfort [3] [4]. As human distrust of the machine, which is largely due to feelings that autonomous driving vehicles can not perform as well as humans [5], there are longer brake timing needed in the case of autonomous driving. The mental state can help to evaluate driving quality during autonomous driving and described driving-related emotions (Frustration/Anger, Panic/Fear, and Boredom/Sleepiness) [6].

One method of objectively evaluating the mental state of drivers is by measure of physiological signals. Common indices of the psycho-physiological stress include measures of skin conductance via eccrine gland activation and muscle tension from the trapezius muscles [7]. In a recent study, differences between non-emergency (soft) and emergency (sharp) braking during simulated driving were detected using event-related potentials (ERPs) [8]. Another study indicated that event-related desynchronization (ERD) and event-related synchronization (ERS) in the alpha band can responses to emotional cues [9]. Heart rate variability (HRV) analysis is commonly used as a quantitative marker depicting the activity of autonomous nervous system (ANS) that may be related to mental stress and ultra short term analysis of heart rate and RR interval could be reliably performed for monitoring mental stress [10]. Therefore, physiological signals can be used to evaluate the mental state during driving task. By surveying the performance of physiological signals, vehicles can recognize the mental state of drivers and know it is a comfortable ride or not.

The purpose of this study is to explore the responses of the EEG and ECG signals between normal and abnormal brake situation in a simulated autonomous car.

II. MATERIAL AND METHODS

To measure physiological signals during normal and abnormal brake in simulated autonomous car, the experiment was divided into two Phases: Phase 1 and Phase 2. During the Phase 1, we created driving simulation of autonomous car and measured the normal brake distance of each subject under different scenes of driving simulation. In the Phase 2, we created normal and abnormal brake situations of driving simulation by use the brake distance recorded in the Phase 1.

A. Subjects

A total of 15 healthy adults (12 males and 3 females, age: 22.26 $\pm$ 0.96 years) with normal perceptual and cognitive functions participated in this study. All subjects had drive license and were measured brake timing, 12 subjects (except subjects 3, 6, and 8) were measured the EEG data. In these 12

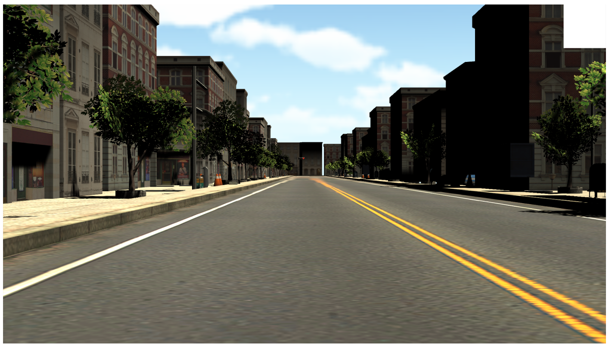

Fig. 1. A screen-shot of a day driving scene

Fig. 2. A photo of the experiment environment and equipment

subjects, 6 subjects (subject 7, 9, 12, 13, 14 and 15; 4 males and 2 females) were measured the ECG data.

B. Create Scenes of Driving Simulator

As stimulus materials, we created five city driving scenes using Unity 3D (Unity Technologies, USA), and extended the driving scenes to day driving scenes and night driving scenes by changing the lighting environment, for a total of ten scenes (five day and five night scenes). A signal light and a stop line are provided in each scene, the vehicle starts at an initial speed of 70 kilometres per hour. The total distance from start to stop line was set in 300 m. Fig. 1 showed a day driving scene used in this experiment. We used photodiode to synchronize the time between stimulus generating machine and physiological signals recording machine. The white square in the right-upper corner was used to send a signal to photodiode.

C. Measure Brake Timing

To ensure the normal brake distance that the subject deems appropriate is available. Subjects were reminded to focusing on the monitor during the vehicle running and press the brake button when they felt should have brake and the vehicle can stop in front of the stop line smoothly and safely. Unity's program recorded the brake distances. After the subject presses the brake button, the vehicle began to decelerate with a constant deceleration and stop in front of the stop line. From the vehicle start to stop as one trial, each scene execution ten trials, 100 trials totally. During the whole experiment, all stimuli were presented on a 31.5-inch LCD monitor (Acer ER320HQwmidx refresh rate 144 Hz). Subjects seated comfortably in a play-seat about 1 m away from the LCD monitor. The experiment environment and equipment can be seen in Fig. 2.

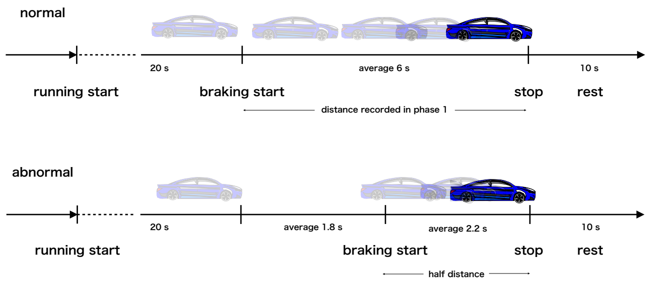

Fig. 3. Phase 2 experiment flow of one trial in normal and abnormal brake situation. There were 80 normal and 20 abnormal trials in the Phase 2.

D. Measure Physiological Signals

In Phase 2, we created auto-driving simulations with two situations: normal and abnormal brake. By using the same brake distance recorded in Phase 1, we created the normal brake auto-driving simulation and by using the half of the brake distance recorded in Phase 1, we created the abnormal brake auto-driving simulation. As can be seen in Fig. 3, when the car arrived at the each vertical line location of the normal and abnormal brake situation, a signal will be sent to photodiode. These signals will be used to synchronize these two different brake situations. The experiment of Phase 2 contained 100 trials (80 normal and 20 abnormal brake). At the end of each trial, the subject will be asked whether they were feeling discomfort with the presented driving simulation.

After the experiment of Phase 2, for each subject, the trials were categorized into two classes (comfort and discomfort) according to the answers of the subject. In the situation of abnormal brake, all subject answers were discomfort. However, in the situation of normal brake, a part of trials answers were discomfort, we removed these trials as bad trials.

E. Data Acquisition

The EEG was recorded with a 32-channel DC amplifier (Polymate AP5148) and acquisition software (AP Monitor). An electro-cap with Ag/AgCl electrodes was used to record EEG from active scalp sites referred to earlobes. As can be seen in Fig. 4, 30 channels (Fp1, Fp2, AF3, AF4, F3, Fz, F4, FC5, FC1, FC2, FC6, T7, C3, Cz, C4, T8, CP5, CP1, CP2, CP6, P7, P3, Pz, P4, P8, PO3, POz, PO4, O1, O2)

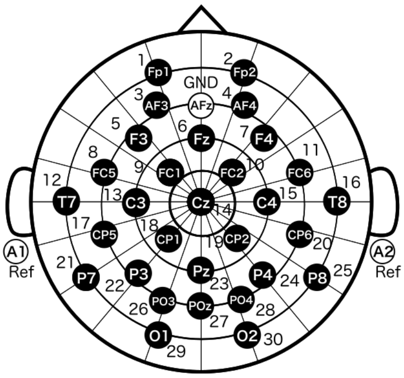

Fig. 4. The electrode locations of EEG

was recorded under the rule of 10-20 system of electrode placement. Additionally, two EOG electrodes were recorded on the outer side of eyes. The data was recorded using the sampling rate of 1000 Hz with a frequency band of 0.03 to 333 Hz.

The ECG RR interval data was recorded with a wearable heart rate sensor(WHS-1, UNINON TOOL CO., Tokyo, Japan). A belt electrode set at the skin below the heart and around the chest was used to record the ECG RR interval.

F. Data Analysis

The current analysis focuses on subjects who have measured ECG signal.

1) Time-frequency (TF) Analysis: Acquired data were analyzed with MNE (A toolbox of Python). The raw EEG signal was filtered to a 0.2-60 Hz band. To show the ERD/ERS of each class (normal brake, abnormal brake), the EEG recording epoch was referenced to normal brake onset, with a total length of six seconds (one second preceding normal brake timing and five seconds after normal brake timing). ERD/ERS is defined as the percentage of power decrease or power increase in relation to the reference period (-500 to 0 ms) [11]. TF maps was calculated by diverse frequency bands [12]. A frequency range of 2-45 Hz and a frequency resolution of 1 Hz was used to calculate average ERD/ERS across trials. Finally, we plot these ERD (red) and ERS (blue) in frequency range of 2-45 Hz across time. In order to compare normal and abnormal brake, 20 abnormal brake trials and adjacent 20 normal brake trials were selected to calculate the TF maps.

2) ECG RR Interval Analysis: Frequency analysis was used for ECG RR interval. The characteristic frequency of heart rate change can be obtained by Fourier analysis.

- Low frequency component (0.04 to 0.15 Hz): LF Indicator of sympathetic nervous system activity
- High frequency component (0.15 to 0.40 Hz): HF Indicator of parasympathetic nervous system activity

For each trial, 10 seconds before and after normal brake RR interval data was extracted and obtained the ratio of LF to HF. To compare normal and abnormal brake situation, 20 abnormal brake trials and adjacent 20 normal brake trials were selected to calculate the average of the ratio of LF to HF.

III. Results

A. TF Maps

Fig. 5, shown the TF maps of normal and abnormal brake for subjects who were measured ECG signals. The Pz channel was used to show the result. In the TF maps, we plot ERD as red and ERS as blue. For subject 12, at the abnormal brake situation, in the period between abnormal brake timing to stop timing, there was an obvious ERD that appeared in the frequency band of 8 to 16 Hz and 20 to 30 Hz. For subject 13 and 14, at the abnormal brake situation, in the period between abnormal brake timing to stop timing, there was an obvious ERD observed in the frequency band of 8 to 13 Hz. However the subject 7, 9 and 15, there were no obvious ERD observed in TF maps.

B. RR Interval

The boxplot in Fig. 5 showed that for subject 12 and 13, the average ratio of LF to HF of normal brake was lower than abnormal brake. For subject 7, 9, 14 and 15, the average ratio of LF to HF during normal brake situation was no significant difference than abnormal brake situation. Welch t-tests were used to analyze the ratio of LF to HF between normal and abnormal brake situation for each subject. In the analysis of subject 12 ($p = 0.015$) and 13 ($p = 0.027$), abnormal brake has significant effect on the ratio of LF to HF. However, in the analysis of subject 7 ($p = 0.48$), 9 ($p = 0.29$), 14 ($p = 0.36$) and 15 ($p = 0.39$), no significant difference was observed in the ratio of LF to HF. The orange asterisks in Fig. 5 was used to point subjects who observed ERD in alpha band and had higher LF/HF ratio in abnormal brake situation.

IV. Discussion

Between the six subjects who have recorded EEG and ECG signals, Two subjects shown the result that the physiological signals have different responses to normal and abnormal brake situation. For those subjects, at the abnormal brake situation, an alpha band (8-13 Hz) ERD was observed before and after braking. Moreover, from the ECG signal, a higher ratio of LF to HF was observed at the abnormal brake situation. From the previous studies, it was generally believed that visual attention was the primary factors lead to a suppression of the alpha rhythm [13]. However, another studies shown that a warning signal preceding the presentation of an imperative stimulus causes a strong short-lasting ERS followed by a ERD which most interestingly appears in the lower alpha band only [14] [15] [16]. Also, the ERD in the local alpha power (8 to 12 Hz) was a response to the unpleasant emotion [17]. Similar to our experiment, the ERD in alpha band was related to abnormal brake which causes nervous and unpleasant.

The sympathetic and parasympathetic nervous system activity (degree of tension) can be evaluated by obtaining the ratio of the power of LF and HF, higher LF/HF ratio was related to mental stress [18]. Compared with these studies, We believe that subjects felt unpleasant and stress by the reason of abnormal brake so that in abnormal brake situation, we can observe the ERD in the alpha band and a higher ratio

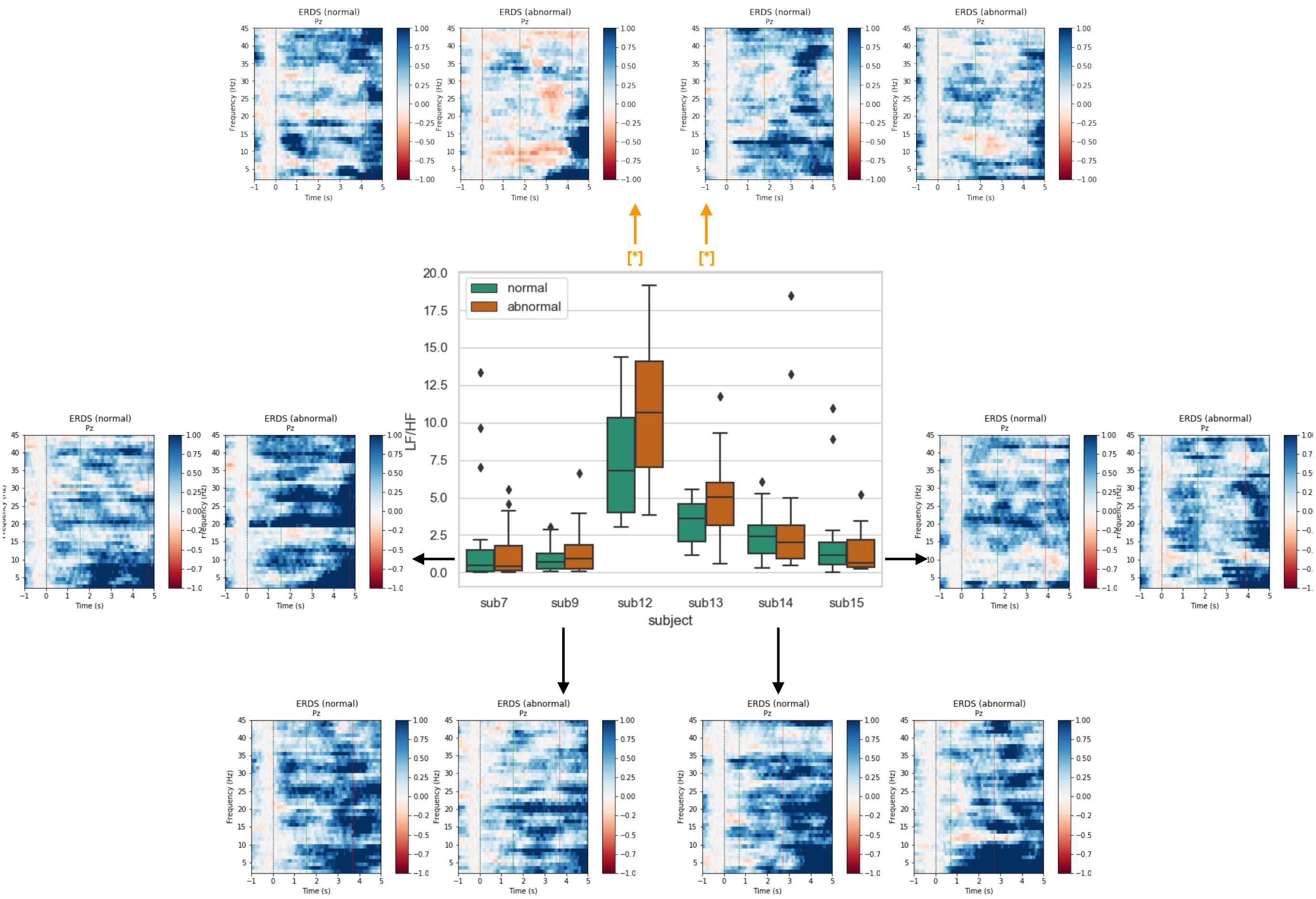

Fig. 5. Boxplot for the ratio of LF to HF of ECG RR interval during normal and abnormal brake across subjects. Arrow pointing to normal (left) and abnormal brake (right) TF maps for each subject. The black vertical line (t=0 s) in TF maps indicates the normal brake timing, The green vertical line (average t=1.8 s) in TF maps indicates the abnormal brake timing, The red vertical line (average t=4 s) in TF maps indicates the stop timing.

of LF to HF. However, for other subjects who shown results that the physiological signals have no different responses to normal and abnormal brake situations, those subjects seemed felt not nervous in the abnormal brake situation. Some factors can be considered to relate to the result, one was that driving simulator brings less pressure to subjects and another was that the brake timing we used to create the abnormal brake situation can not touch the bottom line that produced a physiological response. In the future experiment, we will consider these problems and add more subjects. Another interesting finding in this study was that the alpha band ERD related to higher LF/HF ratio. In the results of subject 12 and 13, the alpha band ERD and higher LF/HF ratio were observed during the abnormal brake situation. According to previous studies, EEG power in alpha and theta band was related to heart rate variability. A recent study showed that in different sleeping stage (awake, NREM, REM), coherencies between LF/HF ratio and EEG power spectra were high for all bands [19]. Moreover, another study indicated that during meditation, the percent change in the alpha band EEG power was increased and the LF/HF ratio was decreased [20]. Contrary to our results, during abnormal brake situation, subjects felt nervous and the alpha band EEG power was decreased (ERD) and the LF/HF ratio was increased. It seemed that the percent change in the alpha band EEG power was negatively correlated with the LF/HF ratio. Therefore these physiological signals can be used to identify the mental state of unpleasant and stress cause by abnormal brake in a simulated autonomous car. However, in a real driving task, there were lots of difficult to measure EEG signal even it has good response to mental stress. Record ECG signal was easier and cheaper and we can use the relation between the alpha band ERD and LF/HF ratio to improve the performance.

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