Investigating the relationship between driver's sense of agency and EEG: mu-rhythm is more suppressed in higher SoA case

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1. Introduction

In recent years, the field of automated driving has made a great progress. Especially, driver assistance and partial automation has been made practicable rapidly. While it is expected to reduce the number of traffic accidents, the assisted driver may feel less control over the vehicle. In other words, they may lose a sense of agency over the vehicle. Sense of agency (SoA) refers to the subjective feeling of controlling events through one's own behavior. It is reported that under less SoA conditions, one's response to an event becomes slower [1]. It can be suggested that poor SoA of driver may result in slow and inaccurate response in emergency cases. Therefore, it is important to maintain the driver's SoA during the assisted driving. For example, if the driving assist system could monitor the driver's SoA, it can give appropriate feedback when the SoA decreased.

In many previous studies, self-rating with questionnaire has been adopted to evaluate participants' SoA. However, such method is not suitable for monitoring the driver's SoA. Continuous and noninvasive measurement of physiological indices, such as electroencephalogram (EEG), is suitable for the real time evaluation of driver's SoA without disturbing driving operations and leaving irreversible effect on the driver. Also, because EEG signal directly reflects the brain activity, investigating the relationship between EEG and driver's SoA may not only enable real time evaluation of SoA, but also help with understanding the attibution process of SoA in the human brain during driving.

As an existing research focused on relationship between SoA and EEG, Kang and colleagues suggested that alpha band activity in EEG is associated with SoA [2]. The alpha band is a frequency band of 8-13 Hz. By conducting a virtual reality experiment with different SoA conditions, Kang et al. reported that relative power of alpha band over central, bilateral parietal, and right temporal areas in brain became weaker in higher SoA conditions. The alpha band activity over central area is also known as mu-rhythm. The mu-rhythm gets suppressed by observation, imagination and execution of body movement, in a phenomenon called event related desynchronization (ERD) [3]. If the alpha band activity associated to SoA corresponds to the mu-rhythm, the effect of ERD by body movement should be considered.

It can be suggested that driver's SoA is associated with mu-rhythm, and it can be detected by monitoring the EEG of the driver. However, the relationship between driver's SoA and mu-rhythm is not fully claryfied. We hypothesized that relative power of mu-rhythm would be suppressed in higher SoA conditions. In present study, our objective is to verify this hypothesis.

2. Method

During driving scenes with different driving conditions, driver's EEG data were recorded. The driving scenes were represented by a driving simulator (DS), and the driver was predicted to have different SoA under different driving conditions. For each condition, driver's SoA was rated by questionnaires and compared with the relative power change of mu-rhythm.

2.1. Driving Condition

In order to set up driving scenes with different SoA, we designed 3 driving conditions:

(a) no assistance nor disturbance (i.e., self-control)
(b) automated steering (i.e., automated)
(c) time delay (300 ms) for steering signal input (i.e., delayed)

Under automated condition, steering operation was carried on by DS program and driver's steering operation rarely affected the movement of the car. Under delayed condition, input of driver's steering operation is delayed for 300 ms. By making the driving task difficult, the delayed condition was expected to result in lower SoA, compared with self-control condition. On the other hand, it is reported that automated operation might enhance operator's SoA if it could improve task performance without noticed by the operator [4]. Therefore, in automated condition, we predicted that the driver would not always report less SoA. We also predicted that the difference in SoA between conditions should become prominent on curving road, because the difference between driving conditions are associated with steering operation. In order to avoid advance bias and to exclude the effect of different body movements in different conditions, participants were not notified about the driving conditions, but they were only suggested that there could be cases in which driving operation did not work well.

2.2. Data acquisition

EEG data were recorded from 27 active electrodes (FP1, FP2, F3, Fz, F4, FC5, FC1, FCz, FC2, FC6, T7, C3, C1,

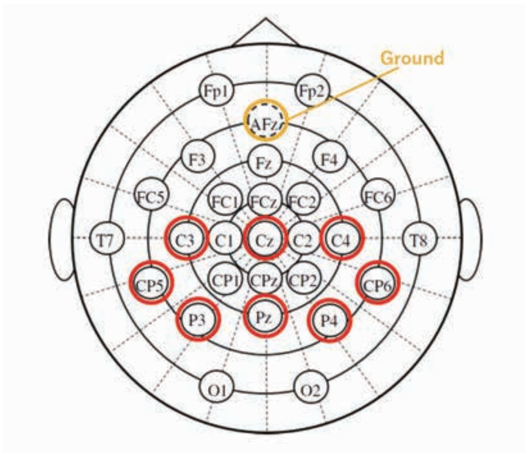

Figure 1. EEG electrodes. Afz was used as a ground. The data from C3, Cz, C4, P3, Pz, P4, CP5, and CP6 were used for analysis.

Cz, C2, C4, T8, CP5, CP1, CPz, CP2, CP6, P3, Pz, P4, O1, O2) attached on an EEG cap according to the extended 10-20 system with a right earlobe reference and a ground electrode on AFz (Fig. 1). EEG data were recorded using g.USBamp (g.tec medical engineering GmbH) at a sampling rate of 512 Hz and no online filter.

2.3. Data analysis

In order to analyze the EEG over central, parietal, and temporal areas, we used EEG data from following electrodes: C3, Cz, C4, P3, Pz, P4, CP5, and CP6 (Fig. 1). The EEG data were converted to digitally-linked earlobe reference, and 7-14 Hz band pass filter was applied. For each band passed data, spectral power was computed by applying short-time Fourier transform (STFT) with a time window of 1 s and a 512 point Hanning window, and the spectral power was averaged over alpha band (8-13 Hz). Then the relative power between each trial and baseline power was calculated. The baseline power for each trial was calculated by computing the alpha band power of resting state by STFT, and averaging the acquired power over 20 s.

The relative power during each trial was averaged over specific curving area on DS course, and averaged across same condition and same electrode.

3. Experiment

We used CarSim 2017 DS (Mechanical Simulation) as a DS software, MATLAB Simulink for applying driving conditions, and Logitech G920 as a driving controller (Fig. 2, Fig. 3).

Five volunteers (all men, 4 with driver's licenses, 1 with no driver's license) participated in the experiment using the DS, and EEG data were recorded in three (2 with driver's licenses, 1 with no driver's license) of them. For the participants with driver's licenses, they had less than five years of driving experience.

Figure 2. Experiment setup. CarSim and MATLAB was run on the laptop. The participant and the desk with driver's screen, Logitech G920 and g.USBamp were surrounded by an electromagnetic shield.

Figure 3. Logitech G920.

3.1. Task

In each trial, participants drove the DS handling course (Fig. 4), with instructed to drive at 40-50 km/h and keep the car in the center of the road. Transmission was automatic, and a speed meter with a gear number was displayed on the DS screen (Fig. 5). During each trial, participants put on earphones and were given a sound feedback representing engine sound, tire sound, and wind noise.

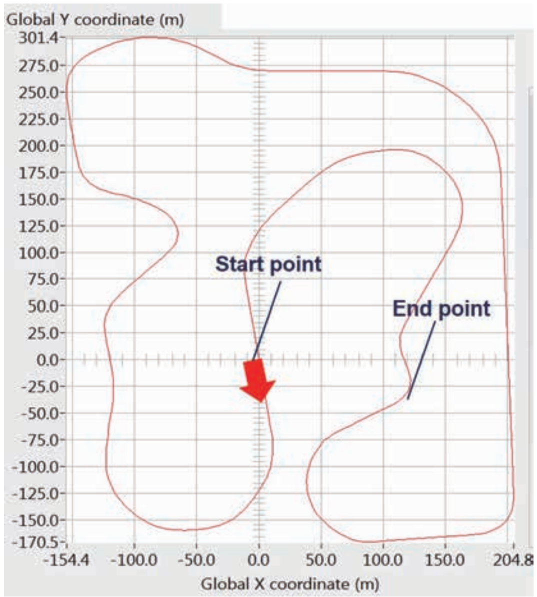

Figure 4. Left edge of DS handling course, start point, and end point of each trial.

Figure 5. DS screen with a speed meter. The number at the bottom of speed meter indicates current transmission gear.

3.2. Experiment procedure

Participants were tested individually. After electrodes were attached, they practiced driving the experiment course for 5 minutes under self-control condition. They were instructed to drive about 40-50km/h and keep the car in the center of the road. After the practice and short break, each participant carried out three sets of trial. Each set included three trials, which were under three different driving conditions. To counterbalance the effect of fatigue, the order of conditions during a set differed between each set and participants. Participants were not notified about the order. Before each trial, EEG signals in resting state were recorded to later calculate the baseline power. Each trial was stopped by the experimenter when the car went off the course and was impossible to come back, or when about 120 s passed.

Following each trial, participants rated their SoA (extent to which they felt that the car was under their control) in 7-points scale (1 = not at all, 7 = a lot). They were also asked to describe the driving scene in which they particularly felt less control over the car in each trial if there was such.

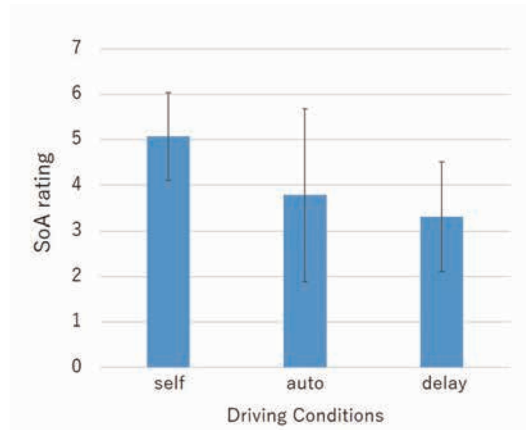

Figure 6. SoA rating results.

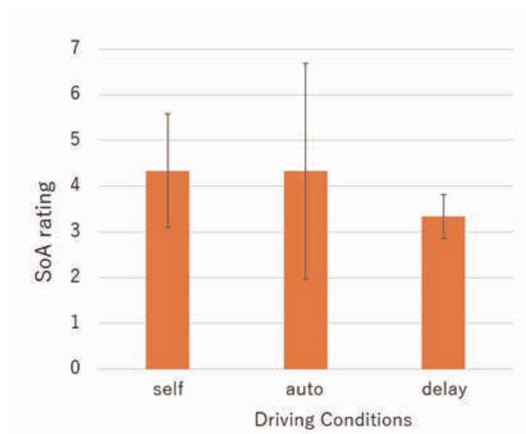

Figure 7. SoA rating results of a participant with no driver's license.

4. Results

4.1. SoA rating

We conducted 45 trials in total, and 4 trials were excluded from the analysis because of technical problems during those trials. The SoA rating result for each driving condition (mean±SD) was as follows. Self-control condition: 5.07 ± 0.96, automated condition: 3.79 ± 1.90, and delayed condition: 3.31 ± 1.20 (Fig. 6). Compared with self-control condition, SoA rating decreased significantly in delayed condition (Bonferroni: $p = 0.0013$, $p < 0.01$), and non-significantly in automated condition (Bonferroni: $p = 0.13$).

In some trials, a participant who did not have a driver's license showed higher SoA in automated condition compared with self-control condition. His mean SoA rating was as follows. Self-control condition: 4.33 ± 1.25, automated condition: 4.33 ± 2.36, and delayed condition: 3.33 ± 0.47 (Fig. 7).

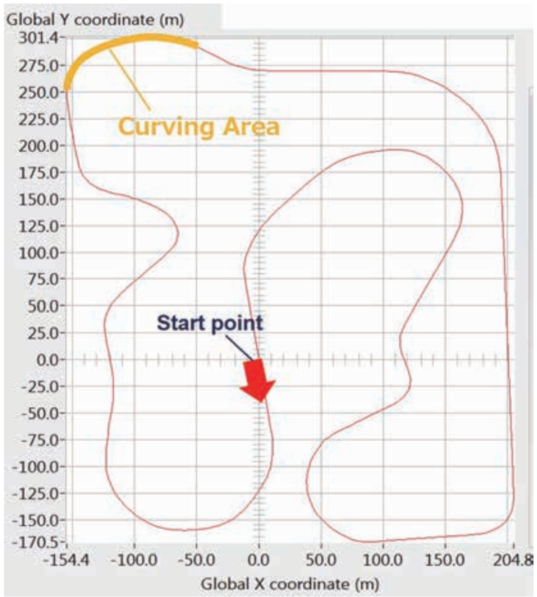

Figure 8. Curving area on DS handling course.

4.2. Relative power of alpha band

Because of technical problems during data acquisition, EEG data from one participant (who had a driver's license) were used in EEG analysis. The relative power of alpha band during each trial and from each electrode was averaged over the curving area shown in Fig. 8. Cz, C2, CP6, P3, Pz, and P4 showed greater mean relative power in automated or delayed condition compared with self-control condition, while C1 showed inverse result (Fig. 9). No electrode showed significant power difference between self-control and delayed condition (ANOVA, $p > 0.05$).

5. Discussion

In present study, we designed three driving conditions to represent driving scenes with different SoA. As we expected, SoA rating result showed that automated condition and delayed conditions caused less SoA of driver compared with self-control condition. However, a participant who did not have a driver's license reported more SoA in automated condition than in self-control condition. It can be implied that inexperienced driver may feel enhanced SoA under driving assistance. This view should be verified through further experiment with more participants including experienced drivers, because the current SoA rating results were only acquired from relatively inexperienced drivers.

In EEG analysis, the relative power of alpha band was averaged over curving area of DS course. Although not significant, some electrodes showed greater alpha band power in automated or delayed condition. In order to verify the significance of this finding, more experiment should be conducted to increase the number of EEG data.

Although the experiment was designed to exclude the different body movement between each driving condition and trial, actual strength of body movement in each trial was not evaluated in this study. It is needed to evaluate the effect of ERD by actual body movements during driving in different conditions.

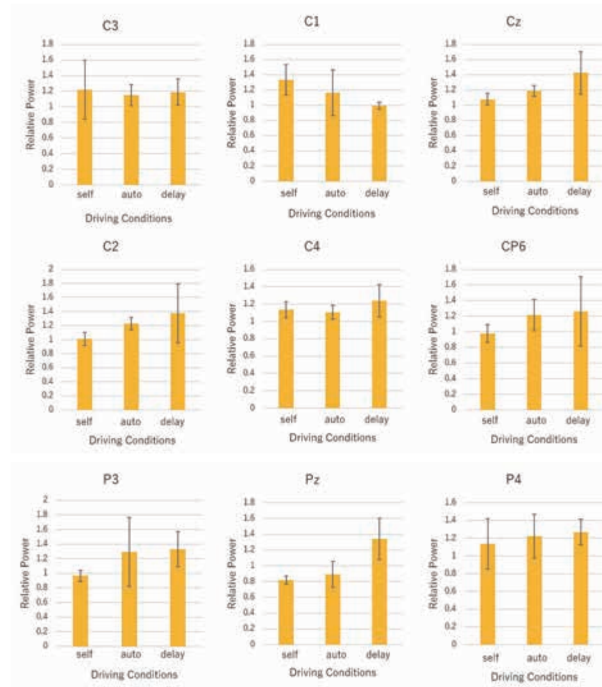

Figure 9. Relative power of alpha band. CP5 was excluded because of technical problems during data acquisition.

In addition to the relative power, Kang et al. also reported that the phase coherence of alpha band over frontal area was related to SoA [2]. The relationship between phase coherence of alpha band and driver's SoA should be investigated as well.

6. Conclusion

The present study investigated the relationship between driver's SoA and relative power of alpha band in EEG. The SoA rating results sugget that driver have less SoA under driving assictance or disturbance generally, while inexperienced driver may have enhanced SoA under driving assistance. In EEG results, although not significant, some electrodes showed greater alpha band power in automated or delayed condition, implying that driver's SoA could be evaluated by measuring the alpha band activity over certain area of brain.

In future plans, more experiment should be conducted to include both experienced and inexperienced drivers, to increase the number of EEG data, and to evaluate the effect of ERD by body movement. Phase coherence analysis should be done as well.

References

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