Biosignal Detection of Expansion of Body Schema Induced by TENS during Driving

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Abstract
As one of the various brain functions, an extension of the body image called the body schema (BS) is known. The BS is required to recognize the positions of our body parts and limbs. To utilize the BS, it is necessary to effectively integrate visual information and haptic information. An extension of the BS often occurs in our daily lives where we use a tool or device by hand; hence, the BS also related to the operational skill of vehicles because the feeling of the car width is an extension of the BS itself. With this background, in our previous study, a lane-keeping assistive method using a weak electrical stimulus based on the consideration of BS extension conditions was presented. It was confirmed in that study that the driving skill was improved using this method through experimental verification using a driving simulator. The induction of the BS extension by the external stimulus was, however, not shown directly in the simulator experiment. Therefore, in this paper, characteristic evidence of the BS extension was investigated from biosignal in the brain measured by near-infrared spectroscopy (NIRS). We monitored the cerebral blood flow (CBF) around the inferior parietal lobule, which is related to the BS. As a result, a significant (p<0.1; Wilcoxon rank-sum) characteristic pattern in the CBF variation was found for all four participants.

1. Introduction
The external body image [1] called the body schema (BS) is known as one of the brain functions of primates. The BS is related to our body perception of the surrounding environment. Specifically the BS plays an important role in our daily lives when using a tool by hand. It is necessary for the BS to adequately integrate visual information and haptic information in our brain [2]. The mechanism of the BS has been explained using the well-known behavior called the rubber hand illusion (RHI) [2,3]. Figure 1 shows the mechanism of the RHI. In the RHI, an actual hand of the participant is hidden so that he/she cannot watch his/her own hand directly, and an imitation hand (the rubber hand) is placed on a table so that it can be seen as the participant’s hand in terms of position. At that time, an external haptic stimulus (denoted as $e$ in Fig. 1) is given to the participant’s hidden hand with a brush or a pen by touching the rubber hand. Then the brain interpolates the visual information $v$ that is transmitted from the participant’s eye and the haptic perception $h$ that they do not contradict each other. As a result, the participant feels the imitation hand as if it was his/her own real hand. It is considered that the BS extension occurs by similar mechanism; when we use tool by hand, our brain expands the BS to the tip of the tool [4].

In addition, it is reported that the BS can be exogenously modified to give the illusion of motion. The most well-known example is the Pinocchio illusion [5]. In this illusion, a person can feel as if his/her nose with the virtually extending while he/she pinches his/her own nose with the fingers when an external vibration stimulus is added to the biceps tendon. For later discussion in this paper, we refer to such an external stimulus inducing a BS extension as a “BS stimulus”. On the other hand, the driving of a vehicle is related to the BS extension. When a driver operates a car on a narrow road, he/she has to recognize the positional relationship between the vehicle and the road environment, and this is often called the “feeling of car width” [6]”. If a beginner driver can master the feeling of car width by the BS stimulus, it can be expected that his/her driving skill will improve. On the basis of this idea, we have been studying a driving assistive method to enhance the feeling of car width. In our previous studies, the BS modification was induced by a low-frequency mechanical vibration...
stimulus similarly to in the Pinocchio illusion. It was, however, found that the illusion took a long time to induce and occurred with large individual differences [7]. Hence, the authors focused on another method called transcutaneous electrical nerve stimulation (TENS). TENS has fewer side effects [8] and can induce the illusion of motion [9]. In our previous studies, using a driving simulator (DS), it was confirmed that the driving skills of a beginner were improved in a lane-keeping assistive experiment using TENS without any recognition of pain caused by the TENS stimulus [10]; however, direct evidence of the BS modification effect by TENS has not yet been investigated. Direct evidence of the BS expansion will be useful because objective evaluation can be utilized as feedback information to review each BS modification skill. This paper reports trials to find such evidence using brain monitoring analysis.

The remaining sections in this paper are organized as follows: in Sec. 2 the DS experimental system used to give assistance based on BS modification to participant drivers is explained. Details of the stimulus intensity, the virtual test course, and the settings are also given. Section 3 describes the analysis involving brain monitoring and its results. Section 4 presents the conclusion.

2. Experimental System and Task Conditions
In order to conduct experiments on lane-keeping assistance using a multimodal haptic stimulus and visual information, the stimulus intensity and view position have to be suitably selected to imitate the actual circumstances of driving. Considering these points, the DS system was constructed by utilizing an actual driving seat, and the vehicle motion and its dynamics were computed using a vehicle dynamics model. In addition, the experimental course was designed with reference to Japanese road construction ordinance. In order to measure the brain response related to the BS, near-infrared spectroscopy (NIRS) which enables cortex activation to be measured without disturbing the driving operation, was used. Since it was reported that monitoring of the inferior parietal lobule [11] in the brain is one means of detecting the BS activity, the cerebral blood flow (CBF) of the lobule was investigated. Details of the setup and experimental procedure are given below.

2.1 Lane-keeping assistance using TENS
When the center of the vehicle on the DS is a certain distance away from the center line on the road (named “lane departure” for later discussion), TENS is given to the tendon of a driver’s right or left shoulder muscle depending on the side of lane departure. It is assumed that the driver will then adjust the steering implicitly and the car will return to the center of the lane.

2.2 System structure of driving simulator
The system configuration of the DS is shown in Fig. 2. To calculate the vehicle dynamics and to compute the timing of TENS for driving assistance, an automotive simulation model (ASM, dSPACE Co., Ltd.) was used with MATLAB/Simulink. Moreover, in order to display the landscape CG and to reproduce the driving sound simultaneously, Motion Desk (ver. 2.1) was used. The driver’s seat of the DS consisted of an actual vehicle seat, a gas pedal, a brake pedal, and a steering wheel. In order to enhance the realism of the sensation, the driving landscape was projected to three 120 inch wide screens. For a better sense of immersion, the driving sound was generated and the sound was listened to by the driver via a noise-canceling earphones. The steering force that was generated depended on the virtual reaction force on the virtual road surface, which was obtained using the above-mentioned virtual vehicle dynamics model. The Trio300 low-frequency therapy device (Ito VHF Co., Ltd.), which can control the output electric current and the frequency, was used as the TENS unit. Since Trio300 has to be manipulated by hand and it is not permitted to remodel the device for reasons of safety, a mechanical triggered interface device, which was named the TENS electrical stimulation device, was developed and the TENS stimulus was given online to the participant at various times, controlled from the control unit of the DS simulator.

2.3 Virtual test course
An overview of the virtual test course is shown in Fig. 3. The course was designed considering two points: the driver does not feel stress, and the driver has to drive a virtual vehicle using the acceleration, braking, and handling operations. Assuming that the course was a typical Japanese highway, the driving speed was assumed to be 60-100 [km/h], and the radii of curves were selected from 149, 280, and 460 [m], which correspond to the relaxation curves for speeds of 60, 80, and 100 [km/h], respectively. The length of straight sections were chosen from 400, 600, 800, and 1,333 [m] to give a total travel distance of 2 [km] per lap of the virtual course. The test course was designed by the random combination of curves and straight sections. The road width was specified as 3.5 [m], which is a Japanese standard road width.
2.4 Conditions of electrical stimulus and view position

Considering the fact that the generation effect of BS modification depends on the type of visual information [1], two types of view conditions were prepared, as shown in Fig. 4: the seat view (a) and the roof view (b).

The types of electrical stimulus were specified as alert assistance (AA), implicit assistance (IA), and no assistance (NA). The current level for AA was tuned so as to be recognized by the driver as a strong stimulus. This AA level was suggested on the basis of so-called pain feedback, which is unrelated to the BS expansion. The IA level was assumed to be an implicit stimulus without pain perception to induce the BS modification [10]. The stimulus frequency was tuned to 70 [Hz] [12] which can induce the illusion of motion. Considering the difference in perception among each participant, the electric current values of IA and AA were determined after preliminary measurement of the TENS stimulus.

2.5 Task procedure

An experiment to investigate the CBF in a driver’s brain in the case of TENS assistance was performed as follows. First, the participant drove the virtual course for 2 min both from the seat view and the roof view in order to become accustomed to the DS system. Second, the participant drove the course under six different conditions, i.e., combinations of the driving view condition (seat view and roof view) and TENS stimulus level (NA, IA, and AA). The participant was asked to drive the course while keeping the vehicle speed between 60 and 100 [km/h] for 8 min per task. A 2 min rest was given between each task, with conditions the participant listening to the idling sound to maintain the feel of driving. The content and procedure of these experiments were approved by the Tokyo Denki University human bioethics review committee. After explanation of the experiment to each participant and approval, experiments were conducted.

3. Results and Analysis

Four males aged from 20 to 24 years participated in the experiment. Their brain activities while driving were measured by optical topography (ETG-4000, Hitachi Medical Co. Ltd.). The CBF on the right and left sides of inferior parietal lobule was monitored using a 3-3 dual probe holder, and the CBF was recorded as 24 channels data. The channels measuring the CBF in the inferior parietal lobule [10] were 2, 4, 5, and 7ch and 13, 15, 16, and 18ch for the left and right hemisphere, respectively.

To counteract any effect of ordering, the order of the six conditions was changed at random, and the same task order was applied to all participants. In order to unify the driving conditions at the driver’s seat, all participants stepped on the pedal while wearing the same type of sneaker.

In the analysis after the driving experiment, we tried to find a characteristic difference in the CBF between the normal status and other statuses assisted by the TENS stimulus. First, the trend of the variation of the raw CBF data, say \( x \), was eliminated. Second, the time derivative of \( x \), \( \dot{x} \), was calculated to observe the perturbation. Since we found some difference in a high-frequency component of \( \dot{x} \) after some trial and error, the high-frequency signal was extracted by subtraction as \( \ddot{x} - \dot{x} \), where \( \ddot{x} \) is the low-frequency trend estimated by a third-order Savitzky-Golay (SG) filter interpolated by 41 sampling points of data. An example of this signal processing is shown in Fig. 5(a).

Figure 5(a) shows the case that the driver was assisted by a TENS stimulus in the IA mode. The raw time derivative \( \dot{x} \), the trend estimated by the SG filter \( \ddot{x} \), and the subtraction \( \ddot{x} - \dot{x} \) are drawn. The time range from the solid vertical line to the dashed vertical line means the duration during which the lane departure occurred. It was
confirmed that the high-frequency component decreases for about ten seconds after the start of lane departure. Figure 5(b) shows another case in the NA mode (no TENS assistance) with the same lane departure. Since a similar decrease in the high-frequency component can be found, it can be concluded that the decrease in the high-frequency component is induced by the BS modification not by the electrical stimulus.

Since this phenomenon might be considered to be a characteristic response of the CBF induced by TENS, the variation of the CBF was investigated. That is, the magnitudes of the high-frequency component before and after the start of timing were computed as \( \alpha = \int_{T_s - 10}^{T_s} (\tilde{x} - \hat{x})dt \) and \( \beta = \int_{T_s + 10}^{T_s} (\tilde{x} - \hat{x})dt \), respectively, where \( T_s \) is the starting time of the lane departure. For the first participant, nine data sets of \( \alpha \) and \( \beta \) were obtained in the case “seat view with NA (NA-Seat); three data sets were each obtained for the case NA-Roof, IA-Seat, and IA-Roof. Both AA-Seat and AA-Roof were excluded because of the small number of data sets. First, the normality of each set of data was tested by the Kolmogorov-Smirnov test, and the normality of each data group was confirmed at a significance level of 0.05. Next, we investigated whether the means of the two sets of \( \alpha \) and \( \beta \) data were statistically different from each other by the Wilcoxon rank-sum test. The result is summarized in Fig. 6. For all four cases, \( \beta \) appears to be smaller than \( \alpha \). In particular, in the case of IA-Roof, a significant difference was found (p < 0.1). Similar tendencies and a significant difference in the case of IA-Roof were also found for the other three participants (data and graph omitted because of space limitations).

4. Conclusion

To find characteristic evidence of the body schema (BS) expansion in lane-keeping assistance by an external stimulus, the cerebral blood flow (CBF) was measured using near-infrared spectroscopy (NIRS). As a result, a characteristic of BS modification was found in the high-frequency component of the CBF at the inferior parietal lobule. The variation was also found to the CBF in the case of implicit weak stimulus and differed significantly (p<0.1) after the start of lane departure. That is, the CBF measured by NIRS can be considered as characteristic evidence of BS modification during driving.

Acknowledgment

This research was in part supported by a JSPS Grant-in-Aid for Challenging Exploratory Research, Japan. The authors wish to thank JSPS for their generous financial assistance.

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