Research Paper 20144194

Cortical Activity while Riding Motorcycles Measured with a Wearable Near Infrared Topography System

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Received on August 28, 2013

ABSTRACT: The purpose of this study was to clarify the cortical activity of the dorsolateral prefrontal cortex (DLPFC) while motorcycles were being ridden. Sixteen healthy right-handed men who use motorcycles in their daily lives were recruited. Their brain activity was measured using a prototype of wearable optical topography while they were actually riding a motorcycle. We found that their brain activation patterns, which reflect the cognitive strategies behind their riding behaviors, differed depending on whether they were users of road bikes or scooters. Also, DLPFC activity, which reflects an increase in cognitive and motor demands, was greater in riders of on-road type motorcycles than scooters.

KEY WORDS: **Human Engineering**, **Driving Behavior**, **Central Nervous System** / Actually Riding Motorcycles, Wearable Near Infrared Spectroscopy, Dorsolateral Prefrontal Cortex, Cognitive Strategies [C2]

1. Introduction

The results of our recent intervention study indicate that when riders go back to using a motorcycle in daily life after having taken a significant break from the activity, it could have the beneficial effect of improving their working memory, executive functions, and visuo-spatial cognition [(1)]. Interestingly, our study's results show an improvement in non-trained cognitive functions (a transfer effect) from riding motorcycles to some other cognitive functions. It has been hypothesized that a transfer effect can be induced if the cognitive processes during training and the transfer tasks overlap [(2-4)]. Cognitive neuroscience acknowledges that the dorsolateral prefrontal cortex (DLPFC) plays a key role in those cognitive functions [(5)]. Therefore, in the current study, we address the question of whether or not riding a motorcycle activates the DLPFC.

Recent advancements in neuroimaging techniques enable us to visualize brain activity during various kinds of cognitive activities. Near infrared spectroscopy (NIRS) is one such technique which is able to measure changes in the concentration of oxygenated hemoglobin (oxy-Hb) and deoxygenated hemoglobin (deoxy-Hb) related to the activity of the cerebral cortex. With it, changes throughout a temporal course can be plotted [(6)] while performing daily life activities, such as driving a car [(7)]. In this study, to measure the activity of the DLPFC while riding a motorcycle, we introduced a prototype of the wearable optical topography (WOT) system (Hitachi Ltd., Tokyo, Japan) [(8)] based on NIRS (Fig. 1).

According to a survey on purchasers of new motorcycles in 2011 by the Japan Automobile Manufacturers Association, Inc., 35.5% of purchasers bought on-road type motorcycles while 41.5% bought scooters. The survey indicates that the majority of scooter users recognize their vehicle as a tool for commuting to and from the office or school, while on-road type motorcycle users view their motorcycles as a hobby. Since general trends differ in the usage of on-road type motorcycles and scooters, in the current study, we recruited users of both vehicle types and measured their brain activity while they rode the different vehicle types.

2. Methods

2.1. Subjects

Sixteen healthy men aged 23 to 60 (mean age, 37.2) participated in this study. All subjects were strongly right-handed according to the Edinburgh Handedness Inventory (laterality quotient was 1.0 for all the subjects) [(9)], and had a motorcycle driver's license. Seven subjects rode mid-sized on-road type motorcycles (Motorcycle), and the other nine subjects rode mid-sized scooters (Scooter) in their daily lives. The mean (SD) age of Motorcycle and Scooter users was 32.7 (8.1) and 40.7 (15.2), respectively, without statistically significant differences ($p = 0.23$, Student t-test). The mean (SD) frequency of the usage of either Motorcycles or Scooters in subjects' daily lives was 3.6 (3.1) or 5.1 (2.9) days per week, respectively. The mean frequency of usage was not statistically significant between the two groups ($p = 0.34$, Student t-test).

This study was approved by the Ethics Committee of the Tohoku University Graduate School of Medicine, and written informed consent was obtained from each participant.

2.2. Measurement of brain activity

We used a prototype of the WOT system [8] to measure the activity of the prefrontal cortex while a Motorcycle or a Scooter was being ridden (Fig. 1). The WOT system can measure changes in concentrations of oxy-Hb and deoxy-Hb using the absorbance change of two wavelengths (754 and 830 nm) according to the modified Beer-Lambert law [8]. The sampling interval was 200 msec. To reject artifacts induced by heartbeat or fast body movements, a 0.8 Hz low-pass filter and smoothing with a convolution of a Gaussian function with a full width at half maximum of 2 s was applied on the data.

Fig. 1 A prototype of the wearable optical topography (WOT) system and the location of the system's measurement points. A probe unit of the WOT system can be accommodated on the head of the subject, and a processing unit can be strapped to the subject's body. During the experiments, the subjects were asked to wear a helmet over the probe unit of the WOT system. 22 measurement points (red circles) cover the area around the dorsolateral prefrontal cortex. We selected four channels covering the DLPFC in each hemisphere (red filled circles) for statistical analyses.

The WOT system has 22 measurement channels, which can cover a large area of the forehead [10, 11]. The inter-subject variability of channel positions has been estimated [11], and it was concluded that any difference or variability in the positions of the measurement channels between the adult subjects could be ignored and that data from the channel of one subject could be compared to those from the same channel of other subjects.

2.3. Experimental setup

We made a driving course in a closed parking area using road cones (Fig. 2). Start and goal lines were made with two road cones at the center of the course (Fig. 2 "a-a"). The subjects were always asked to stop at the start/goal line for 10 s. After a 10 s stop, one of experimenters gave a verbal command to go, and the subjects were asked to drive the course either clockwise or counterclockwise. The subjects were instructed to drive between two cones, "b" and "e", past two cones diagramed as points "c" and "d", and then to return to the start/goal line by driving though cones "b" and "e" again (Fig. 2). In the course we set up two bends with different degrees of curvature, e.g. gentle and sharp bends (Fig. 2).

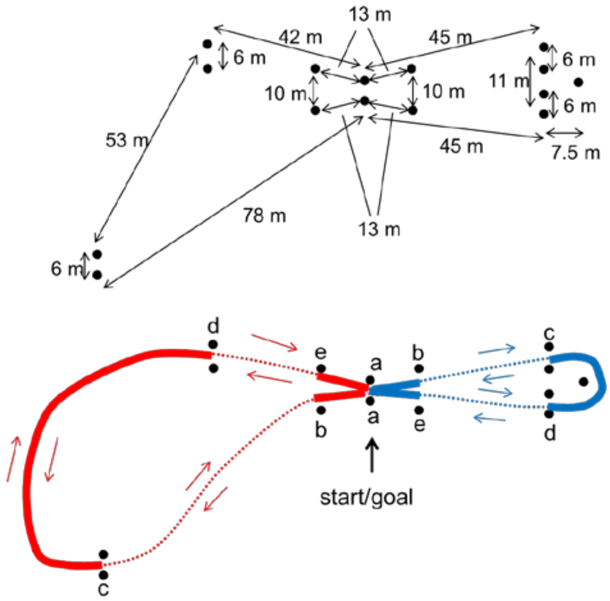

Fig. 2 Layout of the course. A course with two bends of different curvatures was made with pairs of road cones (filled circles). The subjects were always asked to stop at the start/goal line "a-a", then to run the course either clockwise or counterclockwise.

All subjects were asked to ride both a mid-sized on-road type motorcycles (XJR400R, Yamaha Motor Co., Hamamatsu, Japan) and a mid-sized scooter (Grand Majesty, Yamaha Motor Co., Hamamatsu, Japan). The XJR400R is a manual transmission motorcycle with a 399 cc, 4-stroke, 4-cylinder, 4-valve engine. The Grand Majesty is an automatic transmission scooter with a 394 cc, 4-stroke, single cylinder, 4-valve engine.

Prior to the experiments, each subject was asked to familiarize themselves with each vehicle by driving both the Motorcycle and the Scooter around the course several times. During the experiments, the subjects were asked to wear a helmet over the WOT system (Fig. 1). All of the subjects were instructed to drive clockwise around the gentle bend first, then to drive clockwise around the sharp bend after a 10 s stop at the start/goal line. After five clockwise drives around each bend, the subjects were asked to drive counterclockwise around the gentle and sharp bends five times. The riding performance of each subject during the brain activity measurements was recorded with a digital video camera and the time course of each point that was passed, e.g. the start line, b-e line, point c, point d, b-e line, and stop, was extracted from the video recording to use for analyzing brain activity.

2.4. Data analysis

In the present study, we measured changes in the concentration of oxy-Hb as a marker of cortical activity [12]. We selected four channels covering the DLPFC for each hemisphere (Fig. 1), and calculated the mean concentration of the oxy-Hb value for the statistical analyses.

The 4 s prior to each start was defined as a "baseline" (B) period (Fig. 3). During this 4 s period, both the actual performance of the subjects (stopping) and brain activity related to the stop overlapped so that we could eliminate possible noise caused by the physical movement of the subject's head. Mean concentration of oxy-Hb during B was calculated for each run. We also defined the "start and acceleration" (SA), "curving" (C), and "deceleration and stop" (DS) periods as the times between "start and the b-e line", "point c and d", and "the b-e line and stop", respectively (Fig. 2). Activity during those periods was compared with the activity during B. Because the hemodynamic changes induced by the task were delayed 6 s from the task onset [9, 10], mean concentration of oxy-Hb during each period was calculated with 6 s sifted data (Fig. 3).

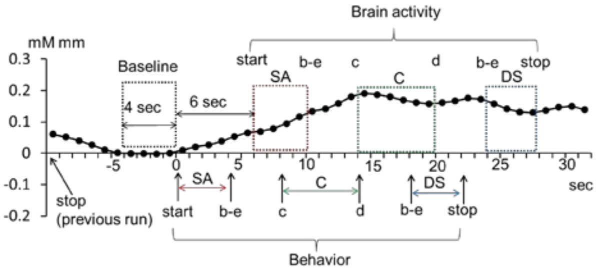

Fig. 3 Schematic diagram for the time course of the task. 0 s marked the subject's start time. 4 s prior to the subject's start time was defined as the baseline period. We defined "start and acceleration" (SA), "curving" (C), and "deceleration and stop" (DS) periods as the times between "start and b-e", "points c and d", and "b-e and stop", respectively, using the video recording. Brain activity was calculated from 6 s sifted data because of the hemodynamic delay. The filled circles are the time course of the mean oxy-Hb concentration.

2.5. Statistical analysis

In this study, we categorized 8 tasks, that is, riding the Motorcycle or Scooter x clockwise or counterclockwise x gentle or sharp bends, for each subject of each user group (Motorcycle or Scooter users). Each subject performed each task five times. For each task, the mean value for B, SA, C, and DS was calculated for each subject.

To determine brain activation while riding Motorcycles and Scooters, a paired t-test was performed between each riding period and the B period. For further statistical analyses, we calculated the value of relative change for each period by subtracting the mean value during B, that is, SA - B, C – B, and DS - B, for each task and for each subject. Then we made the following comparisons of brain activity by paired t-tests: 1) left and right DLPFC; 2) riding clockwise and counterclockwise; 3) riding the Motorcycle and the Scooter; 4) riding on a gentle and sharp bend; and by Student t-test, 5) Motorcycle and Scooter users. The statistical threshold was set at $p < 0.05$ for all comparisons.

To visualize and compare the general trend of brain activity over the time course, we calculated the mean value for each task, for each group, and for each second by subtracting the mean value of B from the data for each trial. Because the actual time course of behavioral data differed among trials and among subjects, we then interpolated each subtracted data to a fixed schedule using linear interpolation. In this study, we set the time course as follows: SA for 4 s, end of SA to start of C for 4 s, C for 6 s, end of C to start of DS for 4 s, and DS for 4 s (Fig. 3).

3. Results

Figures 4 to 7 show the mean concentration change in oxy-Hb during each period compared with B for each task and each user group. Figures 8 to 11 show the time courses of the mean concentration of oxy-Hb for each task and each user group.

3.1. Riding sharp bends with a Motorcycle (Figs. 4 and 8)

The Motorcycle users showed statistically significant activation in the left DLPFC during C and DS when they rode clockwise (Figs. 4A and 8A). Statistically significant deactivation was found during SA when they rode counterclockwise. Activity in the left DLPFC was more statistically significant than that of the right hemisphere during SA and C when drivers rode clockwise.

The Scooter users showed statistically significant activation in the right DLPFC during SA and C when they rode counterclockwise, and in the left DLPFC during DS when they rode clockwise (Fig. 4B, 8B). Activity of the right DLPFC was more statistically significant than that of left hemisphere during SA and C when they rode counterclockwise.

Activity of the left DLPFC during clockwise C was significantly higher in the Motorcycle group compared with the Scooter group, and the right DLPFC during counterclockwise C was significantly higher in the Scooter group than the Motorcycle group. For each group, activity during C was not different for the clockwise or counterclockwise rotation.

3.2. Riding sharp bends with a Scooter (Figs. 5 and 9)

Compared against B, the activities of the Motorcycle users were not statistically significant (Figs. 5A and 9A). The Scooter users showed statistically significant activation in the left and right DLPFC during DS when they rode clockwise or counterclockwise, respectively (Figs. 5B and 9B). In both groups, the activities of the left and right hemispheres were not significantly different.

There were no differences in the groups or the direction of rotation.

3.3. Riding gentle bends with a Motorcycle (Figs. 6 and 10)

The Motorcycle users showed statistically significant deactivation of the right DLPFC during clockwise SA, clockwise C and counterclockwise SA (Figs. 6A and 10A). Activity of the left DLPFC was significantly higher than that of the right during SA and C for both rotation directions. Compared with the B, activities of the Scooter users were not statistically significant (Figs. 6B and 10B).

Activity of the left DLPFC during clockwise C was significantly higher in the Scooter group than in the Motorcycle group. For each group, activity during C was not different between the clockwise and counterclockwise rotation.

3.4. Riding gentle bends with a Scooter (Figs. 7 and 11)

The Motorcycle users showed statistically significant deactivation of the right DLPFC during clockwise SA (Figs. 7A and 11A). Activity of the left DLPFC was significantly higher than that of the right during counterclockwise SA. Compared with B, the brain activities of the Scooter users were not statistically significant (Figs. 7B and 11B).

There was no difference in group or the direction of rotation.

3.5. Comparison between tasks

A statistically significant difference was only observed for riding sharp versus gentle bends during counterclockwise C in the right DPLFC of the Scooter group

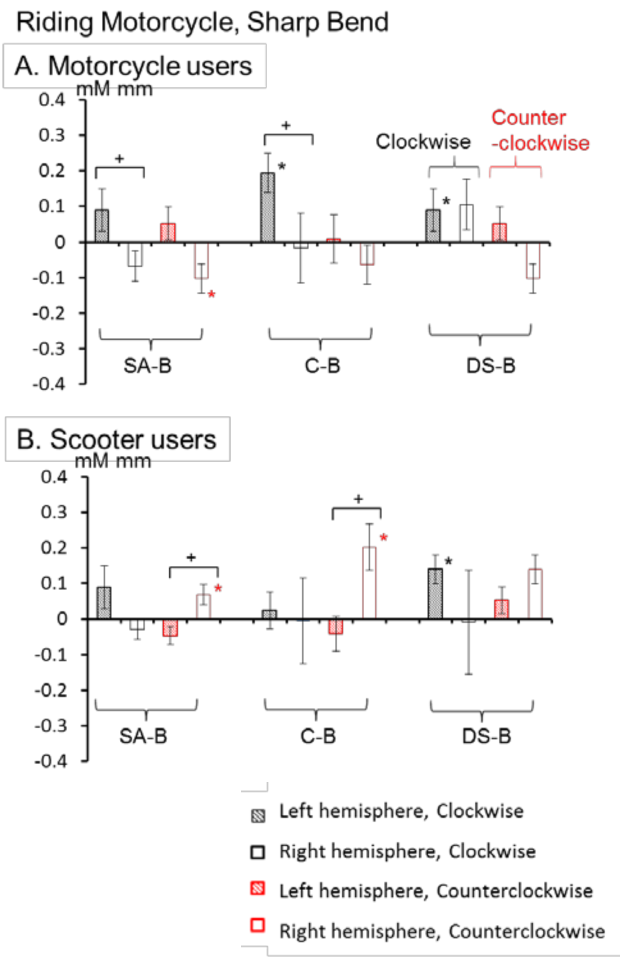

Fig. 4 Mean oxy-Hb concentration change in the DLPFC when riding around a sharp bend on a Motorcycle. Bar graphs show changes in mean concentration of oxy-Hb during each period compared with B. Hatched and open bars indicate left and right hemispheres, respectively, and black and red bars indicate clockwise and counterclockwise, respectively. Error bars indicate standard error of mean. * indicates statistically significant activation ($p < 0.05$) compared with B. + indicates a statistically significant difference between activity of the left and right hemisphere.

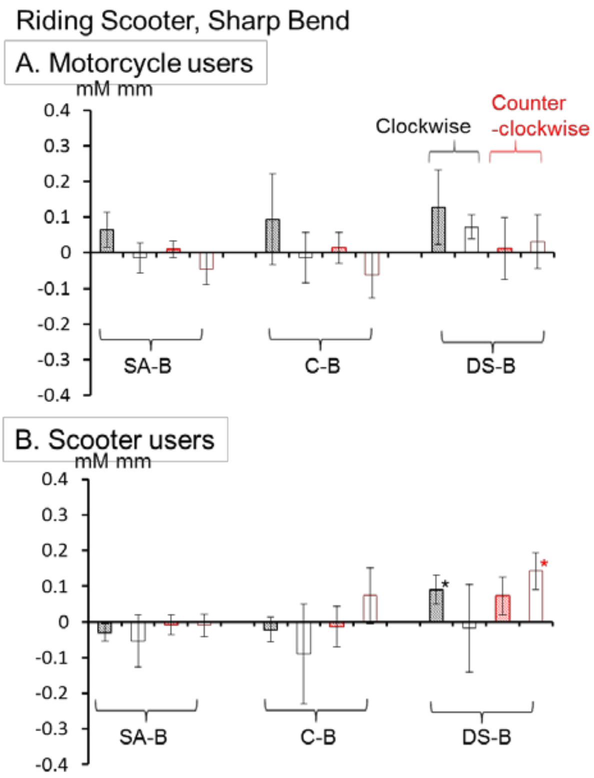

Fig. 5 Mean oxy-Hb concentration change in the DLPFC when riding around a sharp bend on a Scooter. Formatting is the same as Fig. 4.

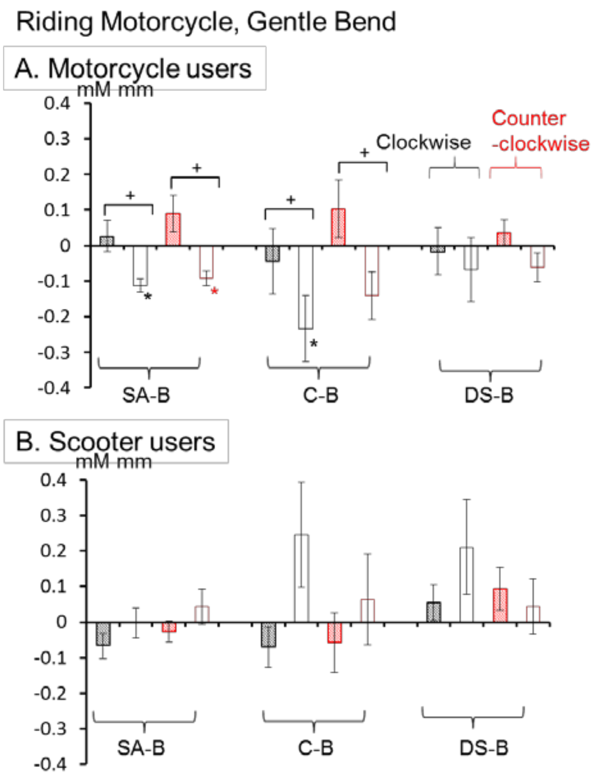

Fig. 6 Mean oxy-Hb concentration change in the DLPFC when riding around a gentle bend on a Motorcycle. Formatting is the same as Fig. 4.

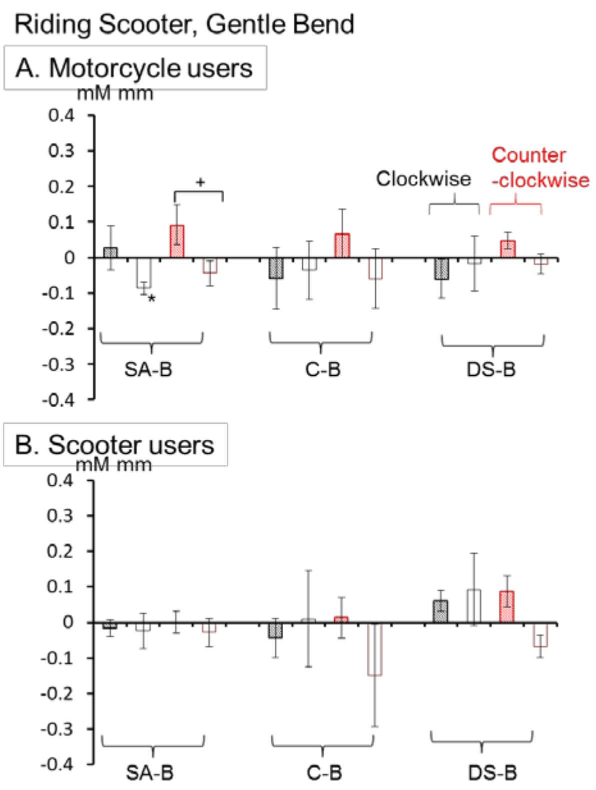

Fig. 7 Mean oxy-Hb concentration change in the DLPFC when riding around a gentle bend on a Scooter. Formatting is the same as Fig. 4.

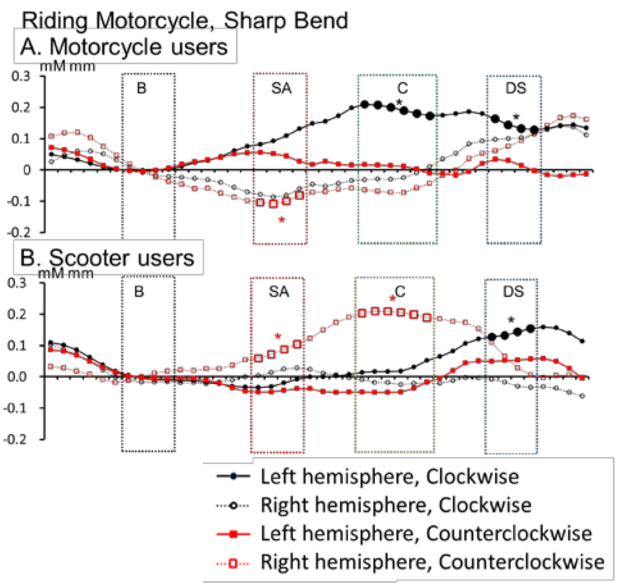

Fig. 8 Time courses of mean oxy-Hb change in the DLPFC when riding around a sharp bend on a Motorcycle. Mean oxy-Hb change during B was normalized to 0. The time course of each subject's data was fixed to the same schedule using linear interpolation to visualize and compare general trends. The vertical axis represents mean concentration of oxy-Hb in mM mm, and the horizontal axis represents time in s, which is the same as Fig. 3. Lines and dotted lines indicate left and right hemispheres, and black circles and red squares indicate clockwise and counterclockwise directions. * and larger marks indicate statistically significant activations compared against B.

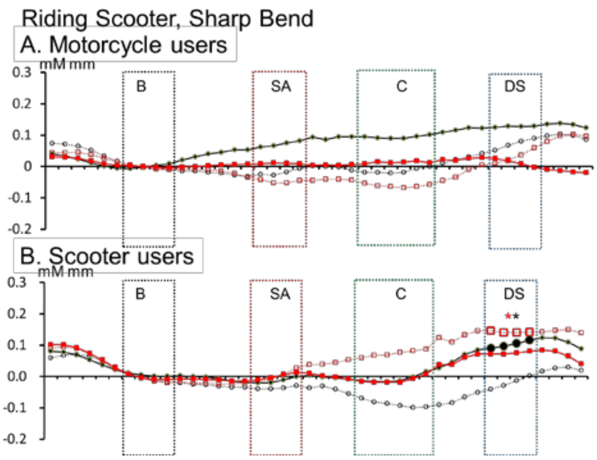

Fig. 9 Time courses of mean oxy-Hb change in the DLPFC when riding around a sharp bend on a Scooter. Formatting is the same as Fig. 8.

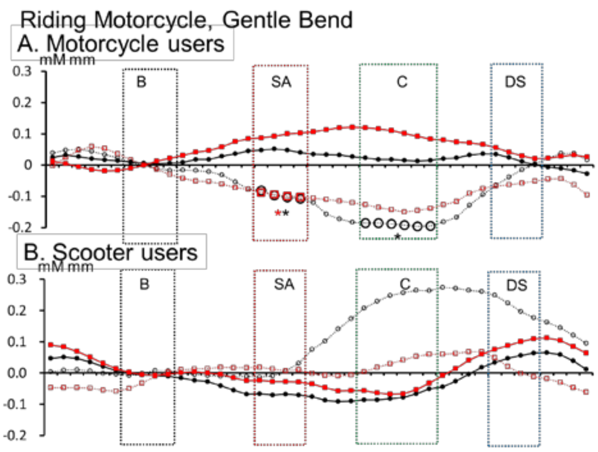

Fig. 10 Time courses of mean oxy-Hb change in the DLPFC when riding around a gentle bend on a Motorcycle. Formatting is the same as Fig. 8.

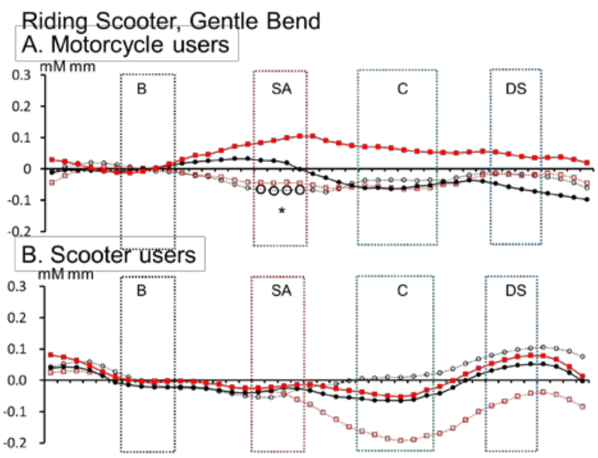

Fig. 11 Time courses of mean oxy-Hb change in the DLPFC when riding around a gentle bend on a Scooter. Formatting is the same as Fig. 8.

4. Discussion

This is the first study that has demonstrated cortical activity while motorcycles were actually being ridden. The striking findings are as follows; 1) the Motorcycle users activated the left DLPFC while riding sharp bends clockwise on a Motorcycle, 2) the Motorcycle users deactivated the right DLPFC while riding gentle bends clockwise on a Motorcycle, 3) the Scooter users activated the right DLPFC while riding sharp bends counterclockwise on a Scooter, and 4) when a Motorcycle was ridden, the activation patterns between the Motorcycle and Scooter groups were different.

4.1. Lateralization of activation

In this study, we found that the lateralization pattern of DLPFC activation was different between Motorcycle and Scooter users. Left lateralization, which occurs when activity of the left DLPFC is significantly larger than that of the right DLPFC, was only observed in the Motorcycle users (Fig. 8 clearly shows this lateralization pattern). Left lateralization of the DLPFC is often related to verbal tasks requiring executive processing [(13)]. The Motorcycle users may be considering how to handle a motorcycle in a logical and/or verbal manner. In contrast, right lateralized activity (right > left) was only observed in the Scooter users. It has been argued that executive demand increases right lateralization in the DLPFC for spatial working memory processing [(12)]. Therefore, the Scooter users may handle motorcycles in a visual and/or non-verbal manner. To our knowledge, this is the first study that has shown the possible differences in the cognitive strategies used for riding motorcycles by comparing Motorcycle and Scooter users. As mentioned in the Introduction section, individual differences in the primary purpose behind the use of the motorcycles may contribute to those differences. Further investigation is needed to reveal the cognitive mechanisms which caused the differences in lateralization.

4.2. Deactivation of the right DLPFC

Statistically significant deactivation of the right DLPFC was found only in Motorcycle users while they rode the gentle bend. In this study, all subjects increased their speed while riding the gentle bend versus the sharp bend. Previous neuroimaging studies indicated that the right DLPFC may be particularly critical for regulating risk-taking behavior [(14-16)]. Knoch et al. [(17)] applied low-frequency, repetitive transcranial magnetic stimulation to transiently disrupt left or right DLPFC functions and found significantly riskier decision-making after disruption of the right, but not the left, DLPFC. They concluded that in real-life scenarios the higher the activity of the right DLPFC, the lower one's appetite for risk. The results of these studies combined with the results of the present study led to a hypothesis that Motorcycle users, but not Scooter users, tend to be risk-takers when driving motorcycles. This argument is somewhat in line with the general view that motorcyclists take greater risks than car drivers [(18)]. Because most of the subjects of this study were middle-aged, the risky behavior cannot be attributed to youth and it is probably related to sport motives (dynamic aspects, performance, thrill, and rivalry).

4.3. Difference between riding Motorcycles and Scooters

Brain activities while riding Scooters were relatively smaller than while riding Motorcycles in both groups. Due to improvements in the technical standards of Scooters, braking performance, stability, and handling have reached a level which is not far from Motorcycles [(19)]. Therefore, the significant difference between the vehicles in this study could be the transmission: whether they were manual or automatic. There is no doubt that driving a motorcycle with manual transmission requires riders to have fine control over the accelerator as well as the clutch. So the higher brain activity seen when a Motorcycle was ridden may be related to the higher cognitive and motor demands needed to control a vehicle with manual transmission. In other words, the Scooter with automatic transmission may have been easier to handle than the Motorcycle with manual transmission. Thus subjects may not have relied as heavily on their DLPFC while riding the Scooter.

4.4. Brain activity during the bend

In this study, brain activities during the gentle bend were relatively small compared with those during the sharp bend. The difference is probably related to differences in cognitive and motor demands. Curving around the sharp bend of course requires finer handling than the gentle bend.

The difference between brain activation during the clockwise and counterclockwise curving observed in this study is somewhat unexpected to us. In this study, the left DLPFC was significantly activated when Motorcycle users drove clockwise around a sharp bend on a Motorcycle. The difference in brain activity compared to when driving counterclockwise around a bend reached marginally significant levels ($p = 0.089$). In Japan as in the UK, vehicles are driven on the left-hand side of the road making drivers, including motorcycle riders, more familiar with sharp left (counterclockwise) than with sharp right (clockwise) turns. So the significant activation during clockwise curves, but not during counterclockwise curves, may also be due to the difference in cognitive and motor demands. Nevertheless, in the current study, Scooter users activated the right DLPFC when driving counterclockwise curves. As we discussed, cognitive strategies for driving motorcycles may well be different for Motorcycle and Scooter users. However, we could not find any possible cognitive or physical mechanisms explaining this counterclockwise-dominant brain activity in the Scooter users. Therefore, we think further investigation is needed to cralify possible mechanisms to explain the difference between brain activation between Motorcycle and Scooter.

4.5. Brain activity during deceleration and stopping

In some tasks, we found statistically significant activation during the DS period. One of the most difficult activities when handling a motorcycle was correct braking [(19)]. The motorcycle rider has to simultaneously maintain stability, prevent the wheels from locking and sliding, and calculate the shortest possible stopping distance in combination with the highest possible deceleration. Therefore, these significant activations should be related to high cognitive and motor demands while breaking.

4.6. Limitation of this study

Although, all of the subjects drove the course at least several times on the Motorcycle and on the Scooter to familiarize themselves with the vehicle, the observed brain activation pattern may be influenced by the subject's degree of familiarity with the Motorcycle/Scooter. For example, the driver's center of gravity is often higher on a Motorcycle than on a Scooter. Scooter users may experience some difficulty and/or feel anxiety when driving a Motorcycle.

Another limitation of this study was the artifacts caused by movement of the subject's head and the acceleration of the motorcycles. This is a known defect of NIRs measurements [8, 9], and may influence the results of the current study to some extent.

5. Conclusion

We measured activity of the DLPFC using NIRS while motorcycles were being ridden. We found left and right lateralized DLPFC activity for users of mid-sized on-road type motorcycles (Motorcycle) and mid-sized scooters (Scooter), respectively. Only Motorcycle users showed deactivation in their right DLPFC. The activity of the DLPFC was larger when riding a Motorcycle than a Scooter. The results may indicate that the cognitive strategies used while riding motorcycles are different between Motorcycle and Scooter users, and that the cognitive processes for handling Motorcycles and Scooters are different as well.

6. Acknowledgements

Part of this study was supported by a cooperative research program between Tohoku University and Yamaha Motor Co., Ltd.

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