Evaluation of Driver's Brain Activity Associated with Advanced Driving Skills Such as Cornering

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(Received March 22, 2024; Accepted May 2, 2024)

Evaluating the driving ability of a vehicle is important in the development of in-vehicle systems and the training of driving skills. Driving ability has been investigated extensively in terms of recognition, judgment, and operation. However, the role of the brain in advanced driving operations within the limits of vehicle performance has not been thoroughly investigated. In this study, we perform functional magnetic resonance imaging to evaluate brain functions associated with advanced driving skills when drivers are shown a video of cornering involving a vehicle slipping sideways.

Based on the results, the skilled driver group indicates broad activity in both the right and left parietal associations, right-side primary somatosensory, left-side premotor, and supplementary motor areas. Because the premotor cortex is a region involved in the execution of movement, whereas the supplementary motor cortex is a region involved in spontaneous movement, it is assumed that the skilled drivers visualized the driving operation, and that the brain functions necessary for the operation are activated. These findings indicate that drivers with high skill levels exhibit distinctive brain activities. We believe that a further understanding regarding the brains of skilled drivers will facilitate the development of in-vehicle control that incorporates high driving skills and training.

Key words: Driving skill, Vehicle controlling, Driver's brain activity, fMRI study

INTRODUCTION

In recent years, technologies associated with autonomous driving, information, and intelligent transport systems, such as services connected to the Internet, have been developed [1-6]. Because of the further diversification of onboard technology, clarifying the driver's driving ability and developing functions that are suitable for that ability will be required in the future so that services can be offered with confidence and safety.

Studies regarding driving ability have been conducted using various methods. Examples include those that investigated differences in gaze-pointing activity. A study revealed that less experienced drivers tended to exhibit narrower gaze fixation areas and view positions that were near the front of the vehicle [7, 8]. Differences in driving ability among different age groups have been reported by examining the reaction speeds to braking of older and younger drivers [9-11]. Some studies have classified the level of driving skills by comprehensively analyzing vehicle signals and driving behavior [12, 13].

Because recognition, judgment, and operation are repeatedly performed when driving a vehicle, driving is associated closely with information processing in the brain. Therefore, revealing driving ability from the viewpoint of brain science is crucial. In a study using electroencephalogram to conduct a frequency analysis of brain waves, it was observed that the frequency band activity changed depending on the driving frequency [14]. In investigations pertaining to the event-related potential of the brain wave, differences between young and elderly drivers were observed, for example, in cognition response [15, 16]. In a study using functional near-infrared spectroscopy to investigate changes in blood flow in the brain, differences in brain activity between young and elderly drivers were observed in the frontal lobe [17, 18].

Functional magnetic resonance imaging (fMRI) can be performed to investigate brain functions in detail. Because the fMRI system is large, it cannot be placed on the board of a driving simulator or an actual vehicle, although it has a high spatial resolution and can, therefore, accurately identify brain activity areas. Recently, fMRI systems have been frequently used in studies pertaining to drivers' brain functions. Previous studies include brain activity evaluation pertaining

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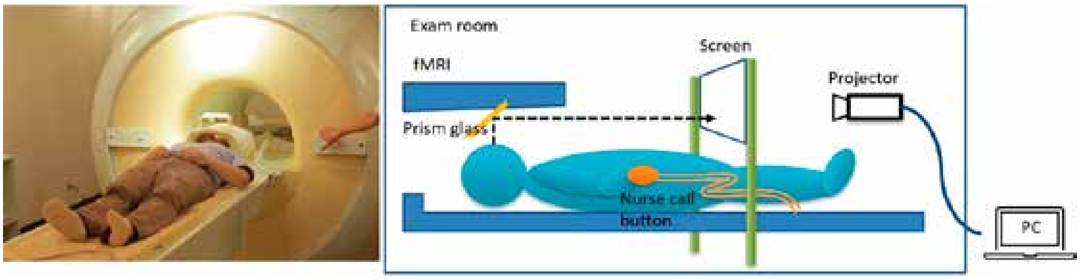

Fig. 1 Configuration of experimental equipment
The fMRI images were obtained while the participants were lying on their back inside the fMRI gantry and participants can watch task videos through a prism glass installed above the participants.

to travel scenes in different traffic environments [19, 20]. Other studies have examined the recognition and judgment required in specific driving situations, such as when entering an intersection or adjusting the safe headway distance to a preceding vehicle [21, 22]. Furthermore, in addition to driving operations, distractions were defined and their effects on drivers' brain function were evaluated [23, 24]. Finally, devices simulating the steering wheel and pedals were installed in an fMRI system for an actual operation by participants, and their effects on the driver's brain function were evaluated [25, 26]. However, the participants were lying on their backs, and the challenges for the participants when using fMRI were limited to those that can be responded to by operating simple devices functioning as button switches or imitating steering devices and pedals. In other words, these studies investigated basic brain activities pertaining to recognition, judgment, and memory. Meanwhile, studies regarding the brain's operating ability for dynamic driving have not been fully investigated.

The aim of this study was to use fMRI to extensively investigate brain functions that are associated with a driver's operating ability. In particular, we focused on high-level vehicle control skills, which have yet to be investigated in detail. Differences in the process by which the brain processes information were compared between average and skilled drivers. In the human brain, the area associated with motion becomes active in the absence of body movement if images of exercise are formed in the brain [27–31]. Therefore, the test participants were shown videos of cornering involving a vehicle slipping sideways and were instructed to visualize driving the vehicle. The brain activity of the participants was evaluated during this period. Finally, the application of brain science to vehicle development was discussed.

MATERIAL AND METHODS

Participants

The participants were openly recruited from among automaker employees. Brain functions of twenty right-handed males (mean age of 38.95 ± 11.93 years) possessing a driver's license were measured by fMRI. Based on their driving skill, the participants were divided into two groups: 12 skilled drivers (mean age of 42.41 ± 11.85 years) and 8 novice drivers (mean age of 33.7 ± 10.67 years). Skilled drivers are drivers who passed the Nissan in-house driving skill test and have experience driving at the limits of the vehicle, whereas novice drivers are drivers with no experience. The skilled drivers learned to operate the vehicle precisely and swiftly, as well as observed the limits of the vehicle such that even if the vehicle slipped, they would be able to perform the necessary braking and steering operations to adjust the orientation of the vehicle. Similar to the skilled drivers, the novice drivers were automaker employees, although they were average drivers who used their vehicles daily.

Ethics Statement

Experiments conform with the principles outlined in the Declaration of Helsinki and were conducted with the approval of the Ethical Review Board of the Tokai University School of Medicine (16R-130) and the Experimental Ethics Committee of Nissan Motor Co., Ltd. (No. 016003). The participants received a detailed explanation of the experimental procedure in writing in advance and gave their informed consent to participate in the experiments before the testing started.

Image Acquisition

A Philips MRI Ingenia 3.0T installed in Tokai University Hospital was used to brain images. The brain structure images (T1 weighted images) had 280 slices, echo time (TE) of 3 ms, Repetition Time (TR) of 3 ms, acquisition matrix of 512 × 512, voxel size of 0.469 × 0.469 × 0.75 mm, field of view (FOV) of 240 mm and flip angle (FA) of 8°. The brain function images had 13 slices, TE of 35 ms, TR of 1 s, acquisition matrix of 128 × 128, voxel size of 1.8 × 1.8 × 5 mm, FOV of 229 mm and FA of 90°.

EXPERIMENTAL DESIGN

Images of the brain structure and function were acquired with the fMRI system. Fig. 1 shows measurements with the fMRI and a configuration of experimental equipment. The images were obtained while the participants were lying on their back inside the fMRI gantry. The brain structural images were first acquired as the participants lay calmly in that posture. A prism glass installed directly above the participants was used to make visible a screen installed in the direction of their lower limbs. Videos of a vehicle being driven were shown onto the screen from a projector positioned behind the screen. The participants watched the videos and have been instructed to imagine that they themselves were driving the vehicle. A video was prepared for showing the experimental tasks on the screen. It showed a driving control task involving the

Fig. 2 Image of videos of the driving control task
Drift 1 is a screenshot of video of cornering by an expert driver taken from outside the test vehicle. Drift 2 is a screenshot of video showing an expert driver cornering as taken from the center pillar behind the driver's seat and showing the driver's operations and test course simultaneously. Straight is a screenshot of video of driving on a straight, monotonous road.

Straight1	Drift1	Straight2	Drift2	Straight3
1min	1min	1min	1min	1min

Fig. 3 Experimental block design
The videos of driving on the straight road and cornering are combined.
Each block represents a one-minute video.

use of high-level driving skill to control a vehicle.

The videos of the driving control task showed a vehicle being driven through a series of corners of different radii, with the vehicle slipping sideways (drifting) as cornering. Fig. 2 is a screenshot of video (Drift 1) taken from a high angle with a camera installed outside the vehicle that shows the movement of the vehicle while cornering. Drift 1 includes ten cornering scenes in the one minute video. Drift 2 in the figure is a screenshot of video taken with a camera installed on the center pillar behind the driver's seat. The driver's steering action was captured simultaneously with the course on which the vehicle was driven. Drift 2 includes sixteen cornering scenes in the one minute video. The driving in video Drift 1 and 2 are not exactly the same. Straight is a screenshot of video of driving at 80km/h on a monotonous, straight road for comparison. This straight road video was created with computer graphics to provide images only of the driver's driving operations by removing any information that might attract the participants' attention. Fig. 3 is an experimental block design of the order in which the videos were presented. The videos were presented consecutively for a total of five minutes, with each one being shown for one minute.

Before the start of the test, the participants were shown the screenshots of the videos and explained them and the procedure of the test. The participants were instructed to lie on their backs inside the fMRI gantry and adjust the view of the screen by changing the position of the prism glass installed directly above the participants. Next, the lights inside the room were turned off, and the participants were instructed to be calm for approximately five minutes. The tests were started after confirming that the participants had become accustomed to the environment inside the gantry. At the beginning of the test, the participants were instructed as follows. "A video of a driven vehicle will be played, and the scene will change each minute. The duration will be five minutes. Please watch the video and imagine that you are driving the vehicle in each scene. Please do not move your body and head during the measurements."

After the test, participants were asked whether they could imagine themselves driving by watching task video.

FUNCTIONAL DATA PROCESSING

Brain activities are identified based on the blood oxygenation level dependent (BOLD) with fMRI [32]. The images acquired with fMRI were processed using SPM12 statistical software [33] that runs in Matlab R2017b (The Mathworks Inc.). The brain structure images were aligned so that they were parallel to the

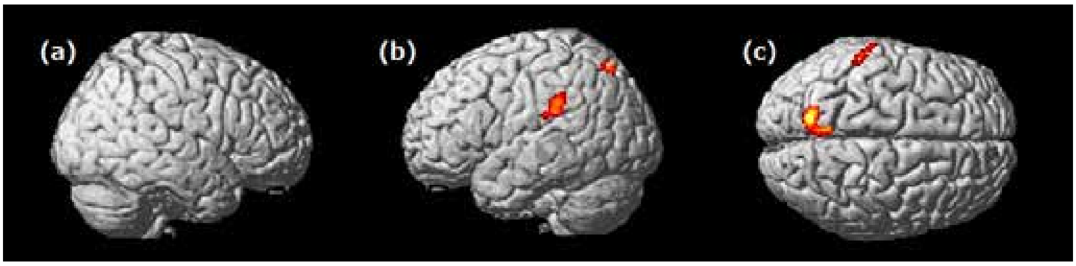

Fig. 4 Areas of brain activity during the cornering video for the novice driver group (Drift 1 − Straight 1 + Drift 2 − Straight 2).
(a), (b) present temporal lobe right and left side respectively, (c) shows the parietal lobe.

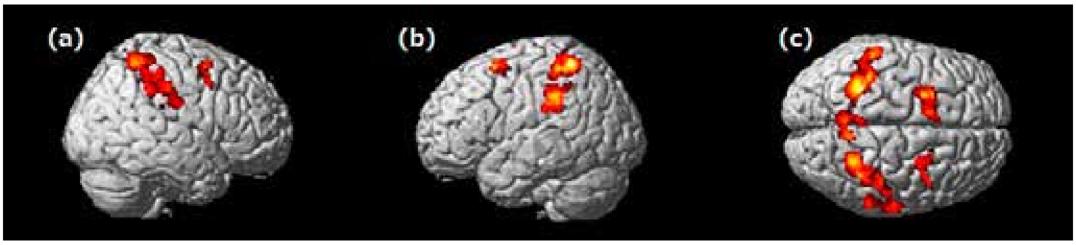

Fig. 5 Areas of brain activity during the cornering video for the skilled driver group (Drift 1 − Straight 1 + Drift 2 − Straight 2).
(a), (b) present temporal lobe right and left side respectively, (c) shows the parietal lobe.

Table 1 Novice driver group

Number of voxels	p(FWE-corr)	MNI coordinates (mm)			Side	Region
		x	y	z		
267	0.003	-28	-42	34	L	Superior parietal lobule
255	0.003	-6	-62	62	L	Precuneus
144	0.036	-56	-36	32	L	Supramarginal gyrus

Table 2 Skilled driver group

Number of voxels	p(FWE-corr)	MNI coordinates (mm)			Side	Region
		x	y	z		
1259	0.000	-48	-38	32	L	Supramarginal gyrus
331	0.006	-24	10	58	L	Superior frontal gyrus
1108	0.000	40	-40	44	R	Supramarginal gyrus
357	0.004	6	-58	68	R	Superior parietal lobule
186	0.046	28	6	58	R	Superior frontal gyrus

anterior commissure-posterior commissure (AC-PC) line. The brain function images were pre-processed for realignment based on body movement and slice timing. The brain structure and function images of each participant were coregistered. In addition, the images were normalized to the standard brain defined by the Montreal Neurological Institute (MNI). A 6 mm full width at half maximum (FWHM) Gaussian filter was used for smoothing.

The contrast of the functional image was compared between the task blocks. The statistical design matrix for the driving control task was based the difference found by subtracting from the drift driving video presentation block the straight driving video presentation block preceding it. That is, Drift 1 − Straight 1 + Drift 2 − Straight 2 in Fig. 3. Statistical analysis was performed based on a general linier model [33]. First, statistical estimates were calculated by individual analysis for every participant. The significant areas of brain activity were then extracted by a group analysis. Age was treated as nuisance variable. For the cluster-level inference, cluster forming threshold of uncorrected p-value < 0.001 was employed. Then, clusters were considered as significant when falling below a cluster corrected familywise error rate (cluster-level FWE-corr) of p-value = 0.05. Next, the areas of brain activity were identified by superimposing the acquired images on the MNI standard brain.

RESULTS

A group analysis was performed for both the novice driver group and the skilled driver group to extract the areas of significant brain activity (cluster-level FWE-corr of p-value < 0.05). The results obtained are shown in Fig. 4 and 5 for the cornering video (Drift). In addition, Tables 1 and 2 show the MNI coordinates, brain area designations, number of voxels and the p-value (cluster-level FWE-corr) for the novice driver group and the skilled driver group, respectively. The results indicate that the novice driver group showed significant activity in the left-side parietal association area. The skilled driver group showed significant activity on both sides of the parietal association area and in the right-side primary somatosensory area and both sides of premotor area and in part of the left-side supplementary motor area. Overall, the skilled driver group showed brain activity over a wider area than the novice driver group.

Regarding the quality of participants' imagination, all skilled drivers reported that they were able to imagine themselves actually driving by watching task video. But some novice drivers said it was difficult for them to imagine that.

DISCUSSION

In the driving control task, it was observed that the novice driver group showed significant activity in the left-side parietal association area. The skilled driver group showed broad activity on both the right and left sides of the parietal association area as well as activity in the right-side primary somatosensory area and in the left-side premotor area and supplementary motor area. Presumably, activity in the parietal association area was indicative of the processing of visual information in the videos by the participants [34]. For the skilled driver group in particular, the broad activity that extended from the parietal association area on both sides and also to the primary somatosensory area probably represented processing for spatial recognition in the driving control task. In a cornering situation involving a series of consecutive corners where the vehicle speed is rising and the rear wheels are slipping sideways because the gripping force of the tires is exceeded, drivers must be aware of both the line the vehicle is tracing and the vehicle width. Moreover, drivers must also have the ability to accurately perceive their own position in space because of the differences in the direction of travel and in the vehicle's orientation (yaw angle). Therefore, one can assume that whether or not drivers can construct a clear mental image of the space in which the vehicle is traveling, strongly affects driving stability.

The skilled driver group also displayed activity in the premotor area and supplementary motor area. It is reported that the premotor area is related to the execution of movement and that the supplementary motor area is related to spontaneous movement, coordinated movement of the hands and feet and the order of actions [35–37]. Driving operations require simultaneous operation of the steering wheel and pedals and awareness of the order of operations involved in cornering such as deceleration, steering and acceleration for slow-in, fast-out driving behavior. It is inferred that the skilled driver group created a mental image of the optimal actions of the hands and feet as they watched the videos. In contrast to that, the parietal association area activity of the novice driver group was displayed on the left side only, so their spatial image may have been narrower. In addition, they displayed only slight activity in their left-side primary motor area. Although they may have created a simple mental image of driving operations, the fact that activity was not observed in the premotor area and supplementary motor area suggests that they did not create a good mental image of the high-level driving operations required for cornering involving side-slipping.

There is a clear difference in the ability of the novice driver group and the skilled driver group to execute driving operations at the limits of vehicle performance. Presumably, the results of the driving control task were greatly influenced by spatial recognition ability and the ability to form mental images of the procedure and how to execute high-level driving operations.

Generally, humans have limited resources for processing information [38, 39]. As the learning level increases, information processing in the brain becomes more efficient, resulting in a narrower area in which the brain becomes active [40, 41]. In previous studies conducted on athletes and musicians with specific abilities, the brain area associated with motion and operations became active in the specialist group, whereas activity was suppressed in the novice group [42–45]. These studies show that within complex brain mechanisms, the brain may or may not function efficiently.

The brain activity state obtained in this study shows that the active brain regions of the skilled drivers were larger than the less active regions of the novice drivers. When the surrounding environment must be assessed continuously (such as when high-level driving on corners), the skilled drivers will be alert to critical factors, such as the line that the vehicle is tracing and the vehicle orientation. Additionally, they will likely visualize images of the operation based on the situation. By contrast, novice drivers are likely to be unaware of the line in which the vehicle is tracing and the vehicle orientation. Hence, it was inferred that when the skilled drivers watched the video, the essential functions in their brains were activated, instead of the more efficient information processing by their brains. Therefore, the results indicate that the broad activity areas exhibited in the parietal association as well as premotor and supplementary motor areas of the brain characterized drivers with a high level of driving skill. Furthermore, the ability to visualize vehicle operation based on situation is associated with driving ability.

The results obtained in this study concerning the characteristics of brain activity are expected to provide clues for understanding the ways in which drivers acquire driving skill and the type of skill needed by beginning drivers. We intend to draw upon these results as helpful hints for developing enable applications, such as efficiently learning or recovering the insufficient ability of new drivers and the declining ability of elderly drivers. Further understanding of the driving ability can also enable to design appropriate driving assistance control according to the driver's ability level in the future vehicle.

It is necessary to note that the results of this study were obtained under limited conditions. The test participants were male, right-handed automaker employees. Furthermore, there is a small sample size and the data of skilled driver is more abundant than that for novice, leading to a numerical bias, and that the fMRI data is not collected under actual driving. Based on the findings of this study, it is necessary to broaden the range of test participants to ordinary drivers in future studies and further accumulate verification results under detailed and controlled test conditions.

CONCLUSION

This paper presented the results of an investigation concerning the states of brain activity related to driving on corners, focusing on driving skill that is one of the attributes of drivers. The results revealed that a skilled driver group showed significant brain activity in areas related to motor control and confirmed that they formed good mental images of driving operations for high-level driving performance in a cornering situation involving side-slipping by the rear wheels. The results suggest that the broad area of activity displayed in the parietal association area and activity in the premotor and supplementary motor areas of the brain characterize drivers who have acquired a high level of driving skill.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Eiichiro Nagata: Conceptualization, Writing - review & editing, Supervision, Project administration. Toshiyuki Shimizu: Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft, Visualization. Gheorghe Lucian: Conceptualization, Writing - review & editing, Project administration. Tomohiro Horie: Methodology, Investigation. Susumu Takano: Methodology, Investigation. Munetaka Haida: Conceptualization, Writing - review & editing, Supervision, Project administration. Nanako Amamoto: Writing - review & editing.

DECLARATION OF COMPETING INTEREST

This study was a collaboration of Nissan Motor Co., Ltd. and Tokai University. The research expense was paid from Nissan Motor Co., Ltd. to Tokai University. Toshiyuki Shimizu, Gheorghe A. Lucian and Nanako Amamoto are employed by Nissan Motor Co., Ltd. The authors declare that there is no competing interest regarding the publication of this paper.

ACKNOWLEDGMENTS

The fMRI was provided by Department of Radiology Clinical Technology Division, Tokai University.

We thank Prof. Niwa for their assistance in data collection and a fruitful discussion.

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