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博 士 論 文

**Frontal lobe activity during simulated driving :
Differences between healthy individuals and individuals
with brain damage**

(運転シミュレータにおける前頭葉の活動について

—健康者と脳損傷者の違いについて—)

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Frontal lobe activity during simulated driving

— Differences between healthy individuals and individuals with brain damage—

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Abstract

Aims: This study aimed to analyze frontal lobe activity in healthy individuals and individuals with brain damage as they simulate driving (i.e., making a left turn [LT], making a right turn [RT], and changing lanes).

Methods: Twenty-six healthy individuals and 19 patients with brain damage were included in the analysis. Frontal lobe activity was analyzed with functional near-infrared spectroscopy using the Driving Simulator for Brain Activity Measurement, a version of the Driving Simulator for safe driving education. Elements, such as pedestrians and oncoming cars, were added to the driving situations, which consisted of LTs, RTs, and lane changes (LCs).

Results: Frontal lobe activity increased when individuals in the healthy group encountered situations such as LTs, RTs, pedestrians, and oncoming cars. In patients, frontal lobe activation was not observed during a LT, RT, or LC.

Discussion: Activity of the frontal lobe increased in the presence of pedestrians and oncoming cars in addition to simple driving in the healthy group, likely as an effect of the dual-tasking required in directing attention to pedestrians or oncoming cars. In the patient group, there were no significant frontal lobe activation may have been affected by declined attention while multi-tasking.

Keywords

frontal lobe activation, attention, driving simulator, traumatic brain injury

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Introduction

Cognitive functions are important when driving automobiles. Based on neuropsychological findings, Reger et al.¹⁾ reported that the necessary cognitive functions associated with driving are attention and visual perception. Thus, patients who manifest an attention disorder due to brain damage are often prohibited from driving, which hinders their ability to recover socially. There have been recent developments in rehabilitation programs to allow these patients to start driving again. The driving rehabilitation specialist certification held by physicians and occupational therapists in the United States helps patients with cognitive function disorders recover their ability to drive²⁾. However, in Japan, there are no regulations for therapists specialized in this type of rehabilitation, and a clear rehabilitation program for driving has not been established.

The frontal lobe is essential for supporting attention-related functions required for driving. Walter et al.³⁾ reported activation in motor areas and the cerebellum when analyzing brain activity, using functional magnetic resonance imaging (fMRI), in subjects visualizing driving. Schweizer et al.⁴⁾ analyzed brain activity with fMRI while individuals viewed a video of driving and reported significantly increased activity in the ventrolateral prefrontal area in the presence of noxious stimuli—a result, they explained, largely associated with attention and executive function. Therefore, frontal lobe attention-related function is essential when driving. Thus, knowledge of the types of situations that effectively activate the frontal lobe during driving can be conducive to driving rehabilitation. However, in previous studies, participants did not actually drive during fMRI testing; therefore, it is difficult to assess associated brain activity as a result of genuine driving. Moreover, these studies were conducted on healthy individuals rather than patients with actual attention function disorders. Hence, this study aimed to investigate prefrontal lobe activity using fMRI, one of the modalities for assessing brain function, on patients with cognitive function disorders—many with attention disorders—who have been prohibited from driving. Functional near-infrared spectroscopy (fNIRS) is a device that irradiates the scalp with near-infrared light at wavelengths around 800 nm, and then uses a personal computer to create an image out of the reflected light. The image obtained from changes in this reflected light reflects blood flow volume, blood volume, and oxygenated hemoglobin (OxyHb) levels in the cerebral cortex, 2-3 cm under the scalp, which is interpreted as the amount of brain activity. A disadvantage of fNIRS is its poorer spatial resolution than that of fMRI, magnetoencephalography, and other techniques, which makes it difficult to evaluate deeper parts of the brain. However, the device can be worn while driving, the equipment is inexpensive, and its maintenance costs are low. Much previous research on driving used fMRI, which requires a fixed body position during the measurements, which does not accurately represent the conditions of actual driving; thus, this technique is considered unsuitable for measuring patient brain activity during driving in clinical settings. Therefore, we selected fNIRS to carry out this study.

A Driving Simulator (DS) was used in this study as a tool to assess driving and treatment. A DS is a close approximation of driving an actual car, while ensuring higher levels of safety than if we were to conduct

the test with an actual car⁵). The Driving Simulator for Brain Activity Measurement (DSBAM), partially adapted for the purposes of this study and based on the Safety Driving Educational DS of Matsunaga and Goshi et al.⁶), was used on healthy individuals who drive regularly and individuals with brain damage who have been prohibited from driving by their physicians due to an attention disorder. Furthermore, individuals wore a functional near-infrared spectroscopy on their heads while using the DS to analyze frontal lobe activity during simulated driving situations, such as a left turn (LT), right turn (RT), and a lane change (LC).

Methods

Participants

This study was approved by the ethics committee of the Kobe University Graduate School of Health Sciences (ethics number 204). All individuals gave their written informed consent prior to study participation. All participants had driver's licenses and driving experience. Patients who had diseases or motor function disorders that may affect their driving behaviors in other ways were excluded.

Individuals were included if they met the following eligibility criteria: 1) had autonomy in daily activities, 2) had bilateral injuries or a diffuse axonal injury of the frontal lobe, and 3) were prohibited from driving due to higher brain dysfunction despite wishes to restart driving.

Twenty-six healthy individuals (13 men, 13 women, mean age 47 ± 15 years: hereafter, the healthy group) and 19 individuals with craniocerebral trauma (13 men, 6 women, mean age 48 ± 11 years, mean disease duration 88 ± 93 months; hereafter, the patient group) were included in the study. There were no differences in age and sex between the 2 groups.

All participants in the patient group presented with an attention disorder, while some also presented with a memory disorder and executive function disorder (EFD) (Table 1). All patients had not driven since the onset of their functional disorders. Prior to injury, all individuals had driven at least once without any major incidents.

Table 2 displays neuropsychological testing results. To screen for attention-related disorders, participants performed the Simple Reaction Time (SRT) task from the Continuous Performance Test, Trail making test A (TMT-A), and Trail making test B (TMT-B). All patients scored below the standard values, confirming the presence of an attention disorder. Patient TMT scores were significantly different from the healthy group (Table 2).

Table 1. Patient demographics

Patient number	Age (years)	Male / Female	Main symptom	Time since symptom onset (months)	Other brain dysfunction
<i>P1</i>	58	<i>Male</i>	<i>HE</i>	48	<i>memory, EFD</i>
<i>P2</i>	65	<i>Male</i>	<i>TBI</i>	72	<i>aphasia</i>
<i>P3</i>	62	<i>Male</i>	<i>TBI</i>	72	<i>memory</i>
<i>P4</i>	58	<i>Male</i>	<i>TBI</i>	65	<i>memory</i>
<i>P5</i>	64	<i>Male</i>	<i>TBI</i>	120	<i>memory, EFD</i>
<i>P6</i>	54	<i>Male</i>	<i>TBI</i>	23	<i>memory, EFD</i>
<i>P7</i>	38	<i>Male</i>	<i>TBI</i>	184	<i>memory, EFD</i>
<i>P8</i>	36	<i>Male</i>	<i>TBI</i>	45	<i>memory</i>
<i>P9</i>	48	<i>Male</i>	<i>TBI</i>	360	<i>memory</i>
<i>P10</i>	37	<i>Male</i>	<i>TBI</i>	240	
<i>P11</i>	24	<i>Male</i>	<i>TBI</i>	24	<i>memory</i>
<i>P12</i>	50	<i>Male</i>	<i>TBI</i>	24	<i>memory</i>
<i>P13</i>	55	<i>Male</i>	<i>TBI</i>	24	<i>memory</i>
<i>P14</i>	35	<i>Female</i>	<i>TBI</i>	33	
<i>P15</i>	44	<i>Female</i>	<i>TBI</i>	48	<i>memory, EFD</i>
<i>P16</i>	49	<i>Female</i>	<i>TBI</i>	96	<i>memory, EFD</i>
<i>P17</i>	39	<i>Female</i>	<i>TBI</i>	40	<i>memory, EFD</i>
<i>P18</i>	49	<i>Female</i>	<i>TBI</i>	30	<i>memory</i>
<i>P19</i>	40	<i>Female</i>	<i>TBI</i>	216	<i>memory</i>

HE: Hypoxic encephalopathy; TBI: Traumatic Brain Injury; EFD: Executive function disorders.

Note: Thirteen men and 6 women, with a mean age of 48 ± 11 years and a mean disease duration 88 ± 93 months, were included in the study. Attention disorders were found in all cases. Memory disorders were found in 15 of the 19 patients. Executive function disorders were found in 7 of the 19 patients.

Table 2. Results of neuropsychological testing for an attention disorder

	Controls	Patients	<i>p</i> -value
SRT (Reaction time) (s)	<i>306 ± 71</i>	<i>346 ± 88</i>	<i>0.13</i>
TMT-A (s)	<i>38 ± 12</i>	<i>105 ± 38</i>	<i>< 0.05</i>
TMT-B (s)	<i>74 ± 31</i>	<i>142 ± 66</i>	<i>< 0.05</i>

SRT: Simple Reaction Time; TMT-A: Trail making test A; TMT-B: Trail making test B.

Note: A significant difference was found between TMT-A and B scores. A marked attention disorder was found in the patient group and was present in all patients. Scores are presented as mean $\pm$ standard deviation.

Driving simulator and driving tasks

The following equipment was used for testing. The hardware consisted of a computer, 3 screens (screen size: 473×296 mm), and a steering-wheel type controller (Logicool, Driving Force GT, Logitech International S.A, Romanel-sur-Morges, Switzerland). The software used was an adapted version of the DSBAM developed by Matsunaga and Goshi et al. (Fig. 1).

The simulated test drive, driven under Japanese traffic laws, was on a road with 2 lanes per side under a 60 km/h speed limit (displayed on street signs) for approximately 20 min, corresponding to a distance of approximately 15 km.



Figure 1. A depiction of the Driving Simulator

A total of 8 on-the-road situations were programmed to appear in the simulation. These included a simple LT, a pedestrian crossing the street on an LT (LT + Pedestrian: LTP), a simple RT, a pedestrian on an RT (RT + Pedestrian: RTP), an RT plus a pedestrian and an oncoming car (RTPO), an LC while driving in a lane, an LC with a car driving at 60 km/h in the passing lane (LC60), and an LC with a car driving at 80 km/h in the passing lane (LC80). Two trials in which each of the 8 situations appear in random order through the entire simulation were created. Trials were programmed such that each task could be performed twice. When required to execute LTs, RTs, or LCs, the participants were instructed with a verbal cue (Fig. 2).

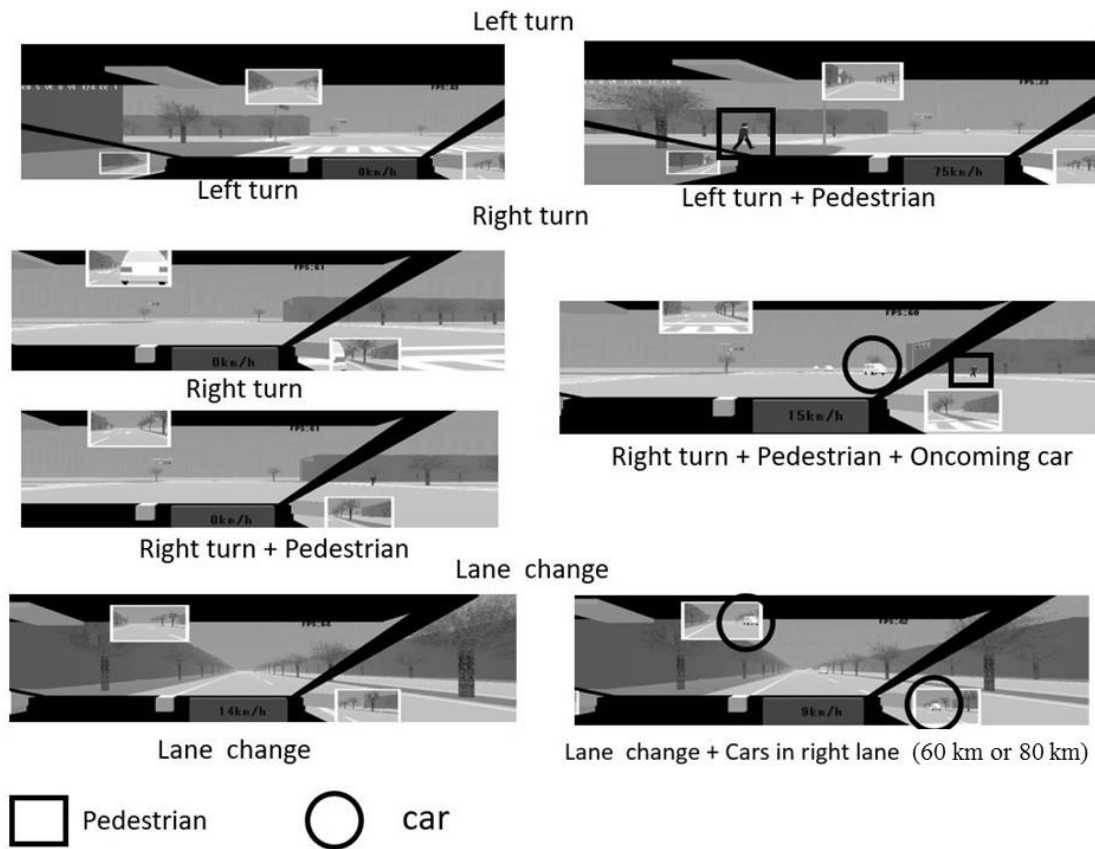


Figure 2. A depiction of the tasks programmed on the Driving Simulator

Note: From top to bottom: left turn, right turn, and lane change situations.

Frontal lobe activation

A portable fNIRS system (OEG-16, Spectratech Inc., Yokohama, Japan) was used to measure changes in cerebral hemodynamics. Probes were positioned so that the central probe in the lowest row corresponded to the Fpz site in the International 10-20 method used for electroencephalography. A 2×8 holder was installed so that measurements could be taken on a total of 16 channels. Infrared spectroscopy was measured at a 6.1 Hz sampling frequency and OxyHb levels were measured as the best parameter for reflecting brain activity (Fig. 3).

Frontal lobe activity during a driving simulation of a 300 m straight line for 1 out of 2 km during the start of the DS was recorded as the baseline value. The mean OxyHb value recorded during the 2 rounds of the LT, RT, and LC situations were compared between healthy individuals and patients. OxyHb levels in the first half until completion of the first round of each situation, and in the second half until completion of the second round of each situation, were compared within groups. Frontal lobe activity during the LT was measured from 5 m before entering the intersection to 5 m after the LT. The RT was similarly measured from 5 m before entering the intersection to 5 m after the turn. Frontal lobe activity during the LC was measured from when participants were instructed to make the LC until the vehicle completely entered the

passing lane.

SPSS version 21 (SPSS Inc., Chicago, IL, USA) was used for statistical analysis. Normality was checked with the F test while the one-way analysis of variance and Bonferroni method of multiple comparison were both used to compare OxyHb levels at baseline and the 2 rounds of LT, RT, and LC. The paired t-test was used to compare OxyHb levels in the first and second half on each channel. A p -value < 0.05 was considered statistically significant.

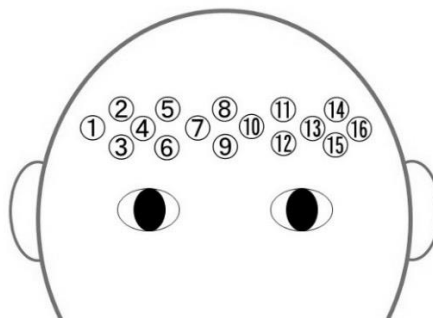


Figure 3. Channel positions in the functional near-infrared spectroscopy (fNIRS)

Implementation procedure

All participants performed the SRT (TMT—A and B tasks), after which they performed a practice run on the DS. The practice run was intended to allow individuals to perform the LT, RT, and LC maneuvers without pedestrians or other cars and to confirm that there were no difficulties driving via the DS, such as simulator-sickness. Participants were fitted with fNIRS probes after completing the practice drives. Before the main drive, the tester checked the participants' state of health and informed them not to exceed 60 km/h, to follow traffic laws, to generally drive in the slow lane, and to inform the tester if they did not feel well.

The DS session was discontinued in the event of repeated accidents in which it was predicted that the driving task could not be completed, or if participants did not feel well due to simulator sickness, etc.

Results

Driving simulator outcomes

All individuals in the healthy group completed the full drive without accidents or other incidents. In the patient group, 2 individuals (patient 17 and 19), who repeatedly had accidents during the practice drive, indicating that they found the task too difficult to perform, were excluded from the study as they did not participate in the main drive. One of these excluded individuals repeatedly drove toward the right side and had accidents and was unable to continue further down the course; the other excluded patient repeatedly made erroneous turns in the wrong direction and could no longer follow instructions. Therefore, the frontal lobe activity of 17 patients who were capable of completing the full test was analyzed.

Frontal lobe activity: Healthy individuals

Left turn: Healthy group

The frontal lobe activity during the 300 m drive at the start of the LT and LTP situations were compared to baseline values in healthy individuals. Frontal lobe activity increased significantly in 15 of 16 channels (with the exception of channel 14) in the LTP and LT situations compared to baseline. Further, the activity increased in all channels in the right hemisphere (channels 1–7), while it did not increase in channel 14 in the left hemisphere (channels 10–16) (Fig. 4).

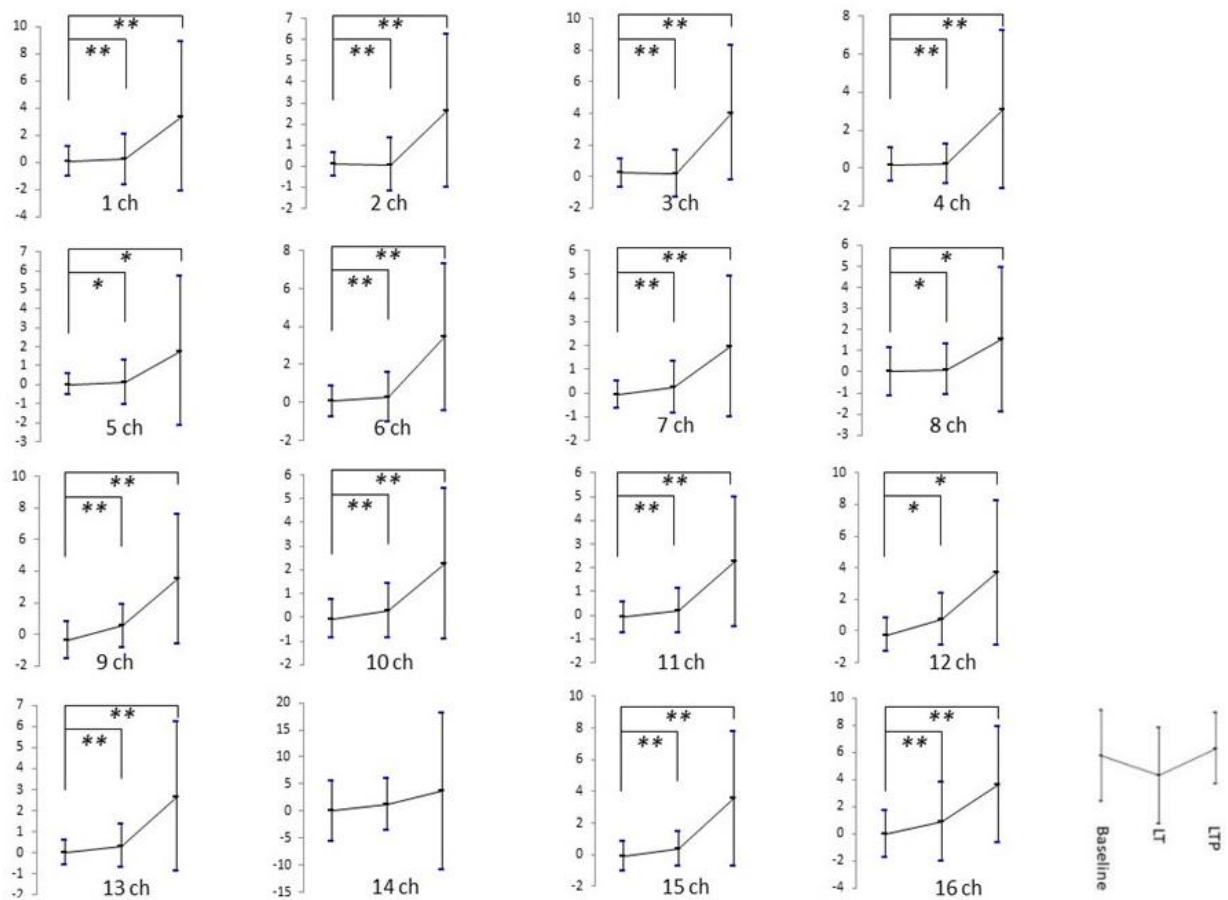


Figure 4. Frontal lobe activity in the LT simulation: Healthy individuals (units: mmol/mm, * $p < 0.05$, ** $p < 0.01$).

Note: Significant differences were found between baseline and LT, and between baseline and LTP, with the exception of 14 ch. LT, left turn; LTP, left turn with a pedestrian; ch, channel.

Right turn: Healthy group

Likewise, RT, RTP, and RTPO situations were compared to baseline to examine the effects of an RT. Frontal lobe activity increased in 12 of the 16 channels in RTPO compared to baseline (channels 1-10, 12, 13, 15, and 16) ($p < 0.05$). Furthermore, significant differences were found in 5 of 15 channels (channels 1,

3, 4, 12, and 13) ($p < 0.05$) in RTP situation and in 7 out of 16 channels in RTPO situations (channels 1, 3, 4, 8, 12, 13, and 15) ($p < 0.05$). Frontal lobe activity increased with an increased need to pay attention to multiple objects, as in the case with RTPO situations. Further, activity increased in all channels in the right hemisphere (channels 1, 2, 3, 4, 5, 6, and 7), while it did not increase in some channels in the left hemisphere (channels 10, 12, 13, 15, and 16) (Fig. 5).

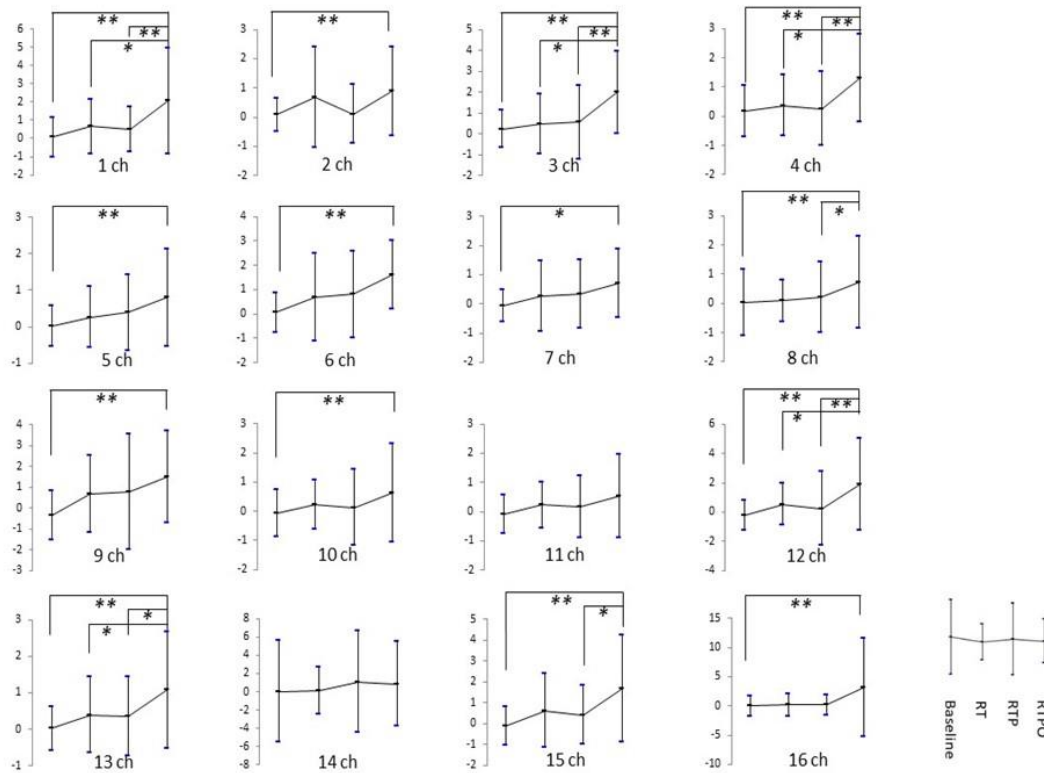


Figure 5. Frontal lobe activity in RT situations: Healthy individuals (units: mmol/mm, * $p < 0.05$, ** $p < 0.01$).

Note: Significant differences were found in channels 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 13, 15, and 16 during an RTPO situation compared to baseline. Significant differences were found between channels 1, 3, 4, 12, and 13 during RT and RTPO situations. Significant differences were found between channels 1, 3, 4, 8, 12, 13, and 15 during RTP and RTPO situations. RT, right turn; ch, channel; RTP, RT + Pedestrian; RTPO, RT + pedestrian and an oncoming car.

Lane change: Healthy group

LC60 and LC80 were compared to baseline values to investigate the effects of an LC. Significant differences were found in channel 3 between baseline and an LC, and in channel 10 between baseline and an LC60 (Fig. 6).

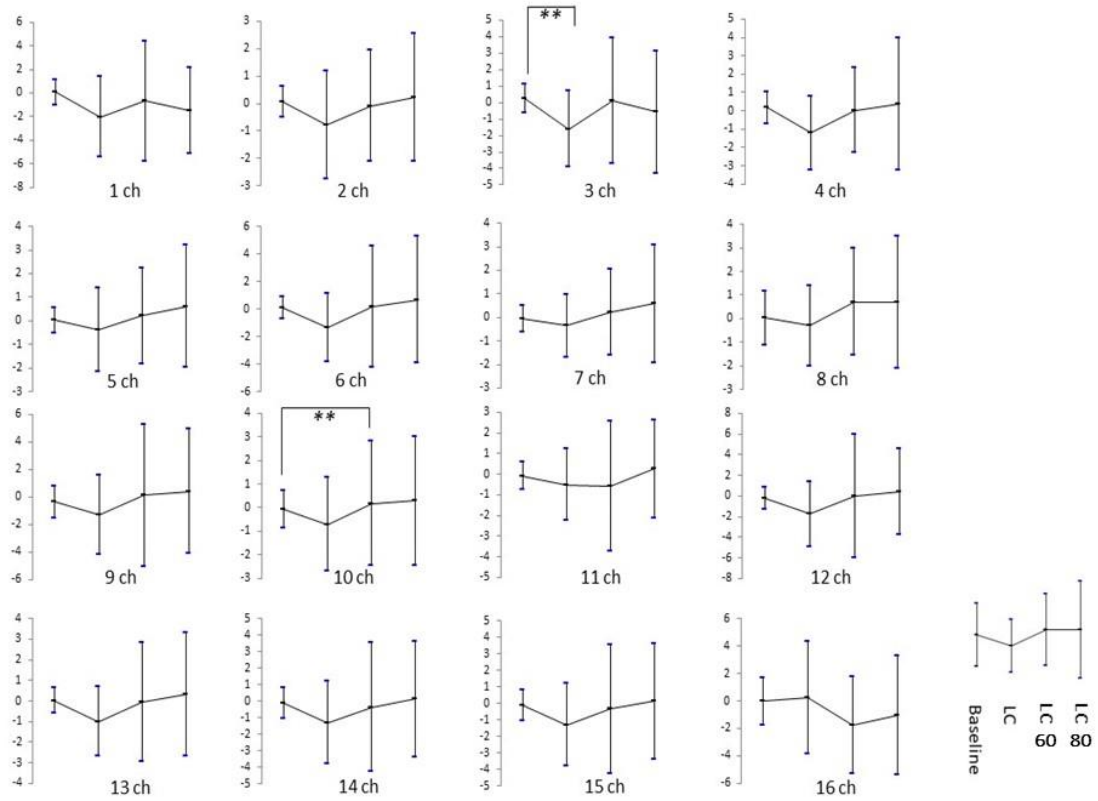


Figure 6. Frontal lobe activity in lane changes: Healthy individuals (units: mmol/mm, * $p < 0.05$, ** $p < 0.01$).

Note: Significant differences were found in channel 3 between baseline and an LC. Significant differences were found in channel 10 between baseline and an LC60. LC, lane change; LC60, LC with a car driving at 60 km/h in the passing lane; LC80, LC with a car driving at 80 km/h in the passing lane; ch, channel.

Frontal lobe activity: Patients

Regarding LT situations, there was a significant difference in channel 2 between baseline and LT and LTP, but there were no significant differences in the other situations. In RT situations, there were no significant differences in any situation. For LC situations, significant differences were only found in channel 16 between baseline and an LC (Figs. 7, 8, 9).

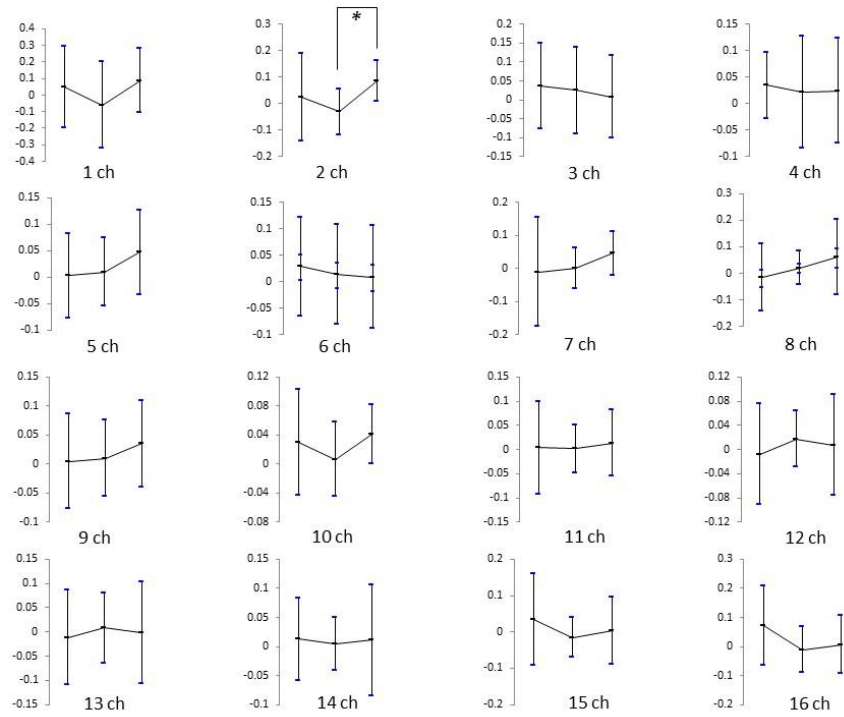


Figure 7. Frontal lobe activity during a left turn: Patients (units: mmol/mm, * $p < 0.05$).

Note: Significant differences were found in channel 2 between LT and LTP. LT, left turn; LTP, left turn with a pedestrian; ch, channel.

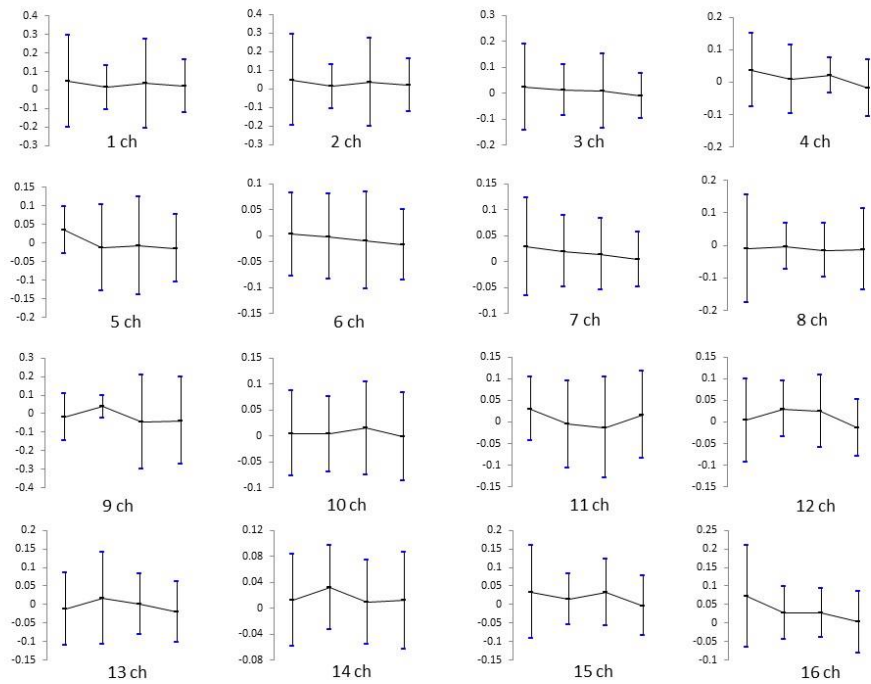


Figure 8. Frontal lobe activity during a right turn: Patients (units: mmol/mm, * $p < 0.05$).

Note: No significant differences were found in any channel. Ch; channel

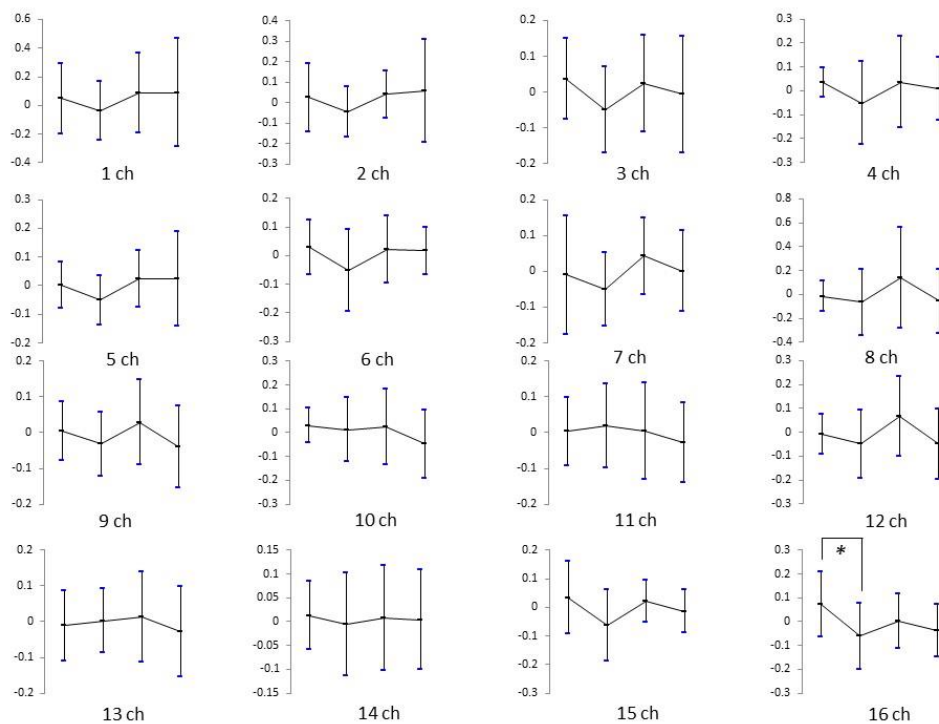


Figure 9. Frontal lobe activity during a lane change: Patients (units: mmol/mm, * $p < 0.05$)

Note: A significant difference was found in channel 16 between baseline and LC. LC, lane change; ch, channel.

Changes in frontal lobe activity during the Driving Simulator test overall: Comparison of first and second halves

There were no differences in any situation between the first round and the second round, between healthy individuals and patients in any channel (Table 3).

Table 3. Comparison of the first round and second round for each situation.

Channel	Healthy group		Patient group	
	First half	Second half	First half	Second half
1 ch	-2.0 ± 5.2	-2.7 ± 5.1	2.0 ± 11	4.2 ± 14.3
2 ch	0.5 ± 3.1	-1.7 ± 4.0	-0.1 ± 5.9	3.4 ± 8.3
3 ch	-2.3 ± 6.2	-2.9 ± 5.7	-1.8 ± 4.9	1.2 ± 5.1
4 ch	-1.3 ± 4.4	-1.8 ± 4.8	-2.1 ± 5.8	1.0 ± 4.8
5 ch	-0.7 ± 4.3	-0.3 ± 4.1	-0.2 ± 4.4	0.001 ± 4.3
6 ch	0.1 ± 5.6	-1.4 ± 5.9	-0.7 ± 4.6	1.7 ± 4.6
7 ch	0.7 ± 2.9	-0.1 ± 5.1	-1.6 ± 5.9	0.7 ± 8.0
8 ch	0.5 ± 4.8	-0.3 ± 4.3	0.8 ± 11.9	-5.4 ± 18.1
9 ch	1.8 ± 7.6	-0.4 ± 6.2	-1.5 ± 4.4	0.8 ± 4.2
10 ch	-0.3 ± 3.8	-0.4 ± 4.5	-0.6 ± 3.8	0.8 ± 7.4
11 ch	0.6 ± 3.0	-1.7 ± 5.6	-1.2 ± 3.9	0.6 ± 6.6
12 ch	-0.2 ± 7.0	-0.9 ± 6.7	1.8 ± 5.4	1.0 ± 4.5
13 ch	-0.4 ± 3.6	-1.5 ± 4.8	0.02 ± 4.9	0.2 ± 6.1
14 ch	-3.0 ± 8.3	-6.5 ± 14.6	0.2 ± 3.1	0.3 ± 3.6
15 ch	-1.0 ± 4.9	-2.3 ± 5.3	-0.4 ± 4.9	-0.02 ± 4.5
16 ch	-7.9 ± 24.9	-9.2 ± 20.4	-0.6 ± 5.0	-0.3 ± 3.8

Units: mmol/mm. Note: There were no significant differences between any channel in the healthy and patient groups.

Discussion

Driving simulation assessment

All healthy individuals completed the full drive without incidents, such as accidents. However, 2 patients were unable to complete the full drive in the practice trial and were excluded from the study. While these 2 individuals had attention disorders and other higher brain dysfunctions in the frontal lobe, their independence in daily life and ability to resume driving were not much different from those of the other patients. That said, all participants underwent the same neuropsychological examinations, and it is unclear whether these tests were able to detect all higher brain dysfunctions. Willson et al.⁷⁾ reported that even when hemispatial neglect is not detected in neuropsychological examinations, it can appear in activities of daily living and daily life in general. Therefore, these 2 individuals may not only have had attention disorders and executive function disorders, but they may have also had hemispatial neglect or other forms of higher brain dysfunction that did not show up in the examinations. Diller et al.⁸⁾ reported that the abilities of patients with higher brain dysfunction depend on their physical and social environments. These 2 patients probably had obtained some kind of compensatory mechanisms to function in their daily lives through repeated practice, but any remaining higher brain dysfunction could have made driving, which

was a new task for them, more difficult.

On the other hand, the remaining 17 patients successfully completed the full driving simulation assessment despite having attention disorders. This may have been a result of the DS courses and situations used in the present test. Pertinently, Fujii et al.⁹⁾ reported that DS situations in which healthy elderly and brain stroke patients often had accidents are characterized by a lack of sufficient breaking maneuvers in response to the sudden appearance of cars, etc. Furthermore, it has been reported that traffic accidents in Japan occur more frequently in complex intersections and at night¹⁰⁾. Despite minor differences in the DS situations used in the present study, assessments of driving ability within a DS may have been affected by the fact that the individuals were tested on a course that had good visibility and that did not require complex driving maneuvers.

Frontal lobe activity: Left turn, right turn, and changing lanes

Regarding LTs, there was a significant difference between baseline and LTP situations, with significantly higher frontal lobe activity during the LTP. With RTs, there were significant differences between the baseline and RTPOs. Characteristics of LTP and RTPO situations require multiple tasks in addition to normal driving, such as checking for pedestrians and avoiding driving over the sidewalk or the road shoulder. RTPOs also involve multiple tasks in addition to the RT itself, such as checking for oncoming cars and pedestrians approaching at different speeds. Solberg et al.¹¹⁾ have described different types of attention, such as paying attention continuously, selecting one out of many different stimuli, and paying attention to 2 tasks simultaneously. Both parietal and frontal lobe function are important for paying attention to 2 or more things. Bogdanov et al.¹²⁾ reported that attention, instantaneous judgment for new tasks, and executive function are important functions controlled by the frontal lobe. LTPs and RTPOs can be considered situations that involve simultaneous attention, and as such, likely involve the frontal lobe. Likewise, Manard et al.¹³⁾ examined brain activity in elderly and young individuals performing dual tasks such as the Stroop task using fMRI; they reported increased activity in the prefrontal area. Szameitat et al.¹⁴⁾ also reviewed studies on dual tasks in response to auditory and visual stimuli; they reported that activity in the middle frontal gyrus increased. This may explain why frontal lobe activation could be achieved more easily in situations that involve other obstacles such as pedestrians and oncoming cars, rather than those that involved a simple left or right turn while driving along a straight line. However, the lack of significant differences in LCs may be attributed to a combination of the following circumstances: checks were generally only needed in the right direction, the driving maneuver only required a slight turn of the steering wheel to the right, no brake was required, and this maneuver was easier than a left or right turn. Moreover, while significant differences from baseline were observed for LTs and LTPs, there were either no or few significant differences between baseline and RTs or RTPs. Attention functions are also thought to have influenced these driving situations. During an LT, the participants not only had to check in front of them in the direction of driving, but also had to look behind them and use the side mirrors to check in other directions, such as

for a pedestrian coming from behind. On the other hand, the RT simulations were performed in clear intersections and the participants only had to look in the direction of driving. During RTPOs, participants had to pay attention to a moving pedestrian and an oncoming car moving at a different speed. Therefore, during LT and LTP situations, attention functions were operating simultaneously in multiple directions while during RT and RTP situations they were one-directional.

Although the healthy group exhibited frontal lobe activation and the patient group did not, both were able to drive. The tasks in this study were simple; the LTs, RTs, and LCs were performed with good views and clear instructions. Also, the fact that these tasks were simpler than regular driving likely impacted the results. While the frontal lobes of the healthy group worked efficiently even during these simple tasks, in reality, the frontal lobe did not need to function very much to execute them, meaning the patient group may have been capable of performing them as well. Nevertheless, actual driving is performed on city streets and other more complex situations, which probably require more extensive neural activity. In the future, the patient group's ability to perform complex driving tasks should be examined. In addition, we should be cautious in assessing whether the patient group is able to drive based on these tasks.

It is also worth noting that although the healthy group exhibited frontal lobe activity while the patients did not, both groups managed to perform the maneuvers. In a similar study, Watanabe et al. used fNIRS to analyze the driving performance of patients with brain injuries, and they found that the patients performed the maneuvers and yet did not exhibit the cerebral activity typically associated with such¹⁵⁾. It can be thought that procedural memory influences these individuals to perform the maneuvers without cerebral activation. Individuals with brain damage generally retain their procedural memory unless they sustained damage to their cerebral basal ganglia or cerebellum¹⁶⁾. Even patients whose cerebral cortex is damaged, because of cognitive dementia for example, retain their procedural memory. The patients in the present study probably only experienced minor damage to their cerebral basal ganglia, which would mean that their procedural memory was intact during the study. Another point to note is that the driving situations in our study were relatively simple in that LT, RT, and LC are all isolated maneuvers. Thus, the patients may have successfully performed the maneuvers because they could access driving-related procedural memory, which was generated from past driving experience, and also because the situations in the study were relatively simple. That said, real-life driving can involve much more complicated situations, especially in busy urban environments, and these situations may require more extensive neural activity. Thus, it is necessary to conduct further research with harder driving tasks and thus determine the kinds of driving maneuvers that patients can perform in more complicated situations. In view of this point, one should not state without qualification that the patients in this study can perform driving maneuvers.

Left- and right-hemisphere differences

In this study, fNIRS measurements were obtained for the right hemisphere from channels 1 to 7 and for the left hemisphere from channels 10 to 16. For LTPs and RTPOs, the LT and RT conditions in which frontal

lobe activation was significantly increased, activation increased in all channels from 1 to 7 but it did not increase in all channels between 10 and 16. This result suggests that the part of the same brain region of the frontal lobe was activated by both LTs and RTs while driving. As represented by unilateral spatial neglect, the right hemisphere is essential for the attentional aspect of visual perception and directed attention. Conversely, the left hemisphere primarily controls verbal functions. Mesulam et al.¹⁷⁾ proposed a concept of directed attention in which the right hemisphere directs bilateral spatial attention, while the left hemisphere directs only right spatial attention. The symptom of unilateral spatial neglect, in which left spatial neglect occurs due to an injury to the right hemisphere, is representative of this. Janssen et al.¹⁸⁾ reported that a phenomenon occurs in patients who have had the right frontal lobe removed in that they fail to notice food on the left when eating, suggesting the importance of the right hemisphere in directed attention. From the above, we hypothesize that, in the present study, the significant difference widely seen in channels 1 to 7 but not in channels 8 to 16 was due to the phenomenon of directed attention.

The DS we used is easily accessible and affordable compared with the commercially available one. Therefore, our DS can be conveniently used every day at a hospital. In a clinical setting, patients can use the DS to practice LTP and RTPO scenarios. We expect that such practice using the DS will lead to improvements in driving skill and cognitive impairments.

Comparison: Frontal lobe activity in the first and second half of the Driving Simulator assessment

Comparisons of frontal lobe activation in the first and second half of the DS assessment revealed no significant differences for either healthy individuals or patients. Furthermore, an analysis of frontal lobe activity of both healthy individuals and patients, after successful completion of the full drive, showed that frontal lobe activity increased significantly during LTs and RTs in healthy individuals, whereas a significant difference was not found in patients. Tomioka et al.¹⁹⁾ measured frontal lobe activity when patients with dementia repeated the same driving situations on the DS and reported that, while there was no change in frontal lobe activation in healthy controls, frontal lobe activation gradually decreased in patients with dementia. Our results from healthy individuals were comparable to the results obtained by Tomioka et al.¹⁹⁾ in that frontal lobe activation required in the first half was activated again in the second half in tasks including the LT or RT, suggesting that frontal lobe activity is consistent and lasting. However, in patients, frontal lobe activity itself remained low when driving on the DS. This suggested that, unlike patients with dementia who have a lasting attention disorder due to a generalized decline in brain function, decreased activity may be due to a divided and selective attention disorder in patients with brain damage.

However, activation of the frontal lobe is inefficient in the patient group when driving in the situations they experienced in the present study, unlike in healthy individuals. Mori et al.²⁰⁾ reported that frontal lobe activation can be achieved in patients with brain damage, such as our participants, when they are given dual tasks such as performing peripheral tasks while walking. Our present results demonstrate that similar levels

of frontal lobe activity could not be achieved by patients compared to healthy individuals when presented with the same driving conditions. This suggests that perhaps introducing dual-tasking situations such as that reported by Mori et al.²⁰⁾, e.g., adding pedestrians, oncoming cars, obstacles, and sounds to simple driving maneuvers, LTs, and RTs, may increase frontal lobe activity. Furthermore, our findings suggest that the DS used in this study may be developed into a program for driving rehabilitation.

Limitations

The fNIRS in this study only used 16 channels, which makes it more difficult to assess specific areas compared to fMRI and other techniques. In addition to frontal lobe function, driving is thought to require the functioning of areas such as the parietal lobe and cerebellum. Functional differentiation even within the frontal lobe has also been reported. Going forward, we would like to increase the number of channels to perform further analyses. In addition, the effects of changes to the DS course, the difficulty of the task, time, and other factors should be examined.

Summary

We examined frontal lobe activity in healthy individuals and patients with craniocerebral trauma as they performed tasks on a DS. In the healthy group, frontal lobe activity increased significantly as the number of obstacles in situations, such as LTs or RTs, increased, which was understood to be affected by the attention required for dual-tasking. In contrast, there were no significant differences in any of the tasks in the patient group. This was interpreted to be caused by the brain damage that impaired the divided and selective attention of these individuals, preventing them from efficiently activating the frontal lobe.

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