Neural correlates of safe driving performance: An fMRI study featuring a pedestrian-rich simulator environment

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Abstract

Distracted attention is considered responsible for most car accidents, and many functional magnetic resonance imaging (fMRI) researchers have addressed its neural correlates using a car-driving simulator. Previous studies, however, have not directly addressed safe driving performance and did not place pedestrians in the simulator environment. In this fMRI study, we simulated a pedestrian-rich environment to explore the neural correlates of three types of safe driving performance: driving accuracy, the braking response to a preceding car, and the braking response to a crossing pedestrian. Activation of the bilateral frontoparietal control network predicted high driving accuracy. On the other hand, activation of the left posterior and right anterior superior temporal sulci preceding a sudden pedestrian crossing predicted a slow braking response. The results suggest the involvement of different cognitive processes in different components of driving safety: the facilitatory effect of maintained attention on driving accuracy and the distracting effect of social–cognitive processes on the braking response to pedestrians.

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Introduction

Driving is based on the continuous adjustment and reallocation of attention, which can be affected by various sources of distraction (Palmiero et al., 2019). The principal factor in fatal traffic accidents is distracted attention on the part of the driver (Klauer et al., 2014). For example, in Japan, distracted driving and inattentive driving, which are violations of the duty to drive safely and are directly related to inattention while driving, accounted for, respectively, 14.8% and 11.7% of fatal accidents in 2019 (White Paper on Traffic Safety in Japan, 2020). A large study of driving in actual driving situations (Dingus et al., 2006) determined that inattention was involved in 78% of accidents and 65% of near-accidents. Several studies have investigated the relationship between attention and driving abilities in experimental settings. For example, Hoffman and colleagues (Hoffman et al., 2005) found that attention deficits in older drivers predicted their impairment in simulated driving, as reflected in an increase in the number of car crashes. Cuenen and colleagues demonstrated that the attentional abilities of elder drivers can predict their reaction times to road hazards in a driving simulator task (Cuenen et al., 2015). To reduce traffic accidents, it is important to investigate the relationship between attentional states and safe driving performance

The neural correlates of safe driving performance have rarely been investigated, although research using driving simulators has begun to explore the neural basis of driving and the role of attention distraction. The introduction of driving simulator into functional magnetic resonance imaging (fMRI) has received considerable attention (Calhoun & Pearlson, 2012; Calhoun et al., 2002; Choi et al., 2017; Kan et al., 2013; Uchiyama et al., 2003; Walter et al., 2001), and these studies have revealed the involvement of brain areas such as the sensorimotor cortices and cerebellum during simulated driving (Navarro et al., 2018). Numerous experiments using a secondary task during simulated driving to distract attention have been conducted in the last 10 years (Graydon et al., 2004; Just et al., 2008; Hsieh et al., 2009; Uchiyama et al., 2012; Schweizer et al., 2013; Chung et al., 2014), although most of these studies have only examined the effect of the distractor on the car driving condition. These studies have suggested a significant shift in activation from the occipital to the frontoparietal brain regions under a dual-task condition (simulated driving plus a secondary task) as compared to a simulated driving condition alone (Palmiero et al., 2019). However, relationships between the frontoparietal network and measures of safe driving performance, such as driving accuracy, have not been investigated. The frontoparietal control network, a robust network mainly comprising the lateral prefrontal cortex (including the rostral and dorsolateral prefrontal cortex) and inferior parietal lobule (Power et al., 2011; Niendam et al., 2012; Cole et al., 2013; Gordon et al., 2016; Gratton et al., 2018; Uddin et al., 2019), is involved in

executive functions such as vigilance or sustained attention, the initiation of complex goal-directed behaviors, the inhibition of prepotent but incorrect responses, flexibility in shifting easily between goal states, planning the steps necessary to achieve a goal, and working memory or the ability to hold information in mind and manipulate it to guide response selection (Niendam et al., 2012; Uddin et al., 2019). Furthermore, in the presence of a distractor, numerous studies have reported a decrease in driving performance and an increase in activation in areas related to perceptual processing of the distractor, such as the visual and auditory cortex (Just et al., 2008; Hsieh et al., 2009; Schweizer et al., 2013; Palmiero et al., 2019). However, little information is available about the relationship between brain activity and safe driving performance. A few studies have reported the neural correlates of driving performance at a between-subjects level, such as the involvement of the anterior cingulate cortex in car-following performance (Uchiyama et al., 2003), the bilateral lateral occipital complex and right inferior parietal lobule activity in car-following performance (Uchiyama et al., 2012), and the right superior parietal lobule in visual multitasking performance (Al-Hashimi et al., 2015). Although the results of between-subjects correlation analysis can reveal the neural correlates of individual differences in driving ability and driving strategy, to clarify the cognitive states related to safe driving, which fluctuate within individuals at the brain level, it is important to examine within-subject correlations based on time series of brain activity and performance.

In most of the studies noted above, the driving environment included landscapes and vehicles but not pedestrians (Walter et al., 2001; Graydon et al., 2004; Just et al., 2008; Hsieh et al., 2009; Uchiyama et al., 2012; Kan et al., 2013; Chung et al., 2014; Choi et al., 2017). Each year, more than 270,000 pedestrians lose their lives on the world's roads, and globally, pedestrians constitute 22% of all road deaths; in some countries, this proportion is as high as two-thirds (WHO, 2013). Millions more people are injured in traffic-related crashes while walking, some of whom become permanently disabled (WHO, 2013). Pedestrians are one type of external distractor (Dingus et al., 2006); furthermore, social information such as that represented by pedestrians captures the driver's attention in a task-irrelevant manner by eliciting spontaneous mentalizing during simulated driving (Spiers and Maguire, 2006). Thus far, a few fMRI studies have placed pedestrians in the driving simulator, but these have not analyzed brain activity in response to the pedestrians (Spiers and Maguire, 2007; Li et al., 2012).

This study aimed to examine, for the first time, the cognitive states associated with safe driving by investigating within-subject correlations between brain activity and safe driving performance. We created a driving simulator that contained rich social information and examined the brain

activity associated with safe driving performance, including driving accuracy as measured by lane keeping and the braking response to a preceding car and pedestrians. Because many studies have suggested the involvement of the frontoparietal control network during simulated driving with distractors (Graydon et al., 2004; Li et al., 2012; Kan et al., 2013; Chung et al., 2014) and assessed lane-keeping as moderated by attention capacity (Cuenen et al., 2015), we specifically predicted that frontoparietal control network activity would explain high driving accuracy.

Methods

Participants

Thirty-eight healthy right-handed participants who had driver's licenses participated in this study. The experiment was stopped for one participant due to visually induced motion sickness. Four participants were removed from the analysis due to low-quality data (more than 20% of the trials with misses for either the preceding car or the crossing pedestrian). The data of three participants were removed from the analysis due to a technical problem during the simulator presentation. Ultimately, the data of 30 participants were used for the analysis (mean [M] age = 21.9 years, standard deviation [SD] = 3.7 years). Participants had no history of psychiatric or neurological disorders. All participants provided written informed consent before their participation. This study was approved by the Research Ethics Committee of Tohoku University School of Medicine and was conducted in accordance with the tenets of the Declaration of Helsinki.

Task

We created a task, experienced from a first-person perspective, in which participants continuously drove along a one-way, gently S-shaped road (Figure 1). With pedestrians on the sidewalks on both sides and another car in front of their car, the participants were asked to control their car such that it stayed in the middle of the street as much as possible by pushing left/right buttons using MRI-compatible response buttons (Current Designs; Philadelphia, PA, USA). Two types of situations were set as emergency events while driving, similar to a previous study (Yanko and Spalek, 2013): braking by a preceding car (the brake lights of the vehicle ahead glow, and the vehicle slows down) and a pedestrian crossing (heading toward the road from the sidewalk on the right or left). During an experimental scenario (16 min, 10 sec), preceding car slowdowns or pedestrian-crossing events occurred pseudorandomly 30 times, each at intervals of 15 sec or more. Participants were asked to press a button using the right thumb as soon as possible to avoid the dangers (braking response). A 500-Hz pure tone was fed back to the participant to indicate the right thumb button press.

Successful avoidance was visualized as the own vehicle slowing down or the pedestrian disappearing. The vehicle speed was kept constant at 40 km/h except during temporary deceleration and re-acceleration when the preceding car slowed down. Four scenarios were created, and the order of scenario presentation was counterbalanced among the participants. The driving simulator task was created using UC-win/Road Driving Sim Ver.13(SS) (FORUM 8 Co., Ltd).

fMRI measurements

Scanning was conducted using a 3 T MRI scanner (Achieva Quasar Dual, Philips). Blood oxygenation level-dependent (BOLD) T2*-weighted MR signals were measured using a gradient echo-planar imaging sequence. Forty 3-mm-thick contiguous slices covering the entire brain were acquired (repetition time [TR] = 2,500 ms, echo time = 30 ms, flip angle = 85°, field of view = 192 mm², and scan matrix = 64 × 64). Excluding the first two “dummy” volumes to stabilize the T1-saturation effect, 388 volumes were acquired in each fMRI session.

Analysis

The following preprocessing procedures were performed using CONN (Whitfield-Gabrieli & Nieto-Castanon, 2012) implemented in MATLAB R2018a (MathWorks; Natick, MA, USA): realignment and unwarp, slice timing correction, outlier detection for scrubbing (intermediate setting: framewise displacement above 0.9 mm or global BOLD signal changes above 5 SD), direct segmentation and normalization to Montreal Neurological Institute (MNI) space, and smoothing using a Gaussian kernel with a full-width at a half-maximum value of 8 mm.

The relationship between brain activity and safe driving performance for each voxel was estimated using a general linear model (GLM). To examine the neural correlates of driving accuracy and hazard detection (preceding car and pedestrian), two types of GLM analysis were performed using statistical parametric mapping (SPM12) software (Wellcome Department of Imaging Neuroscience; London, UK). Brain areas that exhibited significant relationships with safe driving performance were mapped onto the brain surface and sections using bspmview (Spunt, 2016).

(1) Driving accuracy

As a measure of driving accuracy, the time to line crossing (TTLC) was calculated based on the car position, which was sampled continuously throughout the session. TTLC represents the duration of time available before any lane boundary is crossed; the larger the value, the more accurate the

performance (Mammar et al., 2006). TTLC time-series data were down-sampled to the minimum value of 2.5 sec, which matched the TR value, and then convolved with the hemodynamic response function (HRF) for use as the regressor of interest representing the expected hemodynamic response related to TTLC. In the same way, the road curvature regressor was constructed and incorporated into the model to exclude the possible effect of curvature on brain activity. In addition, the model included the following regressors constructed by convolving delta functions on each event onset and the canonical HRF: pedestrian crossing, preceding car slowdown, button press by the right index finger for hazard detection, button press by the left index finger to turn the wheel to the right, button press by the left index finger to turn the wheel to the left, scenario switch (at around 5 and 10 min), and error (no response to both pedestrian crossing and preceding car slowdown). The timing of the outlier scan and realignment parameters were also included in the model to remove the effects of head movement. A high-pass filter (128 sec) was used to remove low-frequency noise.

(2) Braking response to a preceding car and a crossing pedestrian

To investigate brain activity related to hazard detection, such as a preceding car and a crossing pedestrian, the relationship between the brain activity prior to these events and the reaction time (RT) for each event was investigated using parametric modulation analysis. In this analysis, positive and negative correlations indicated brain areas related to distraction and to facilitation of the hazard detection response, respectively. Based on a previous study that examined the neural correlates of mind wandering (Christoff et al., 2009) and the current experimental task in which an event occurs every 15 sec on average, brain activity in the 10 sec prior to event onset was convolved with the canonical HRF for both the preceding car and crossing pedestrian conditions. Additional regressors were as follows: pedestrian crossing, preceding car slowdown, button press by the right index finger for hazard detection, button press by the left index finger to turn the wheel to the right, button press by the left index finger to turn the wheel to the left, scenario switch, and error (no-response event). These events were convolved with the canonical HRF. Similar to the model for TTLC, the timing of the outlier scan and realignment parameters was included in the model, as was a high-pass filter (128 sec).

After the parameter estimation for each regressor in each participant, statistical inference for each regressor of interest was performed with a between-subjects (random effects) model using a one-sample t-test. Both positive and negative correlations were examined. Based on our *a priori* hypothesis that the frontoparietal network would be involved in driving accuracy, a region of interest (ROI) analysis using a small-volume correction (SVC) implemented in SPM12 was applied

to the analysis of positive correlations. A frontoparietal network ROI was created based on a study that examined cortical parcellation from resting state functional connectivity (Gordon et al., 2016). From 24 coordinates comprising the frontoparietal network, two inferior frontal regions and two middle cingulate regions were removed to specifically focus on the core of the frontoparietal network (Cole et al., 2013; Uddin et al., 2019). The 8-mm-radius spheres centered on the reported MNI coordinates of the frontoparietal network were first created using marsbar (<http://marsbar.sourceforge.net/>) and then combined. Finally, an intersection between the 20 spherical ROI mask and brain mask (mask.nii) derived from the current participants was created to exclude the area outside the functional image. The core frontoparietal ROI shown in Figure 2A. In the other analyses, a whole-brain voxel-by-voxel analysis (cluster-defining threshold: $p < 0.001$ uncorrected; family-wise error (FWE) cluster-extent threshold: $p_{\text{FWE}} < 0.05$) was conducted to identify relevant areas across the entire brain.

Results

Participant behavior

On average, 1.3% (SD = 1.4) and 0.6% (SD = 1.0) of trials responding to a preceding car slowing down and a crossing pedestrian, respectively, were miss trials. The mean RT of the hit trials for the preceding car and crossing pedestrian conditions was 0.81 sec (SD = 0.03) and 0.95 sec (SD = 0.04), respectively. The RT for the slowdown of a preceding car was significantly shorter than that for a crossing pedestrian ($t(29) = 4.94$, $p < 0.001$).

fMRI results

(1) Driving accuracy

A hypothesis-based ROI analysis targeting the frontoparietal network revealed a significant positive correlation between TTLC (index of driving accuracy) and bilateral inferior parietal lobule and right middle frontal gyrus activity (Figure 2B, Table 1, SVC; voxel-level threshold $p_{\text{FWE}} < 0.05$). In the additional voxel-by-voxel whole-brain analysis, the right inferior parietal lobule and left middle frontal gyrus exhibited significant positive correlations (Figure 2C, Table 1, cluster-defining threshold: $p < 0.001$ uncorrected; cluster-extent threshold: $p_{\text{FWE}} < 0.05$).

There was a robust negative correlation between TTLC and broad cortical areas centered on the right sensorimotor cortex (Figure 3, Table 1, cluster-defining threshold: $p < 0.001$ uncorrected; cluster-extent threshold: $p_{\text{FWE}} < 0.05$).

(2) Braking response to a preceding car and a crossing pedestrian

The parametric modulation analysis with RT representing the braking response to a preceding car showed no significant clusters for positive and negative correlations representing distraction and facilitation processes, respectively (Table 2, cluster-defining threshold: $p < 0.001$ uncorrected; cluster-extent threshold: $p_{\text{FWE}} < 0.05$). The parametric modulation analysis using RT as a braking response to a crossing pedestrian revealed significant positive correlations in the right anterior superior temporal sulcus and left posterior superior temporal sulcus, indicating distraction (Figure 4, Table 2, cluster-defining threshold: $p < 0.001$ uncorrected; cluster-extent threshold: $p_{\text{FWE}} < 0.05$). The analysis of negative correlations revealed no significant clusters.

Discussion

Using a pedestrian-rich environment, we explored the neural activation associated with three types of safe driving performance. Driving accuracy was associated with higher activation of the bilateral frontoparietal control network and lower activation of bilateral extensive sensorimotor cortices. Activation of the left posterior and right anterior superior temporal sulci preceding the sudden crossing of a pedestrian was associated with a longer RT (slower braking response). We thus successfully identified neural correlates of safe driving performance.

The association of driving accuracy with activation of the frontoparietal control network identified here is supportive of the expected role of this network in driving safety. Previous studies have suggested a significant shift in activation from the occipital to the frontoparietal network under dual-task conditions (simulated driving plus secondary tasks) as compared to simulated driving only (Graydon et al., 2004; Just et al., 2008; Hsieh et al., 2009; Uchiyama et al., 2012; Schweizer et al., 2013; Chung et al., 2014). However, the relationship between the frontoparietal network and safe driving performance has not been investigated previously, and the question of which aspects of driving are associated with the frontoparietal network has remained unanswered. When this network was active, the car remained closer to the middle of the road and was less likely to run off the road. Conversely, with low activity in this network, the driver moved along the edge of the road, increasing the risk of going off the road. The frontoparietal network is involved in executive functions (Niendam et al., 2012; Uddin et al., 2019), and activity in this network is considered to enable accurate vehicle control by maintaining attention despite distractions.

On the other hand, we are cautious in associating the identified relationships between the driving accuracy and decreased activation of sensorimotor cortices with driving safety. The activation of these areas has been associated with simulated driving itself (Walter et al., 2001;

Uchiyama et al., 2003; Kan et al., 2013), and it is hard to imagine that sensorimotor processes would degrade driving accuracy. It would be more plausible to interpret the negative correlation with the sensorimotor cortices as reflecting a situation in which the driver is more engaged in recovering from the risk of approaching the edge of the road due to inaccurate driving. This interpretation is also supported by a prominent finding in the right sensorimotor cortices that could reflect control of the left thumb positioned on the steering buttons.

The pedestrian-rich environment enabled us to identify the association between activation of the bilateral temporal cortices and a delayed braking response to a crossing pedestrian for the first time. The finding seems in line with the conceptual framework holding that the processing load of a distractor reduces the detection of important environmental information and thereby driving safety (Marciano and Yeshurun, 2012, 2014; Murphy et al., 2016). The lateral temporal lobe is associated with the processing of social information (Lahnakoski et al., 2012; Pitcher and Ungerleider, 2021); more specifically, the posterior part is associated with the perceptual component of social processing (Allison et al., 2000), whereas the anterior part is more closely related to higher semantic processing (Binney et al., 2016; Oba et al., 2020). Because pedestrians are one of the major external distractors that capture a driver's attention (Dingus et al., 2006), it is believed that such a stimulus could cause a task-irrelevant processing load for social information ranging from perceptual to higher semantic processing. This finding showed for the first time that the processing load associated with a pedestrian as a distractor is actually associated with a decrease in safe driving performance.

We identified no neural predictors of the braking response to a preceding car slowing down. One of the few studies in this area showed a positive correlation between car-following performance and activation of the bilateral lateral occipital complex and right inferior parietal lobule (Uchiyama et al., 2012). Similar findings were not obtained in the present study, probably due to differences in tasks and analyses. One reason for the lack of significant findings is that various influencing factors are involved in the braking response to a preceding vehicle, and the respective degrees of influence may be different for each individual. The difference between these results and those for the pedestrians may be because a pedestrian crossing the street causes the appearance of clear stimuli in the peripheral visual field, whereas a preceding car slowing down causes little change in terms of visual stimuli in the central field.

This study has several limitations. Because the participants were young people, mainly university students who had been driving for a few years, it is unclear whether the same results would be obtained for more experienced drivers or elder drivers. To confirm the general

applicability of the results of this study, it is important to conduct further experiments with groups with different driving proficiencies and of different ages. The car was controlled using a response button box, which is different from a car steering wheel. Therefore, the results of the current study might have been influenced by the response button. It would be important to confirm whether the frontoparietal network and driving accuracy are positively correlated in an experiment using an MRI-compatible steering wheel as well.

Our overall results suggest the involvement of different cognitive processes in different components of driving safety: a facilitatory effect from maintained cognitive control on driving accuracy and a distracting effect from social–cognitive processes on the braking response to pedestrians. Research using a more realistic driving simulator that includes more factors is needed to elucidate the various cognitive processes that support and inhibit driving safety (Calhoun and Pearlson, 2012).

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Table 1. Brain regions correlated with TTLC

Brain region		x	y	z	T	pFWE	cluster
<i>Positive correlation</i>							
Inferior parietal lobule*	R	46	-60	44	5.13	0.006	18
Inferior parietal lobule	R	52	-64	36	8.48	0.008	494
		58	-56	32	5.87		
Inferior parietal lobule*	L	-40	-66	44	4.65	0.019	3
Middle frontal gyrus*	R	30	56	0	4.56	0.023	12
		38	22	54	4.36	0.037	3
		42	24	50	4.30	0.042	1
Middle frontal gyrus/superior frontal gyrus	L	-38	22	52	6.01	0.025	370
		-20	36	52	5.73		
		-26	22	58	5.06		
<i>Negative correlation</i>							
Superior frontal gyrus	R	22	-4	64	16.27	0.000	66954
		14	-54	62	15.97		
		22	-16	68	15.76		
Middle frontal gyrus	L	-28	40	22	6.50	0.001	762
		-28	36	32	6.31		

Asterisks indicate the results of SVC analysis within the frontoparietal network. x, y, and z indicate the MNI coordinates. Abbreviations: TTLC, the time to line crossing; SVC, small-volume correction; FWE, family-wise error; MNI, Montreal Neurological Institute

Table 2. Brain regions predicting the braking response to a preceding car slowing down or a crossing pedestrian

Brain region		x	y	z	T	pFWE	cluster
Preceding car							
<i>Positive correlation</i>							
no suprathreshold clusters							
<i>Negative correlation</i>							
no suprathreshold clusters							
Pedestrian crossing							
<i>Positive correlation</i>							
Posterior superior temporal sulcus	L	-60	-50	10	5.40	0.014	505
		-64	-32	4	5.03		
		-56	-64	10	3.74		
Anterior superior temporal sulcus	R	50	-10	-14	4.81	0.010	552
		48	0	-20	4.41		
		30	16	-22	4.22		
<i>Negative correlation</i>							
no suprathreshold clusters							

x, y, and z indicate the MNI coordinates. Abbreviations: FWE, family-wise error; MNI, Montreal Neurological Institute

Figure 1. Driving simulator and emergency events

(A) While driving along a gently S-shaped road, participants were asked to control the car so that it was positioned in the center of the road as much as possible (driving accuracy) by pushing the left and right buttons of an MRI-compatible response button. They were also asked to perform braking responses to two types of emergency events: (B) deceleration of the vehicle ahead (the brake lights of the vehicle ahead would glow) and (C) a pedestrian moving from the sidewalk on the right or left toward the road (in this case, a man in a blue shirt is walking toward the road).

Figure 2. Frontoparietal network and its positive correlation with TTLC

(A) The frontoparietal network ROI (green) based on Gordon et al. (2016). (B) The result of hypothesis-based ROI analysis. Within the ROI, activity in the bilateral IPL and right MFG was positively correlated with TTLC, an index of driving accuracy (SVC; voxel-level threshold $p_{FWE} < 0.05$). Arrows indicate significant voxels. Numbers in each axial section indicate the z coordinates in MNI space. (C) Exploratory whole-brain analysis showed significant positive correlations between activity in the right IPL and left MFG with TTLC (cluster-defining threshold: $p < 0.001$ uncorrected; cluster-extent threshold: $p_{FWE} < 0.05$). Abbreviations: ROI, region of interest; TTLC, the time to line crossing; IPL, inferior parietal lobule; MFG, middle frontal gyrus; SVC, small-volume correction; FWE, family-wise error; MNI, Montreal Neurological Institute

Figure 3. Brain activity negatively correlated with TTLC

Activity in wide-ranging bilateral cortical areas, especially the right sensorimotor cortex, was negatively correlated with TTLC (cluster-defining threshold: $p < 0.001$ uncorrected; cluster-extent threshold: $p_{\text{FWE}} < 0.05$). Abbreviation: TTLC, the time to line crossing

Figure 4. Brain activity associated with the braking response to a pedestrian crossing
Activity in the left pSTS and right aSTS preceding a pedestrian crossing was positively correlated with the RT for that event (cluster-defining threshold: $p < 0.001$ uncorrected; cluster-extent threshold: $p_{\text{FWE}} < 0.05$). Abbreviations: pSTS, posterior superior temporal sulcus; aSTS, anterior superior temporal sulcus; RT, reaction time