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Suppression of brain activity related to a car-following task with an auditory task: An fMRI study

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ABSTRACT

Driving a car in daily life involves multiple tasks. One important task for safe driving is car-following, the interference of which causes rear-end collisions: the most common type of car accident. Recent reports have described that car-following is hindered even by hands-free mobile telephones. We conducted functional MRI with 18 normal volunteers to investigate brain activity changes that occur during a car-following task with a concurrent auditory task. Participants performed three tasks: a driving task, an auditory task, and a dual task in an fMRI run. During the driving task, participants use a joystick to control their vehicle speed in a driving simulator to maintain a constant distance from a leading car, which moves at varying speed. Language trials and tone discrimination trials are presented during the auditory task. Car-following performance was worse during the dual task than during the single-driving task, showing positive correlation with brain activity in the bilateral lateral occipital complex and the right inferior parietal lobule. In the medial prefrontal cortex and left superior occipital gyrus, the brain activity of the dual task condition was less than that in the single-driving task condition. These results suggest that the decline of brain activity in these regions may induce car-following performance deterioration.

1. Introduction

Car driving in daily life involves many tasks such as lane-keeping, speed control, car-following, following traffic lights, and navigation to destinations. An important task for safe driving is car-following. Failure of the car-following task causes rear-end collisions: the most common type of car accident in Japan and the US (Statistics 2007 Road Accidents Japan, 2008; Traffic Safety Facts 2008, 2009). Prevention of rear-end collisions is expected to be effective for reducing economic and human losses attributable to automobile accidents.

One cause of rear-end collisions is distractions caused by mobile telephones. Results of previous reports have described that mobile telephone use engenders a higher likelihood of rear-end collisions (Neyens & Boyle, 2007; Sagberg, 2001). Sagberg (2001), using a questionnaire administered to drivers who had caused a car accident within the prior few months, demonstrated

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that rear-end collisions were the most frequent car accident type occurring during mobile telephone use. Neyens and Boyle (2007) associated cellular telephone distractions with a higher likelihood of rear-end collision among teenage drivers.

The hazards posed by mobile telephone use while driving are classified as those affecting tasks of two types: manual operation of the phone while holding and dialing a mobile telephone; and conversing, listening, and talking with the phone. Manual operations of mobile telephones while driving have been prohibited in many countries. However, conversation using hands-free mobile telephones while driving has not been prohibited. In addition, results of several earlier studies suggest that even hands-free mobile telephone use interferes with driving (Alm & Nilsson, 1995; Brown, Tickner, & Simmonds, 1969; Horrey & Wickens, 2006; Strayer, Drews, & Johnston, 2003). These studies revealed that the auditory linguistic task caused a delay of the brake reaction time. The auditory linguistic task interferes with car-following performance. The mobile telephone market penetration rate continues to increase, implying further increases in rear-end collisions caused by mobile telephone use. To prevent such rear end collisions caused by hands-free mobile telephones, more detailed understanding of auditory task interference during the car-following task will be necessary.

Recent development of brain imaging techniques has revealed the neural substrates related to driving. Previous neuroimaging studies of driving using measurements obtained with fMRI or FDG-PET have indicated the feasibility of measuring brain activity during simulated and real driving (Calhoun, Carvalho, Astur, & Pearlson, 2005; Calhoun et al., 2002; Graydon et al., 2004; Horikawa et al., 2005; Hsieh et al., 2009; Jeong et al., 2006; Just et al., 2001; Mader et al., 2009; Meda et al., 2009; Spiers & Maguire, 2007; Uchiyama, Ebe, Kozato, Okada, & Sadato, 2003; Walter et al., 2001). These studies have revealed that driving tasks recruit regions related to vision, motor skills, and visuo-motor integration, which are represented by the task-related activation in the parieto-occipital cortices, cerebellum, and cortical regions associated with perception and motor control.

Neuroimaging studies have also elucidated the neural substrates that are used under dual-task circumstances. Earlier functional imaging studies have shown that brain activity evoked by the single task was reduced by the concurrently performed task (the dual-task condition). Just et al. performed a dual-task experiment using mental rotation and a sentence comprehension task (Just et al., 2001), finding that, in the dual-task condition, the activated voxels in the association areas (primarily temporal and parietal areas of cortex) were fewer than when two tasks were performed singularly. This result was replicated with the same task combination (Newman, Keller, & Just, 2007). Taken together, these results suggest that the activation associated with a given task decreases while a secondary task is being performed concurrently (Just et al., 2001; Newman et al., 2007).

Using fMRI, Just et al. also investigated brain activation under a dual-task condition using a combination of a driving task and a language task (Just, Keller, & Cynkar, 2008). The driving task was lane-keeping without speed control using a driving simulator; the language task was auditory sentence comprehension. The lane-keeping performance of the dual-task condition was lower than that of the single-driving task condition. The authors also found that the brain activities of the widely distributed bilateral parietal and occipital areas were more suppressed by the dual-task condition than by the single-task condition.

The driving dual task imaging study by Just et al. used a lane-keeping task in which participants only steered without speed control (i.e. their own car ran at constant speed) as the driving task (Just et al., 2008). From the perspective of avoiding many car accidents, car-following is more important than lane-keeping. However, the change of brain activity of the car-following task with concurrent auditory task has not been studied using neuroimaging methods. Consequently, in this study, we sought to identify which brain regions related to a car-following task are hindered by an auditory task.

In previous dual task functional imaging studies (Just et al., 2001, 2008; Newman et al., 2007), suppression of activity in the parietal regions was found when both behavioral performances of the rotation task and the lane-keeping task were decreased. In our previous car-following imaging study (Uchiyama et al., 2003), activation of the right parietal regions was observed. These two facts indicate the existence of brain regions in which brain activity under the single-car following condition is lower than that under the dual task condition in which the car-following and an auditory task were performed concurrently.

Additionally, the decrease of brain activity from a rest condition, which is the default mode network (DMN), was investigated in this study. The DMN is a set of brain regions showing higher activity during rest than during goal-directed cognitive tasks (McKiernan, Kaufman, Kucera-Thompson, & Binder, 2003; Raichle et al., 2001). Moreover, activity of these regions is directly related with the task difficulty (McKiernan et al., 2003). McKiernan et al. (2003) concluded that the decrease of brain activity when performing the goal directed task accompanying the increase of the task difficulty as a reallocation of limited attentional resources from the resting task to the goal-directed task. In this study, the dual-task condition is shown to require more attentional resources than the single-task condition. This view suggests that the brain activity of a brain region showing decreased activity, such as DMN, in the dual-task condition is decreased more than in the single-task condition.

To assess these suppositions, we compared brain activation in the regions recruited for the car-following task to that in the regions recruited for the dual task when the participants concurrently performed a simulated car-following task and auditory task. Additionally, in the suppressed region, we identified brain regions in which the brain activation was correlated with the car-following performance.

2. Materials and methods

2.1. Participants

In this study, 18 volunteers (10 male and 8 female; mean age ± standard deviation [SD] = 27.7 ± 4.3 years) participated. All subjects were right-handed according to the Edinburgh handedness inventory (Oldfield, 1971). The participants had no

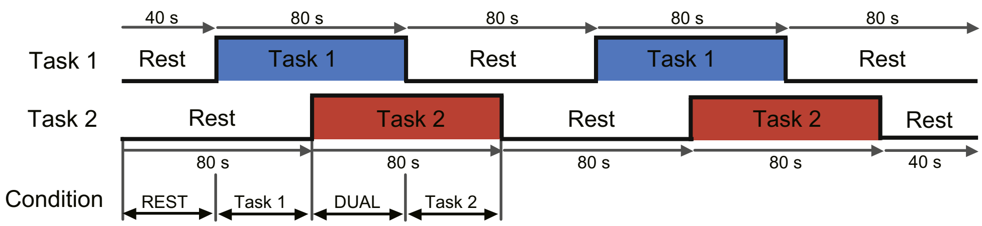

Fig. 1. Schematic diagram of the experimental task run. The simulated driving task (DRIVING) and the auditory task (AUDIO) were assigned respectively to Tasks 1 and 2, or the reverse. Each participant performed the four task runs. The assignments of DRIVING and AUDIO were counterbalanced for participants.

history of neurological or psychiatric illness, and no developmental disorder. All participants gave their written informed consent to participation. The protocol was approved by the Ethical Committee of the National Institute for Physiological Sciences, Japan.

2.2. Tasks

An experimental run includes four conditions: driving alone (DRIVING), auditory task alone (AUDIO), driving with auditory task (DUAL), and a baseline passive viewing condition (REST). The experiment run consisted of two 40-s epochs each of DRIVING, AUDIO, and DUAL, and three 40-s epochs of REST (Fig. 1).

The car-following task was the same as that used in our previous study (Uchiyama et al., 2003). During DRIVING, the participants performed a car-following task that was presented using a driving simulator. Regarding the simulated driving scenery, the road was two lanes wide, straight, and flat with green berms on each side. A leading car ran straight in the left lane, changing its speed between 40 km/h and 60 km/h. The participants followed the leading car while maintaining the between-car distance as constantly (5 m) as possible. The participants' car speed was controlled by manipulating the simulator joystick with the right hand. The lateral position of the participants' car was fixed in the center of its lane. The simulated scene, with lane width matched to Japanese expressway specifications, included no intersections, other vehicles, or obstacles except the leading car. No auditory stimulus was presented.

In AUDIO, the participants alternately performed auditory trials of two types (sentence comprehension and tone discrimination). In each type of trial, the three phases were presented sequentially: a 2-s cue phase, a 4-s presentation phase, and a 4-s response phase. The cue phase began with a beep tone (frequency = 1 kHz; duration = 160 ms). The response phase began with a high or low beep tone (frequency = 2 kHz or 500 Hz, respectively; duration = 160 ms for each). During the AUDIO condition, the participants viewed the scene from the driving simulator, in which their own car followed the leading car automatically, traveling straight ahead at 50 km/h, at a distance of 5 m from the leading car.

In the sentence comprehension trials, an auditory cue indicated the start of a sentence comprehension trial. During the subsequent presentation phase, a spoken sentence comprising six phrases was presented. The sentences were identical to those used in our previous study (Uchiyama et al., 2008). During the response phase, the sentence was made up of a noun and a verb connected with a "-ga:" nominative marker. The participants heard a sentence and judged whether the subject of the verb corresponded to the person in the paired words.

In the tone discrimination trials, initially an auditory cue indicated the trial type. During the presentation and response phases, the presented sounds were reversed versions of those used in each phase of the sentence comprehension trials. Participants judged whether the beep tone in the response phase was high or low and pushed the button as quickly as possible.

The AUDIO condition included trials of two types: sentence comprehension and tone discrimination. This AUDIO condition design makes it possible to analyze the difference of brain activation between sentence comprehension and the tone discrimination. We attempted to perform analyses with separated AUDIO conditions using sentence comprehension and tone discrimination. However, the difference in brain activation between the sentence comprehension and the tone discrimination was not statistically significant. A one-sample Student *t*-test ($p < .001$ uncorrected at the voxel level) was used for every voxel within the brain using group level analysis. Consequently, the following analysis was performed using the large AUDIO epoch including both trials.

In DUAL, the participants performed DRIVING and the AUDIO concurrently. The participants were asked to perform both tasks as equally as possible.

In REST, the same scene was projected by the driving simulator as in the AUDIO condition. No auditory stimulus was presented.

Each participant performed four 6-min runs in one scanning session. The interval between the runs was 3–5 min. The run order was counterbalanced across participants (Fig. 1). Before each run, the participants were instructed which task (DRIVING or AUDIO) starts first. After the four runs, anatomical images were acquired. The participants performed two practice runs outside the scanner the day before their fMRI experiment.

2.2.1. Apparatus

The driving simulator, which ran on two PCs (Windows XP; Microsoft Corp.), was created using Visual C (Microsoft Corp.) and OpenGL library. One PC, which recorded the movement of the joystick, was connected to a non-ferromagnetic joystick outside the scanner room through a waveguide in the wall. The joystick was made of a commercially produced joystick (Microsoft Side Winder Joystick; Microsoft Corp. WA, USA) with removal of its ferromagnetic parts. The other PC, which generated the driving scene, was connected to an LCD projector (DLA-M2000L; Victor Company of Japan, Ltd., Yokohama, Japan) outside the scanner room. The driving simulator system was the same as that used in our previous studies (Uchiyama et al., 2003). The driving scene was projected through another waveguide to a translucent screen (OS-MR1; Kiyohara Optics Inc., Tokyo, Japan). The participants viewed the scene via a mirror attached to the head coil of the 3 T MRI scanner (Allegra; Siemens AG, Erlangen, Germany).

The auditory task was presented by another PC using fMRI experiment software (Presentation; Neurobehavioral Systems Inc., CA, USA). Auditory stimuli were presented through headphones (Hitachi Advanced Systems Corp., Yokohama, Japan). The speech sounds were produced by a male voice generated using speech-synthesis software (Smarttalk Ver. 3.0; Oki Electric Industry Inc., Tokyo, Japan). The participants heard the speech sounds and then pushed a response button (HH-1x4D; Current Designs Inc., PA, USA) with their left thumb. Both the driving simulator and auditory task presentation system were synchronized to the MRI scan pulse.

2.3. Magnetic resonance imaging (MRI) data acquisition

During each run, a time-course series of 125 volumes was acquired using T2-weighted gradient-echo echo-planar imaging (EPI) sequences. Each volume consisted of 36 transaxial slices, with a slice thickness of 4 mm without a gap, which covered the entire cerebral and cerebellar cortices. The slices were acquired in the interleaved mode. Oblique scanning was used to exclude the eyeballs from the obtained in-plane images. The time interval between two successive acquisitions of the same image (repetition time [TR]) was 3000 ms with a flip angle (FA) of 85° and an echo time (TE) of 30 ms. The field of view (FOV) was 192 mm, and the in-plane matrix size was 64×64 pixels.

2.4. Task performance analysis

The driving performance of each participant was evaluated using the coefficient of variation (CV) of the car-following distance. The distance CV is the standard deviation of the car-following distance divided by its mean value. The reason of using the distance CV is that the standard deviation positively correlated with the mean distance. Consequently, to cancel the difference of the mean car-following distance of each participant, we used the distance CV to indicate the driving performance.

2.5. Functional MRI (fMRI) data analysis

2.5.1. Preprocessing

The MRI data were analyzed using statistical parametric mapping (SPM5; Wellcome Department of Cognitive Neurology, London, UK) (Ashburner & Friston, 1999; Friston, Holmes, Poline, Price, & Frith, 1996) implemented using software (Matlab 2007a; The Mathworks Inc., Sherborn, MA, USA). The first five volumes of each fMRI run were discarded to allow for stabilization of the magnetization; the remaining 120 volumes/run (a total of 480 volumes/participant) were used for analysis. The MRI data were realigned to correct for head motion: The echo-planar images of each run were realigned to the first image of the run. Then the four images were realigned together. The realigned data were normalized spatially into a standard stereotaxic brain space (Evans, Kamber, Collins, & MacDonald, 1994) using an EPI template. The anatomically normalized fMRI data were resampled to a voxel size of $2 \times 2 \times 2$ mm. Then they were spatially smoothed using a Gaussian kernel with a full-width at half maximum of 8 mm in the x, y, and z axes.

Statistical analyses were conducted at two levels. First, the individual task-related activation was evaluated. Second, the summary data for each were incorporated into a second-level analysis using a random-effect model (Friston, Holmes, & Worsley, 1999) to make inferences at a population level.

2.5.2. Individual analysis

The signal was scaled proportionally by setting the whole-brain mean value to 100 arbitrary units. The signal time course for each participant was modeled using a general linear model. Regressors of the interest (trial effects: DRIVING, DUAL, and AUDIO) were generated using a box-car function convolved with a hemodynamic-response function. Regressors of no interest, such as run effect and high-pass filtering with a cut-off period of 256 s, were also included. To test hypotheses related to regionally specific trial effects, the estimates for each model parameter were compared with the linear contrasts. The resulting set of voxel values for each contrast constituted a statistical parametric map (SPM) of the t statistic (SPM{t}).

2.5.3. Group analysis with a random-effect model

The weighted sum of the parameter estimates in the individual analysis constituted "contrast" images, which were used for group analyses (Friston et al., 1999). Contrast images obtained via individual analyses represented the normalized task-related increment of the MR signal of each participant. For each contrast, a one-sample Student t-test was performed for every voxel within the brain to obtain population inferences. The resulting set of voxel values for each contrast constituted an SPM{t}. The threshold value for the SPM{t} was $p < .001$ uncorrected at the voxel level and $p < .05$ with correction for multiple comparisons at the cluster level for the entire brain (Friston et al., 1996).

To specify the region(s) related to driving performance degradation and brain activation, correlation analysis between the distance CV and the percent BOLD signal change was performed. The regressor for the generalized linear model was the driving performance (CV) for each participant and condition. Statistical tests were performed inside the region in which activation for driving was suppressed (i.e. DRIVING–DUAL masked by DRIVING). The statistical thresholds were $p < .001$, uncorrected at the voxel level and $p < .05$, corrected for multiple comparisons at the cluster level.

3. Results

3.1. Task performance

The distance CV increased from 20.3% (SD = 4.46) in the driving-alone condition to 24.4% (SD = 6.08) in the driving with the auditory tasks condition ($t(17) = 4.14$, $p < .01$).

The sentence comprehension task accuracy was 88.9% (SD = 12.23) in the auditory-task-alone condition and 86.2% in the driving with the auditory tasks condition (not significantly different ($t(17) = 0.90$, $p = .381$)). The accuracy of the tone discrimination task was 96.5% (SD = 6.51) in the auditory-task-alone condition and 92.4% in the driving with the auditory tasks condition (not significantly different ($t(17) = 2.06$, $p = .055$)).

The mean reaction time for the sentence comprehension task in the auditory-task-alone condition was 1841 ms (SD = 300), whereas that in the driving with the auditory task condition was 1668 ms (SD = 320); these values were significantly different ($t(17) = 2.77$, $p < .05$). The mean reaction time for the tone discrimination task in the auditory-task-alone condition was 1053 ms (SD = 531 ms), whereas that in the driving with the auditory task condition was 1031 ms (SD = 485 ms); these values were not significantly different ($t(17) = 0.43$, $p = .676$).

3.2. Task-related brain activation

Group-level random-effect analysis in the three conditions (DRIVING, AUDIO and DUAL) showed large areas of activation. The DRIVING condition activated the bilateral cerebellum and basal ganglia, the left primary sensorimotor cortex, supplementary motor area (SMA), thalamus, midbrain, superior frontal gyrus and the right superior and inferior parietal lobule (SPL and IPL), middle temporal gyrus (MTG), superior frontal gyrus, middle frontal gyrus, and inferior frontal gyrus (IFG) (Table 1).

The AUDIO condition activated the bilateral primary auditory cortex, cerebellum, IPL, MTG, the left IFG, and pre-SMA, and the right superior temporal gyrus, SPL, and middle frontal gyrus (Table 2).

The DUAL condition activated the bilateral cerebellum and superior temporal gyrus, the left primary motor area, primary auditory cortex, SMA, superior frontal gyrus, the right inferior frontal gyrus, IPL, middle occipital gyrus, and middle frontal gyrus (Table 3).

3.3. Suppression of activation in the dual-task condition compared with each single-task condition

To find the suppressed region in DUAL inside the region activated by DRIVING, DRIVING was compared to DUAL masked by DRIVING (DRIVING–DUAL masked by DRIVING). The suppressed regions were the bilateral middle occipital gyrus, left cingulated gyrus, inferior occipital gyrus, and right superior parietal lobule, IPL, MTG, and fusiform gyrus (Fig. 2a and Table 4).

Table 1
Brain regions significantly activated by the driving task (DRIVING).

Cluster size (number of voxels)	Z score	MNI coordinates (mm)			Side	Location	BA
		X	Y	Z			
21,439	6.4799	24	−56	−26	Right	Cerebellum	–
	6.2813	24	−76	−12	Right	Fusiform gyrus	19
	5.6736	−32	−60	−30	Left	Cerebellum	–
	5.3156	46	−62	4	Right	Middle temporal gyrus	37
	4.9936	34	−90	14	Right	Middle occipital gyrus	19
	4.8066	−46	−78	−10	Left	Middle occipital gyrus	18
22,692	6.4619	−4	2	50	Left	Supplementary motor area	6
	6.2385	−24	−6	70	Left	Superior frontal gyrus	6
	6.1909	52	10	30	Right	Inferior frontal gyrus	9
	5.9977	−10	−18	0	Left	Thalamus	9
	5.9951	−34	−20	56	Left	Primary motor area	4
	5.8023	−12	−12	−6	Left	Midbrain	–
	5.7429	−22	8	6	Left	Lentiform nucleus	–
	5.5224	16	−10	−4	Right	Lentiform nucleus	–
3428	5.2701	38	−44	44	Right	Inferior parietal lobule	40
	3.9968	16	−62	66	Right	Superior parietal lobule	7
709	4.4043	38	40	20	Right	Middle frontal gyrus	10

BA, Brodmann area; MNI, Montreal Neurological Institute. The statistical threshold is $p < .001$ uncorrected at the voxel level and $p < .05$ corrected for multiple comparisons at the cluster level.

Table 2
Brain regions significantly activated by the auditory task (AUDIO-CTRL).

Cluster size (number of voxels)	Z score	MNI coordinates (mm)			Side	Location	BA
		X	Y	Z			
6535	5.6219	−40	−28	6	Left	Primary auditory cortex	41
	4.0746	−64	−50	4	Left	Middle temporal gyrus	21
	3.9267	−36	16	−6	Left	Inferior frontal gyrus	47
	3.9195	−52	12	18	Left	Inferior frontal gyrus	44
5039	6.3804	58	−22	0	Right	Superior temporal gyrus	22
	5.5932	60	−10	−8	Right	Middle Temporal Gyrus	21
	5.1605	46	−30	4	Right	Primary auditory cortex	41
1198	4.9574	−4	8	50	Left	Pre-supplementary motor area	6
728	3.8184	46	−50	48	Right	Inferior parietal lobule	40
	3.7246	40	−66	56	Right	Superior parietal lobule	7
233	4.3438	42	40	24	Right	Middle frontal gyrus	10
	3.2122	48	32	38	Right	Middle frontal gyrus	9
878	4.3316	−14	−52	−20	Left	Cerebellum	0
650	4.0809	−46	−36	46	Left	Inferior parietal lobule	40
276	3.941	28	−60	−28	Right	Cerebellum	–

BA, Brodmann area; MNI, Montreal Neurological Institute. The statistical threshold is $p < .001$ uncorrected at the voxel level and $p < .05$ corrected for multiple comparisons at the cluster level.

Table 3
Brain regions significantly activated by the dual task (DUAL–CTRL).

Cluster size (number of voxels)	Z score	MNI coordinates (mm)			Side	Location	BA
		X	Y	Z			
40,471	6.4331	28	−52	−30	Right	Cerebellum	–
	6.3614	−58	−26	10	Left	Primary auditory cortex	41
	6.3055	−4	2	52	Left	Supplementary motor area	24
	5.9775	−62	−42	16	Left	Superior temporal gyrus	22
	5.8114	58	−22	−2	Right	Superior temporal gyrus	21
	5.6203	−26	−6	70	Left	Superior frontal gyrus	6
	5.5555	−28	−60	−30	Left	Cerebelllum	–
	5.4661	−36	−18	58	Left	Primary motor area	4
	5.465	54	12	28	Right	Inferior frontal gyrus	9
373	4.7156	38	−44	44	Right	Inferior parietal lobule	40
482	3.5752	46	−84	−6	Right	Middle occipital gyrus	19
210	3.9976	38	40	20	Right	Middle frontal gyrus	10

BA, Brodmann area; MNI, Montreal Neurological Institute. The statistical threshold is $p < .001$ uncorrected at the voxel level and $p < .05$ corrected for multiple comparisons at the cluster level.

To find the suppressed region in DUAL related to AUDIO, AUDIO was compared to DUAL masked by AUDIO (AUDIO–DUAL masked by AUDIO). The suppressed region was the right MTG (Fig. 2b and Table 5).

3.4. Correlation between driving performance and brain activation in the driving and dual-task condition inside the suppressed region

Significantly correlated regions in the right hemisphere were the right postcentral gyrus, IPL, precuneus and lateral occipital complex (LOC), which include the inferior temporal gyrus, middle occipital gyrus, and fusiform gyrus (Fig. 3 and Table 6). In the left hemisphere, the correlated regions were the left LOC, which is the fusiform gyrus and inferior occipital gyrus. The most statistically prominent cluster was the right LOC.

3.5. Default mode network

The two peak voxels were identified by DRIVING–DUAL masked by negative DRIVING in the medial prefrontal cortex (MPFC) (Fig. 4a) and the left superior occipital gyrus (SOG) (Table 7). In the two identified peak voxels, the percent BOLD signal change was compared between DRIVING and DUAL and between AUDIO and DUAL. In both voxels, the activity of DRIVING was significantly higher than that of DUAL ($t(17) = 5.02$, $p < .01$ in MPFC; $t(17) = 6.60$, $p < .01$ in left SOG). The

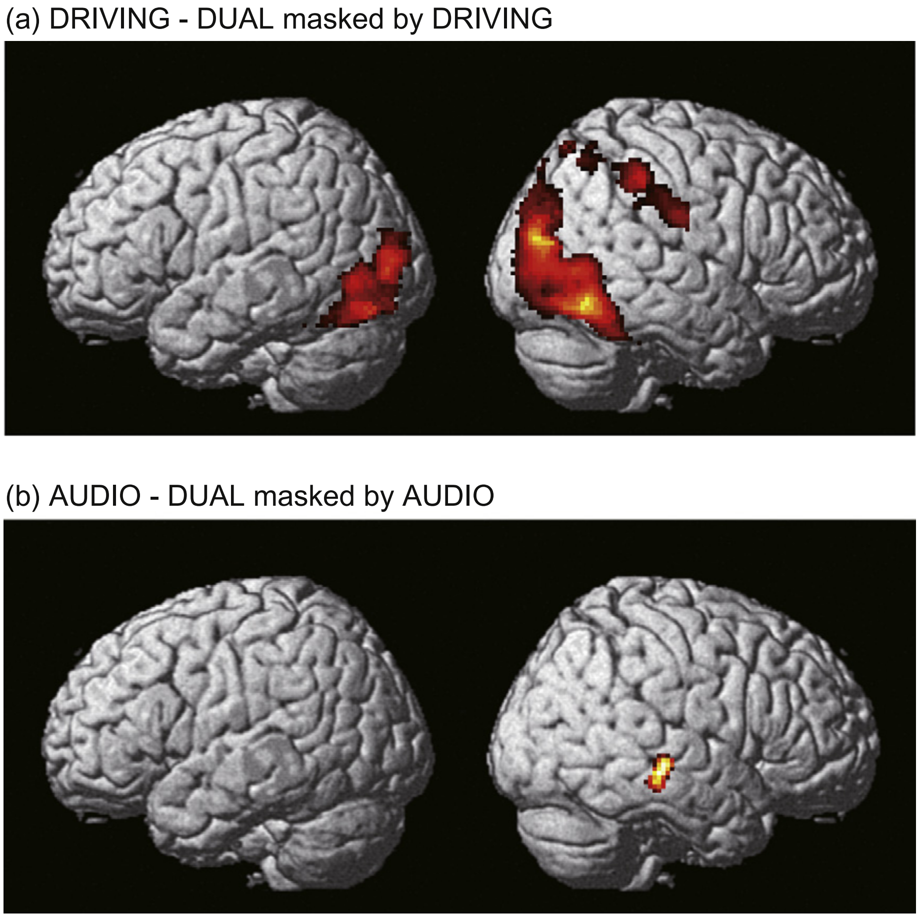

Fig. 2. Activation maps for the suppressed region of dual-task condition compared to each single-task condition (DRIVING or AUDIO) by the group-level random-effect analysis rendered on the standard anatomical 3D surface. (a) Dual-task condition was compared to the single-driving task condition inside the driving-task related region (DRIVING–DUAL masked by DRIVING). (b) Dual-task condition was compared to the single-auditory-task condition inside the auditory task related region (AUDIO–DUAL masked by AUDIO).

Table 4
Brain regions significantly more activated by the driving task than the dual task inside the activated regions by the driving task (DRIVING–DUAL masked by DRIVING).

Cluster size (number of voxels)	*Z* score	MNI coordinates (mm)			Side	Location	BA
		X	*Y*	*Z*			
3241	4.7727	50	−60	4	Right	Middle temporal gyrus	39
	4.5187	30	−64	−10	Right	Fusiform gyrus	19
	4.4093	38	−90	6	Right	Middle occipital gyrus	19
1566	5.003	−32	−88	12	Left	Middle occipital gyrus	19
	3.2516	−28	−88	−12	Left	Inferior occipital gyrus	18
515	4.4851	46	−36	44	Right	Inferior parietal lobule	40
329	4.1719	14	−68	58	Right	Superior parietal lobule	7
177	4.1243	−12	−24	46	Left	Cingulate gyrus	31

BA, Brodmann area; MNI, Montreal Neurological Institute. The statistical threshold is $p < .001$ uncorrected at the voxel level and $p < .05$ corrected for multiple comparisons at the cluster level.

Table 5
Brain regions significantly more activated by the auditory task than by the dual task inside the activated regions by the auditory task (AUDIO–DUAL masked by AUDIO).

Cluster size (number of voxels)	*Z* score	MNI coordinates (mm)			Side	Location	BA
		X	*Y*	*Z*			
158	4.057	64	−32	−14	Right	Middle temporal gyrus	21

BA, Brodmann area; MNI, Montreal Neurological Institute. The statistical threshold is $p < .001$ uncorrected at the voxel level and $p < .05$ corrected for multiple comparisons at the cluster level.

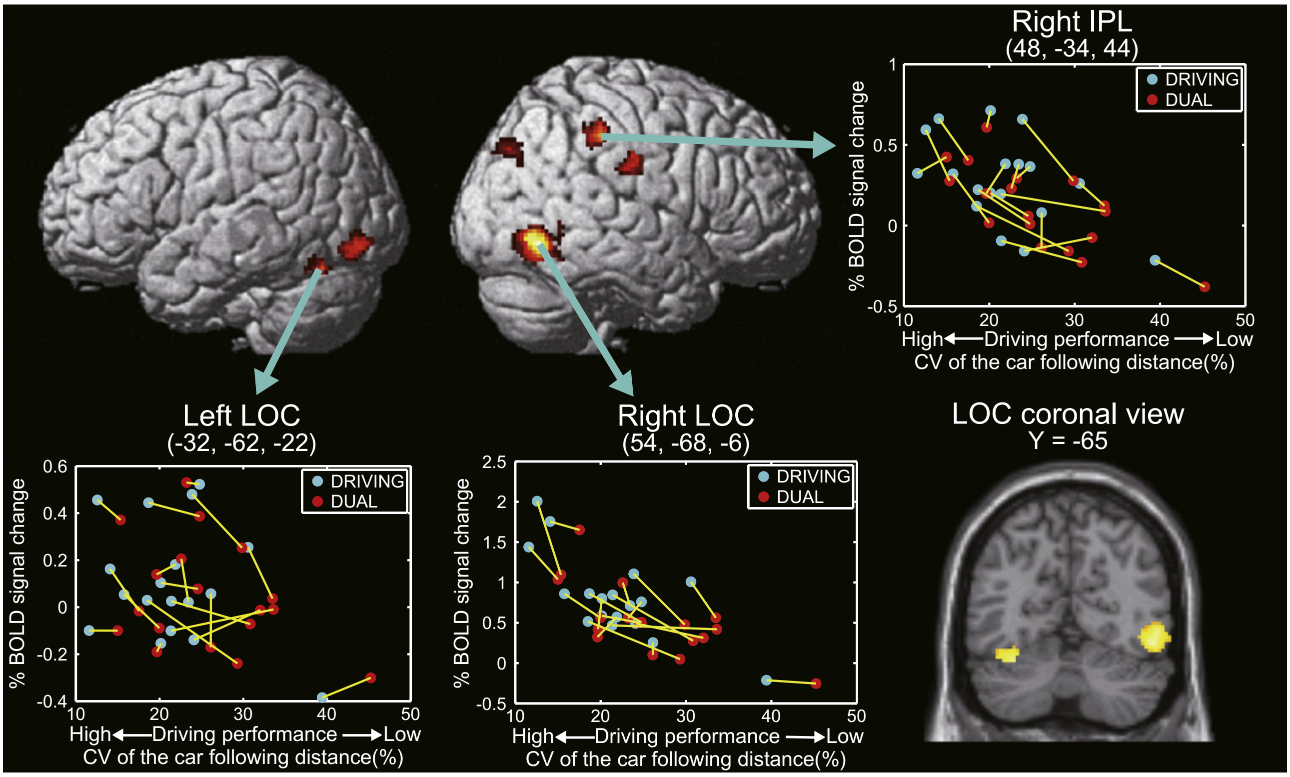

Fig. 3. In the top left and middle panel maps of the region, activation was correlated with the driving performance under the single-driving task condition and the dual-task condition inside the activation maps of Fig. 2a (i.e., the region where activation of the single driving condition was significantly larger than the dual-task condition). Scatter plots (top right, bottom left, and middle) show the correlation between the driving performance and the percentage BOLD signal change for each participant on the peak voxels of the right inferior parietal cortex (IPL) and the left and right lateral occipital complex (LOC). The driving performance is the coefficient of variation (CV) of the car-following distance. The large CV reflects that participants were unable to maintain a constant distance between the leading car and the own car. The yellow lines connecting the two data points of DRIVING and DUAL show that the points were taken from the same participant. The lower right panel portrays the coronal view of the region correlated with the driving performance of the bilateral LOC.

Table 6
Brain regions in which the activation of DRIVING and DUAL statistically significantly correlated to the driving performance.

Cluster size (number of voxels)	*Z* score	MNI coordinates (mm)			Side	Location	BA
		X	*Y*	*Z*			
407	5.0772	54	−68	−6	Right	Inferior temporal gyrus	37
	4.6466	50	−64	−12	Right	Middle occipital gyrus	37
	4.378	40	−52	−16	Right	Fusiform gyrus	37
76	4.6708	68	−18	34	Right	Postcentral gyrus	3
163	4.4178	−38	−62	−20	Left	Fusiform gyrus	37
118	4.2517	48	−34	44	Right	Inferior parietal lobule	40
118	4.1279	−44	−84	−10	Left	Inferior occipital gyrus	19
83	3.9572	28	−78	38	Right	Precuneus	19

BA, Brodmann area; MNI, Montreal Neurological Institute. The statistical threshold is $p < .001$ uncorrected at the voxel level and $p < .05$ corrected for multiple comparisons at the cluster level.

activity between AUDIO and DUAL revealed no significant difference ($t(17) = 1.54$, $p = .140$ in MPFC; $t(17) = 1.14$, $p = .269$ in left SOG) (Fig. 4c). Additionally for the same voxels, the percent BOLD signal change of our previous study (Uchiyama et al., 2003) was compared between passive viewing and DRIVING conditions. The fMRI data of the earlier study were reanalyzed using SPM5 using the same process as that described for this study. In the MPFC peak voxel, the activity of passive viewing was significantly higher than that of the DRIVING ($t(17) = 3.99$, $p < .01$) (Fig. 4b). In the left SOG peak voxel, no significant difference was found ($t(17) = 1.69$, $p = .107$).

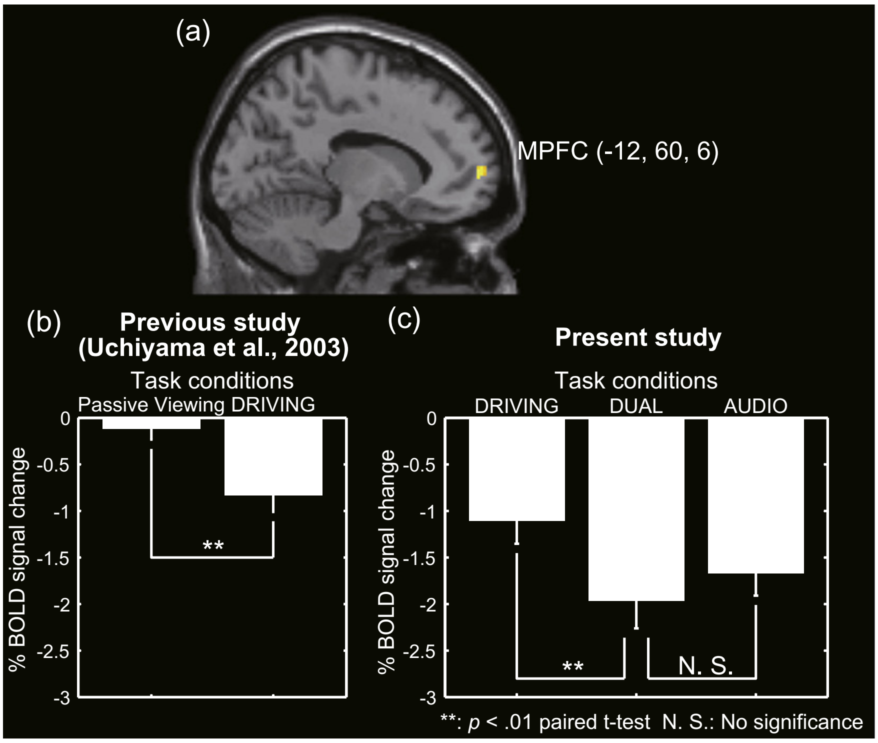

Fig. 4. Task-induced deactivation in the MPFC. (a) Region was identified by the DRIVING–DUAL masked by negative DRIVING. (b) Comparison of deactivation between passive viewing and DRIVING in our previous study (Uchiyama et al., 2003) in the MPFC peak voxel (−12, 60, 6). (c) Comparison of deactivation between each task condition in this study in the MPFC peak voxel (−12, 60, 6).

Table 7
Brain regions significantly more activated by the driving task than by the dual task inside the deactivated regions by the driving task (DRIVING–DUAL masked by negative DRIVING).

Cluster size (number of voxels)	*Z* score	MNI coordinates (mm)			Side	Location	BA
		X	*Y*	*Z*			
104	4.5858	−38	−86	28	Left	Superior occipital gyrus	19
174	3.881	−12	60	6	Left	Medial prefrontal cortex	10

BA, Brodmann area; MNI, Montreal Neurological Institute. The statistical threshold is $p < .001$ uncorrected at the voxel level and $p < .05$ corrected for multiple comparisons at the cluster level.

4. Discussion

4.1. Driving task activation

The activated region of the DRIVING replicated the results of our previous driving study (Uchiyama et al., 2003) well. The activities of the bilateral SMA, premotor region, basal ganglia and cerebellum, the left primary motor area, and the right parietal region are almost identical to those our previous study. The regions that differed between the current study and our previous study are the bilateral occipital region and the right middle frontal gyrus (BA10). These regions were not activated in our previous study. These differences might result from differences in the experimental designs of the respective studies.

Brain activation in the bilateral occipital region was found not to be significant in our earlier study because the findings for driving specific regions the active driving condition were contrasted against the passive viewing condition. Consequently, the vision-related bilateral occipital regions were not activated in our previous study.

Activation of the right middle frontal gyrus might be related to the task-switching process. The area was activated commonly in the DRIVING, AUDIO, and DUAL conditions. The region was related to the central executive system, which controls attention and information flow (D'Esposito et al., 1995). This might be related to the preparation process for the other task start.

4.2. Suppression of brain activation during the car-following task with the auditory task

4.2.1. Bilateral occipital region

The bilateral occipital regions were suppressed in the DRIVING–DUAL contrast (Fig. 2a and Table 4) and in the statistical test of correlation between brain activation and driving performance (Fig. 3 and Table 6).

Numerous reports describe the roles of the bilateral LOC in visual perception of interactions between objects (Kim & Biederman, 2010), of animacy (Morito, Tanabe, Kochiyama, & Sadato, 2009), of faces (e.g. fusiform face area, FFA) (Grill-Spector, Knouf, & Kanwisher, 2004; Kanwisher, McDermott, & Chun, 1997), of biological motion (Grossman & Blake, 2002), and of body and body parts, but not of faces (e.g. extrastriate body area, EBA) (Grossman & Blake, 2002). The MNI coordinates of the peak voxel derived from these studies and the distance between the peak voxel of our study and those of the selected studies are presented in Table 8 and Fig. 5. The distance between the peak voxels of our study and of those reported by Kim and Biederman (2010) is the shortest among those shown in Table 8. That short distance implies the common functional role assessed in the study by Kim and Biederman (2010) and in our study. In the report by Kim and Biederman (2010), the activation of LOC when the scenes depicted the interaction of two objects was presented as higher than when the scenes depicted two objects side by side. The results suggest that the role of the bilateral LOC is object interaction. In our study, the car-following task involves a similar process to that assessed in the study by Kim et al. In the simulated car-following task, to maintain constant distance between the leading car and one's own, participants were asked to observe the distance. The simulated scene was presented without 3D depth information. Consequently, participants were asked to direct their attention to evaluation of the leading car's position on the road. This evaluation process might involve the perception of the interaction of two objects: the leading car and the road.

4.2.2. Right parietal region

The right parietal region was suppressed in the DRIVING–DUAL contrast (Fig. 2a and Table 4). Furthermore, brain activation of the right IPL was correlated with the driving performance (Fig. 3 and Table 6). In the driving dual-task study conducted by Just et al. (2008), the bilateral parietal regions were suppressed in the dual-task condition in comparison to the single-driving condition. Suppression of the left parietal region differed between that found in the study by Just et al. (2008) and in the present study. This difference might have resulted from the difference of the driving tasks: a lane-keeping task and the car-following task. Originally the left parietal activation of the driving-alone conditions between these two studies differed. The left parietal region was activated in the study by Just et al. and not in our study. This left parietal activation difference might result from the attention control directions: the lateral direction for the lane-keeping task and the depth direction for the car-following task. For the lane-keeping task on a winding road, drivers must move their scope of attention horizontally to gain information of the tangent point on the inside of the curve (Land & Lee, 1994). Such horizontal visual attention control requires the activity of the bilateral parietal region (Posner, Walker, Friedrich, & Rafal, 1984; Schluppeck, Curtis, Glimcher, & Heeger, 2006; Sereno, Pitzalis, & Martinez, 2001). Posner et al. reported that patients with parietal damage exhibited delayed response to the cues on their ipsilateral side but showed no delay on their contralateral side (Posner et al., 1984). Neuroimaging studies support these results (Schluppeck et al., 2006; Sereno et al., 2001).

The correlation results of the right IPL are consistent with the functional roles of the region revealed in previous studies. Many reports describe the roles of the right IPL in spatial transformation from auditory information to hand movement (Zatorre, Bouffard, Ahad, & Belin, 2002), polymodal motion processing (i.e., a region in the right IPL responds to moving visual, auditory, and tactile stimuli) (Bremmer et al., 2001), coding of the plausibility of actions (Costantini et al., 2005), distinction between self-produced actions and those generated by others (Ruby & Decety, 2001), and depth perception in near viewing (Quinlan & Culham, 2007). The MNI coordinates of peak voxel derived from these studies and the distance

Table 8
Distance of peak voxels between our LOC VOIs in which brain activity correlated with car-following performance and VOIs in which selected studies derived activation around LOC.

Study	Functional role	Left				Right				Marker color in Fig. 5
		MNI coordinates (mm)			Distance (mm)	MNI coordinates (mm)			Distance (mm)	
		X	Y	Z		X	Y	Z		
Present study	–	−38	−62	−20	0	40	−52	−16	0	Red
Kim and Biederman (2010)	Interaction between objects	−39.3	−57.6	−17.3	5.36	37.5	−56.6	−16.9	5.28	Blue
Morito et al. (2009)	Animacy	−46	−72	−8	17.55	–	–	–	–	Green
Grill-Spector et al. (2004)	Fusiform face area (FFA)	−37.4	−42.4	−21.5	19.65	39.4	−40.4	−21.4	12.85	Violet
Grossman and Blake (2002)	Biological motion	−41.7	−55.0	9.9	30.98	46.6	−50.6	10.8	27.66	Yellow
Grossman and Blake (2002)	Extrastriate body area (EBA)	−39.7	−72.9	10.8	32.75	41.0	−68.2	7.9	28.92	Cyan

MNI, Montreal Neurological Institute.

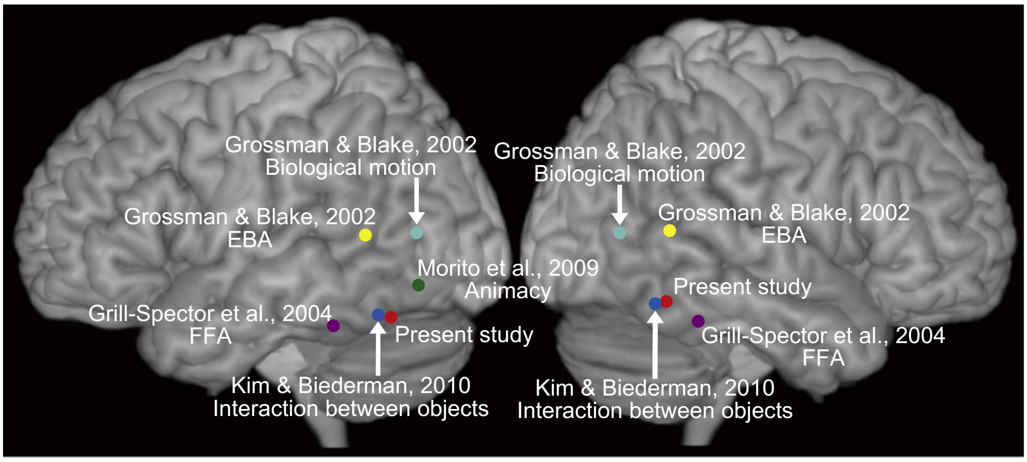

Fig. 5. Positions of peak voxels of Table 8 in which the brain activity was correlated with the car-following performance in bilateral LOC and other selected previous studies showed some functional role around the bilateral LOC from the left and the right sides of the brain. The left panel shows peak voxels for the left hemisphere. The right panel shows those for the right hemisphere. Positions shown as colored circles represent the *Y* and *Z* MNI coordinates.

Table 9
Distance of peak voxels between our right IPL VOI in which brain activity correlated with car-following performance and VOIs in which selected studies derived activation around the right IPL.

Study	Functional role	MNI coordinates (mm)			Distance (mm)	Marker color in Fig. 6
		X	*Y*	*Z*		
Present study	–	48	−34	44	0	Red
Zatorre et al. (2002)	Spatial transformation	47	−28	48	7.28	Blue
Bremmer et al. (2001)	Polymodal motion	38.4	−47.7	47.5	17.09	Green
Costantini et al. (2005)	Impossible hand movement	64	−28	40	17.55	Purple
Ruby and Decety (2001)	Third person simulation	50	−58	30	27.86	Yellow
Quinlan and Culham (2007)	Depth perception	26	−50	52	28.35	Cyan

MNI, Montreal Neurological Institute.

between the peak voxel of our study and those of the selected studies are presented in Table 9 and Fig. 6. The distance between the peak voxels of our study and that of Zatorre et al. (2002) is the shortest in Table 9. In a study conducted by Zatorre et al. (2002), participants move the joystick to indicate the position of perceived sound. The brain activity of the right IPL was correlated to the localization performance. The results suggest that the role of the right IPL is spatial transformation from sensory information to hand movement. In our study, the car-following task required a similar process to that described for the study by Zatorre et al. (2002), which is transformation from the information of the driving scene, the distance and the relative movement between the driver's own car and the leading car, to the joystick movement with the right hand. This transformation process is indispensable for the car-following task. Consequently, our correlation results between the brain activity of the right IPL and car-following performance suggest that the auditory task interferes with the transformation process from visual information to hand movement.

4.3. Suppression of brain activation related to the auditory task with the car-following task

Regarding the activated region by AUDIO condition, DUAL suppressed the activities of the right middle temporal gyrus (Fig. 2b and Table 5). This decrease of activity of the temporal region by a visual task was observed in earlier dual task neuroimaging studies (Johnson & Zatorre, 2005; Newman et al., 2007). In this study, suppression was observed only on the right MTG. This asymmetric suppression on the MTG might result from the functional difference between the left and the right MTGs for sentence comprehension processing. The left temporal region mainly processes syntactic and semantic information. The right temporal region processes prosodic information for auditory sentence comprehension (Friederici & Alter, 2004). The driving task might interfere with prosodic information processing, but it might not interfere with syntactic and semantic information processing.

4.4. Default mode network

Inside the region deactivated by DRIVING, more deactivated regions by DUAL were MPFC and left SOG than by DRIVING (Table 7 and Fig. 4). This deactivation pattern is consistent with those described in reports of studies of DMN (McKiernan et al., 2003; Raichle et al., 2001).

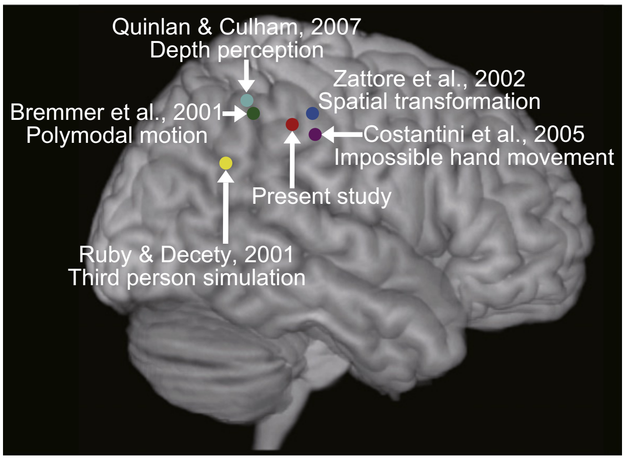

Fig. 6. Positions of peak voxels of Table 9 in which the brain activity was correlated with the car-following performance in right IPL and other selected previous studies showing some functional role around the right IPL from the right side of the brain. The positions shown as colored circles represent the *Y* and *Z* MNI coordinates.

In the MPFC, the order of the deactivation level compared to REST is the following: DUAL, DRIVING, passive viewing (Fig. 4). The REST and DRIVING task of the present study are the same as the conditions of the rest and driving task (active car-following) of our previous study (Uchiyama et al., 2003), respectively, except for the task duration. The passive viewing task was to observe the car-following scene that was performed by the participant during the prior session. Consequently, the deactivation level of the DRIVING of this study and the active car-following condition of the previous study are regarded as the same level.

This order of the MPFC deactivation level is consistent with the results presented by McKiernan et al. (2003). McKiernan et al. (2003) demonstrated that deactivation increases more difficult tasks. In our present and our previous studies, the order of the task difficulty is the following: DUAL, DRIVING, passive viewing. This order of difficulty matched the order of the MPFC deactivation level. Moreover, it is consistent with the conclusions reported by McKiernan et al. (2003).

4.5. Limitations of this study

In this discussion, the correlation results in the right IPL and bilateral LOC respectively suggest correlation with functions of the spatial transformation from sensory information and the perception of the interaction of two objects. To support this inference, the distances of MNI coordinates of a few arbitrarily selected studies were explored. Additionally, the functional selectivity of these regions might be narrower than we expected. However, these approaches linking the driving task and simple cognitive tasks through the brain imaging studies might be useful to proceed with studies of driving. To divide the driving task into simple cognitive tasks was necessary to assess some aspects of driving studies, to produce a driving behavior model (Groeger, 2000), and to produce a method of evaluating elderly drivers' abilities (Owsley, 1994). For such studies, the selection of cognitive task depends on the insights of researchers. Functional brain imaging studies of driving are expected to be useful to obtain novel hypotheses related to driving and simple cognitive tasks.

5. Conclusions

Car-following performance impairment by the auditory task is correlated with brain activity on the bilateral LOC and the right IPL. In the MPFC and left SOG, brain activity in the dual task condition was lower than that of the single-driving task condition. These results suggest that the decline of brain activity in these regions may induce car-following performance deterioration.

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