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The neural substrates of driving at a safe distance: a functional MRI study

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Abstract

An important driving skill is the ability to maintain a safe distance from a preceding car. To determine the neural substrates of this skill we performed functional magnetic resonance imaging of simulated driving in 21 subjects. Subjects used a joystick to adjust their own driving speed in order to maintain a constant distance from a preceding car traveling at varying speeds. The task activated multiple brain regions. Activation of the cerebellum may reflect visual feedback during smooth tracking of the preceding car. Co-activation of the basal ganglia, thalamus and premotor cortex is related to movement selection. Activation of a premotor-parietal network is related to visuo-motor co-ordination. Task performance was negatively correlated with anterior cingulate activity, consistent with the role of this region in error detection and response selection.

Keywords: Driving; Functional MRI; Basal ganglia; Visuo-motor coordination; Cerebellum; Premotor cortex; Blood flow

Driving is a complex task requiring many psychological processes including perception, attention, learning, memory, decision making and action control. Understanding the psychological process of driving is important for car safety. Although little is known about the psychological process of following a preceding car, drivers clearly derive speed and distance information from their environment mainly through the visual system [7]. This visual information is then used to decide whether to accelerate or decelerate the car; hence on-line error detection and prevention is required. One of the important skills for safe car driving is remaining at a safe distance from the preceding car while it varies its speed. Failure to keep a safe distance can cause rear-end collisions, which are one of the most common types of traffic accidents and account for 30% of all traffic accidents in Japan [18] and the United States [17]. The neural substrates of the behaviours involved in following a preceding car are not known. Indeed, few functional MRI (fMRI) studies have been conducted to explore any of the neural mechanisms of car driving. Walter et al. [19] reported the result of a simulated driving task without any other traffic. Calhoun et al. [1] conducted fMRI of a complex driving task that required overtaking other traffic and maintaining speed. Functional neuroimaging studies focusing on maintaining a safe driving distance have not previously been performed. The purpose of the present study is to determine the neural substrates of maintaining a safe driving distance and to identify brain regions that correlate with task performance.

Twenty one right handed healthy volunteers (16 men and five women, mean age 33.5 ± 5.8 years) participated in this study. There was no history of neurological or psychiatric illness or developmental disorders including reading disabilities. The protocol was approved by the ethical committee of the National Institute for Physiological Sciences, and all subjects gave their written informed consent for the study.

Car driving was simulated using a home-made driving simulator (Toyota Central R&D Labs., Inc., Nagakute, Japan) (Fig. 1). The non-ferromagnetic and shielded joystick controller was connected to a computer outside the scanner room though a waveguide in the wall. An LCD projector (DLA-M200L; Victor, Yokohama, Japan) outside the scanner room and behind the scanner projected through another waveguide to a translucent screen, which the subjects saw via a mirror attached to the head coil of the 3 Tesla MRI scanner (Allegra; Siemens, Erlangen, Germany).

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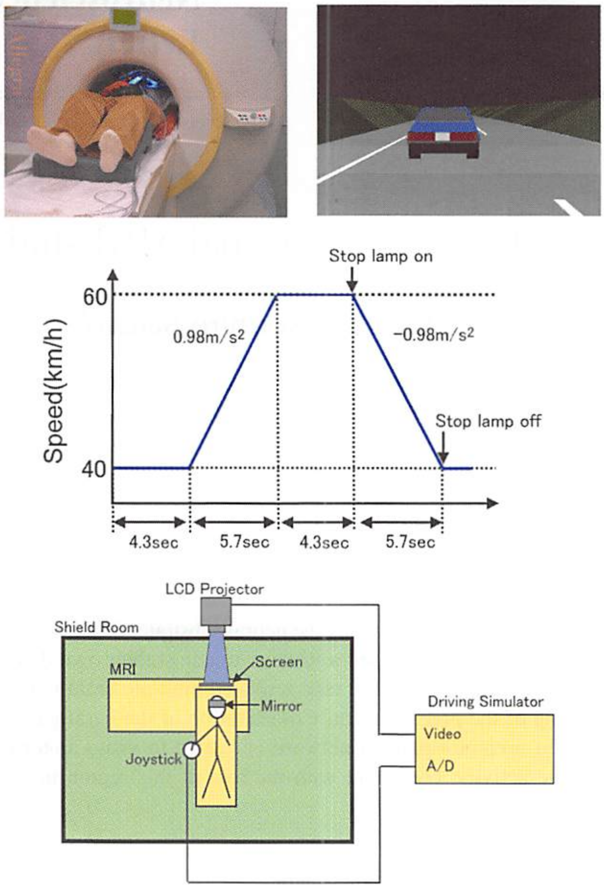

Fig. 1. Experimental setup for functional MRI (bottom). The subject manipulates the speed of the simulated car using a joystick on his or her abdomen (upper left). Screenshot from the driving simulator (upper right), and temporal pattern of the velocity of the preceding car (middle) are also shown.

The screen subtended approximately 40° in width and 30° in height of visual field. In the driving scene on the screen, the road was straight and two lanes wide without any other traffic except a single preceding car. The subject controlled the speed of their own car by manipulating the joystick back and forth with the right hand. No steering control was required.

The experiment consisted of an active car-following session (active session) and a passive car-following session (passive session). The active car-following session consisted of three pairs of a control epoch and a task epoch. Each epoch was 1 min in duration. During control epochs, the subject viewed the screen of the driving simulator following the preceding car automatically, travelling straight ahead at 50 km/h, at a distance of 5 m from the preceding car. During task epochs, when the preceding car was accelerating or decelerating, the subject was required to keep the distance between the cars distance as close to 5 m as possible by manipulating the joystick. The speed pattern of the preceding car during task epochs of the active session is shown in Fig. 1. During task epochs, the preceding car initially maintained a constant speed of 40 km/h for 4.3 s, linearly accelerated for 5.7 s to reach and maintain a speed of 60 km/h for 4.3 s, then linearly decelerated for 5.7 s, returning back to 40 km/h. This pattern lasted 20 s and was repeated three times in one task epoch. During the deceleration phase the brake lights of the preceding car were turned on. Performance was measured by the standard deviation of the distance between the cars divided by the mean (coefficient of variation, CV). Therefore, smaller values of CV value indicated better performance. The CV was calculated for each task epoch of the active session. During the passive session, the subject did not manipulate the joystick and passively viewed the scene from the preceding active session that had been recorded and was replayed.

The active session and passive session were repeated twice. So that we were able to replay the scene from the preceding active session during the passive session, the subject always began with the active session. Before the experiment the subjects practiced the active session three times.

In each session, a time course series of 125 volumes were acquired using T2*-weighted, gradient echo, echo planar imaging sequences with the 3.0 Tesla MR imager. Each volume consisted of 32 transaxial slices, with a slice thickness of 4 and 0 mm gap, which covered the entire cerebral and cerebellar cortex. The time interval between two successive acquisitions of the same image was 3000 ms with an 84° flip angle, and the echo time was 30 ms. The field of view was 192 mm and the in-plane matrix size was 64×64 pixels. For anatomical reference, T1-weighted images were also obtained. The data were analyzed using statistical parametric mapping (SPM99; Wellcome Department of Cognitive Neurology, London, UK) [4,5]. Following realignment anatomical normalization, all images were filtered using a Gaussian kernel of 10 mm (full width at half maximum) in the x, y, and z axes.

Statistical analysis in the present study was conducted at two levels. First, individual task-related activation was evaluated. Second, the summary data for each individual were incorporated into the second level analysis using a random effects model to make inferences at a population level. The signal was proportionally scaled by setting the whole-brain mean value to 100 arbitrary units. The signal time course for each subject was modeled using a box-car function convolved with a haemodynamic response function and temporally high pass filtered using a filter of 256 s width. Session effects were also included in the model. The explanatory variables were centered at zero. To test hypotheses about regionally specific condition effects (i.e. active − passive), estimates for each model parameter were compared using the linear contrasts. The resulting set of voxel values for each contrast constituted a statistical parametric map (SPM) of the t statistic (SPM$\{t\}$). The threshold for SPM$\{t\}$ was set at $P < 0.05$ with a correction for multiple comparisons.

The weighted sum of the parameter estimates in the individual analyzes constituted 'contrast' images, which were used for the group analysis. Contrast images obtained via individual analyzes represent the normalized task-related increment of the MR signal of each subject. To examine activation without the effect of visual perception, the active session was contrasted with the passive one. A one sample Student's t-test was performed for every voxel within the brain to obtain population level inferences. To identify areas in which activation correlated with driving task performance measured by CV, the contrast images were also entered into a simple correlation model. The resulting set of voxel values for each contrast constituted a statistical parametric map of the t statistic (SPM{t}). The threshold for SPM{t} was set at $P < 0.05$ with a correction for multiple comparisons.

The driving task activated multiple cortical regions including the bilateral cerebellum, basal ganglia, pulvinar nuclei of the thalamus, ventral and dorsal premotor cortex, inferior parietal lobule, left primary sensorimotor cortex, supplementary motor area (SMA) and anterior cingulate cortex (ACG) (Fig. 2).

Adjacent to the anterior cingulate activation, a region on the periphery of the ACG showed activation that was negatively correlated with task performance (Fig. 3). This suggests that subjects with poorer performance recruited the ACG more extensively.

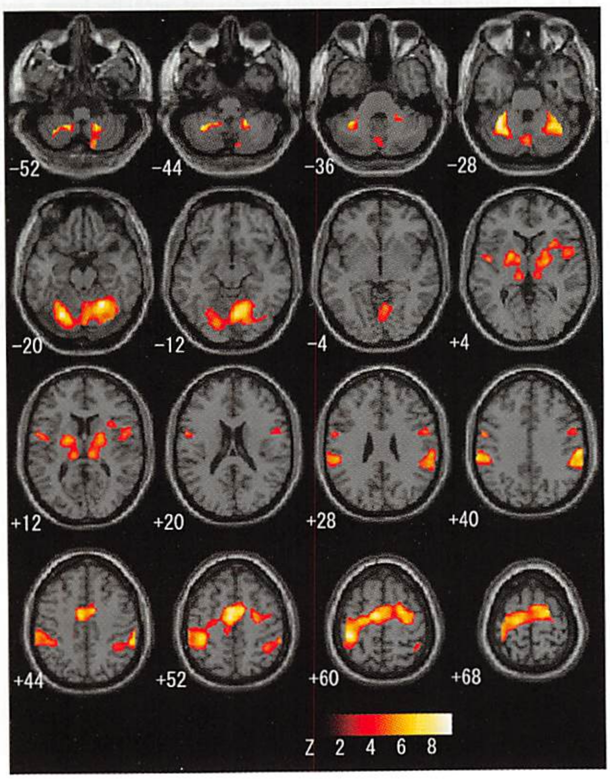

Fig. 2. Statistical parametric maps of the enhanced neural activity during the active car-following (active) session compared with the passive viewing (passive) session. Activated foci are shown as a pseudocolor functional MRI superimposed on a high-resolution anatomical MRI in contiguous 16 transaxial planes with an 8 mm interval, extending from 52 mm below the AC-PC plane (top left) to 68 mm above the AC-PC plane (bottom right). The statistical threshold was $P < 0.05$ with a correction for multiple comparisons.

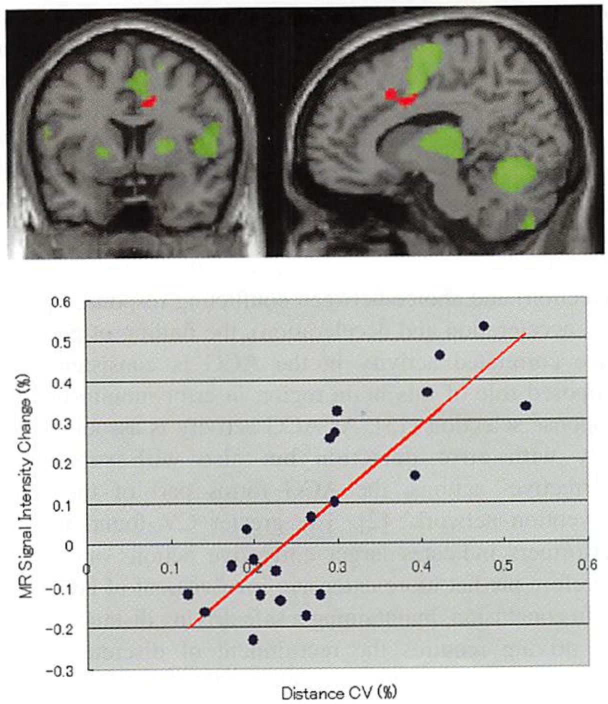

Fig. 3. Statistical parametric maps showing task-related neural activity during the active car-following period that positively correlated with the CV (i.e. negatively correlated with task performance). The focus of activation is shown as a pseudocolor functional MRI superimposed on a high-resolution anatomical MRI in the coronal (upper left) and sagittal (upper right) planes, sectioned at x = 12 mm, y = 6 mm, and z = 36 mm in Talairach's coordinates, a location corresponding to the anterior cingulate gyrus. Red indicates significant positive correlation with CV and green indicates activation during active sessions compared with passive sessions. Task related MR signals in the anterior cingulate gyrus (x = 12 mm, y = 6 mm, and z = 36 mm in Talairach's coordinates) of each subject are plotted against their CV (bottom). Significant positive correlations between the task-related MR signal changes and CV are shown ($P = 0.039$, corrected for multiple comparisons).

The task in the present study involved smooth tracking with visual feedback. During online control of smooth tracking movements, visual feedback is predominantly processed by the cerebellum [8,11,16]. The present finding of activation in the bilateral cerebellar hemispheres and dentate nuclei is consistent with this notion.

The basal ganglia-cortex pathway is more concerned with selection of appropriate movements or muscle activations than with visuomotor guidance [10,12]. The basal ganglia can focus on and filter desired motor patterns during movement, optimizing them and inhibiting unwanted movements [15]. The co-activation of the basal ganglia, thalamus and premotor cortex is thus suggestive of the involvement of the basal ganglia loop with premotor cortical areas monitoring the spatial location of different movement cues [14].

Activation of the premotor-parietal network may be related to visuo-motor coordination. Previous studies involving non-human primates [9], as well as human neuroimaging studies [3,6], have revealed that visuomotor control involves the dorsal premotor and parietal areas working in concert to select, prepare, and execute movements.

During active sessions compared with the rest condition, performance was negatively correlated with the activity of the anterior cingulate gyrus. Considering that the task of maintaining a safe driving distance requires the continuous evaluation of the distance between the cars (i.e. error detection) and choice between conflicting response options (i.e. acceleration and deceleration), the finding of performance correlated activity in the ACG is consistent with proposed role of this brain region in error monitoring and response selection [13]. As ACG activity is associated not only with error detection but also with subsequent 'corrective' actions, the ACG forms part of the 'error prevention network' [2]. The greater CV found in poor performers indicates larger corrective actions and would therefore predict more extensive involvement of ACG.

In conclusion, maintaining a safe driving distance during car driving requires the recruitment of discrete sets of cortical and subcortical regions that are related to visuomotor control and to error detection and prevention.

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