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Using fMRI to Explore the Influence of Road Network Patterns on Geospatial Cognition

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Abstract: Road networks play an important role in our daily life. People strongly interact with roads in commuting and tourism. The road network patterns influence human cognition, behaviour and the road safety. However, how the influence takes places remains unclear. In this paper, we experiment with fMRI (functional Magnetic Resonance Imaging) to explore the influence of regular and irregular road networks on spatial cognition. Nine subjects were asked to accomplish orientation and shortest-route-selection tasks in both a regular and an irregular road network using street view. SPM (Statistical Parametric Mapping) was used to analyse the brain activities in the process. The results of orientation tasks show more activation in the middle frontal gyrus, relating to cognition, the superior frontal gyrus, relating to voluntary movement and eye movement, and the medial frontal gyrus, relating to executive process in irregular road network. The results indicate that the orientation task in an irregular road network is more demanding and requires more information. For shortest route selection tasks in both road networks, no common active brain areas among different subjects were found. This indicates that the associated cognition process is hardly influenced by road network patterns. In summary, orientation tasks are harder for subjects in irregular road networks, while the cognition difficulty is almost the same for shortest-route-selection tasks in regular and irregular road networks. Besides, subjects tend to use egocentric frame of reference more and switch between ego- and allocentric frame of reference more frequently in irregular road networks.

Keywords: Road network patterns, spatial cognition, fMRI, spatial orientation

1. Introduction

Roads are important in people's daily life, whether commuting or tourism, as they are essential to the movement between any two places. Previous studies have found that road network patterns can influence people's cognition (Byrne 1979, Green 1994), behaviour (Fitzpatrick, Carlson et al. 2001, Hochmair and Karlsson 2004) and traffic safety (Haynes, Lake et al. 2008, Hamdar, Qin et al. 2016). However, what results in such differences are not clear. In this study, we aim to explore how the road networks influence the cognition process in wayfinding.

During the last decades, functional magnetic resonance imaging (fMRI) has attracted researchers' interests in spatial cognition. The current widely used technology is blood-oxygen-level dependent fMRI (BOLD fMRI), which measures the blood oxygen level in brain. When a certain brain area is in use, blood flow to this area would increase, then the oxygen-rich blood overcome consumption of oxygen and results in an increase of blood oxygen level. This can further changes the magnetic field and thus be detected by machine. Previous spatial studies based on fMRI are mainly done by psychologists, who usually cared more about orientation, picture recognition and other cognition issues in small scale. However, these small-scale abilities have no strong relationship with environmental spatial ability (Hegarty, Richardson et al. 2002, Wakabayashi and Ishikawa 2011) and it is till recently that researchers start applying fMRI on geospatial ability and cognition study.

Although it was difficult to apply fMRI or other technologies based on certain neurons on geospatial ability study (Griffin and Robinson 2010), researchers realize the importance of carrying on the investigations of fMRI for geospatial ability study. Montello (2009) proposed in 2009 that fMRI is going to play an important role in geoscience cognition study. Lobben, Olson et al. (2005) first reported more activated voxels in sleuthing tasks than in map rotation based on the fMRI results of one single subject. They also found that for this subject, map rotation involved right hemisphere more actively than left, while sleuthing task initiated both hemispheres equally. Later, Lobben, Lawrence et al. (2009) reviewed fMRI-based researches related to cartography and concluded that fMRI is promising in geography-specific studies and would help improving the theories of map design and map use.

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Furthermore, some evidence show that cingulate gyrus, parahippocampal gyrus, superial temporal gyrus and middle temporal gyrus play important roles in navigation related tasks (Lawrence 2011, Schinazi, Nardi et al. 2013, Howard, Javadi et al. 2014, Spiers and Barry 2015, Boccia, Guariglia et al. 2016). Therefore, we focus on the function of frontal and temporal lobes in this study.

2. Method

2.1 Experiment design

In this study, we aim to explore the influence of regular and irregular road networks on spatial cognition based on fMRI experiment. Regular road networks are those with orthogonal intersections and straight segments, and irregular road networks are roads with non-orthogonal intersections or curved segments. We instructed all subjects to perform orientation (ORI) and shortest-route-selection (SRS) tasks, which are very common in daily life and can reflect people's sense of distance and direction, in both networks.

The experiment was conducted in two days. On Day 1, the subjects were asked to use street view maps to familiarize themselves with a regular and an irregular road network. On Day 2, they needed to complete a set of ORI and SRS tasks based on the road networks they learned the day before, while being scanned in a magnetic resonance imaging machine.

2.2 Subjects

Nine right-handed students (5 males and 4 females; age = 26.8±3.6 years) from universities in Beijing participated in the experiment. All subjects had normal or corrected-to-normal vision, without having or having had neurological or psychiatric disorders. The experiment data of 2 male subjects were excluded in the analyses due to movement. The study was approved by the Institutional Review Board of Beijing Normal University, and all subjects signed the written informed consent.

2.3 Apparatus

FMRI scanning was conducted at the BNU Imaging Center for Brain Research, Beijing, China, on a Siemens 3T scanner (MAGENTOM Trio, a Tim system) with a 12-channel phased-array head coil. Whole brain structural T1-weighted scan were acquired with a 3D magnetization-prepared rapid acquisition gradient-echo pulse sequence (MP-RAGE, TR = 2530 ms, TE = 3.45 ms, flip angle = 7°, slice thickness = 1 mm, matrix size = 256×256, voxel size = 1.0×1.0×1.0 mm, sagittal orientation).

2.4 Materials

Considering the fact that pedestrians, weather and traffic conditions will influence the subjects' memory of the road network (Fotios, Uttley et al. 2015), we used street views from Google Maps as experiment material in this study. A part of business areas in Stamford, Lincolnshire and Ashton-under-Lyne, Greater Manchester served as the study area for irregular road networks and regular road networks, respectively (Figure 1). On Day 1, we asked the subjects to learn and remember the road networks using Google Maps while road labels and compass were shown and other widgets were hidden using Google Maps API (https://developers.google.com/maps/documentation/javascript/tutorial). On Day 2, the materials used in the ORI and SRS tasks were screenshots of Street View (1024 * 640), in which the road signs were removed, leaving only the compass.

Figure 1 Experiment area (from Google Maps, (a) for irregular road network and (b) for regular road network).

2.5 Procedure

On Day 1, we first obtained written informed consents from each subject and explained the ORI and SRS tasks to them using the street view from Baidu Maps of the area near Beijing Normal University (Table 1), which was familiar to them. After knowing how to move in Google Street View freely by mouse or keyboard, subjects were guided to "walk" along the boundaries of the irregular road network in street view and asked to remember the specified area by traveling in it. Finally, we provided 10-12 screenshots of street view and required subjects to judge whether the screenshots were from the road network they had learned within 5 s for each. If the accuracy was above 90%, the same procedure would begin for the regular road network. Otherwise, the subjects needed to continue "walking" in the area.

One Day 2, first we confirmed with the subjects about the safety regulations again. Then they were explained the task instructions (Table 1) and required to answer some example questions to prove they understood the tasks correctly. During the task phase, no further instruction would be provided unless the task section changes (i.e. from ORI to SRS). Event-related design was used in the fMRI experiment, including anatomical MRI scan, resting state fMRI scan and 4 task fMRI scans (10 trials for each

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task scan). The process of the scan was as follow: T1 anatomical scan with 10 min, resting state scan with duration 200TR (400 s), task fMRI scan with duration 4*116 TR (4*232 s, TR = 2000 ms, TE = 30 ms, flip angle = 90°, FOV = 220 mm, resolution = 64, matrix size = 384×384, voxel size = 3.125×3.125×3.5 mm, interleaved odd sequence). The tasks were presented in the sequence of Ir-ORI (Orientation tasks in irregular road network), R-Ori, Ir-SRS (Shortest-Route-Selection tasks in regular road network), and R-SRS. For each trial, first there would be a black picture with a white "+" at the middle for 2 s, then the picture of destination for 6 s, and the picture of current position where participants should make a choice within 15s. Response time was recorded.

Description	Material
Imagine that all the scenes are what you see from a first-person-view, and you cannot see the origin and destination point where you stand on in the picture.	
This picture is shot in the road network you learnt yesterday, and it is the destination in the task (this is only a sample, in the actual tasks you will see the roads you learnt). This picture will last for 6 s.	
(for ORI task) This picture is also shot in the road network you learnt yesterday. It is where you stand right now (the origin). You should choose which is the relative direction of the destination point labelled on the four arrows (1-4). If the relative direction is not exactly front /behind /left /right, please choose the closest one.	
(for SRS task) This picture is also shot in the road network you learnt yesterday. It is where you stand right now (the origin). You should choose the road leading the shortest route to the destination point labelled on the four arrows (1-3).	

Table 1. Task description

2.6 Data Analysis

The raw scanned images acquired was first converted from DICOM format to .inn format by MRIConvert (https://lcni.uoregon.edu/downloads/mriconvert). Then we analyzed the functional imaging data using the SPM8 software package (Statistical Parametric Mapping, Department of Cognitive Neurology, London) and visualized the analysis results with xjView toolbox (http://www.alivelearn.net/xjview). The processing steps include slice timing correction, realignment, coregister and normalization. The middle slices were used as reference in time slicing. Functional volumes with movements exceeding 2 mm in translation errors or 2 in rotation errors (in any direction) were excluded. The high-resolution structural images were then coregistered with the mean BOLD image obtained during motion correction. Finally, the coregistered BOLD images were spatially normalized into standard Montreal Neurological Institute (MNI) space.

The single-subject analysis was used using fMRI First level analysis in SPM. We used the t-contrasts method to compare the active brain function area under the same task with different road networks (uncorrected $p<0.01$, cluster size>10), taking the 4 tasks as 4 conditions, the response time of each task as the parametric modulations and the head motion parameter as the multiple regression parameter.

We admit that there were some flaws in the experiment, as the different kinds of tasks should have been in the same run so that the interval time could have been better controlled. In this experiment, there might be some uncovered active brain areas due to these separated runs, however, the results we got from this experiment should be the most significant difference and still worth being reported here.

3. Results and Discussion

3.1 Orientation task

Table 2 shows the active brain areas in Orientation task (irregular road networks – regular road networks, only show + values). Compared with the orientation tasks in regular road networks, those in irregular road networks evoked more active response mainly in middle frontal gyrus, superior frontal gyrus and medial frontal gyrus. Middle frontal gyrus is part of high cognition network, relates to working memory, attention and planning. Superior frontal gyrus is related to voluntary movement and eye movement. Medial frontal gyrus is about decision-making. Specifically, Subject A showed stronger activation in precentral gyrus, which is also related to voluntary movement; Subject E shows stronger response in cingulate gyrus and inferior parietal lobule, which relates to switch between egocentric and allocentric perspective and egocentric perspective itself, respectively. Frontal lobe plays an important role in human navigation. Boccia, Guariglia et al. (2016) found that at the beginning of route learning, frontal gyrus' activation was strong, but it would decrease as the subjects get familiar with the study area, which indicates that activation of frontal lobe is related to familiarity of route. In this study, it indicates that subjects are more familiar with the regular road compared with irregular ones.

The results indicate that in orientation tasks, subjects had worse memory about irregular roads. The orientation tasks in irregular roads required more concentration with a higher workload, and possibly evoked more memories about switch of view during learning.

Orientation	Irregular-Regular				
Subject	Peak MNI Coordination			Peak Value	Peak MNI Coordination Area
	58	-2	46	4.0546	Precentral Gyrus
Subject A	54	-8	54	3.6858	Precentral Gyrus

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Subject	Peak MNI Coordination			Peak Value	Peak MNI Coordination Area
	26	10	52	4.0066	Middle Frontal Gyrus
	-22	10	56	4.1213	Superior Frontal Gyrus
Subject B	-20	18	60	3.9072	Middle Frontal Gyrus
	-10	34	-22	4.0659	Rectal Gyrus
Subject C	-36	64	6	4.0857	Middle Frontal Gyrus
Subject D	32	66	8	4.0194	Superior Frontal Gyrus
	-6	48	-10	3.898	Medial Frontal Gyrus
	4	56	4	4.234	Medial Frontal Gyrus
	-10	46	8	4.7715	Medial Frontal Gyrus
	-26	52	16	3.92	Middle Frontal Gyrus
	26	58	26	3.8386	Middle Frontal Gyrus
	-8	22	32	4.2863	Cingulate Gyrus
	-56	-38	38	4.149	Inferior Parietal Lobule
Subject E	6	24	60	4.7982	Superior Frontal Gyrus

Table 2. Active brain areas in orientation tasks (irregular - regular)

Table 3 shows the active brain areas of regular road networks – irregular road networks (only + values are shown) and no unified active brain area was found. This shows that the detected active brain area might not be related to the task or indicates special strategies in performing the tasks. For example, Subject C's superior temporal gyrus, which is related to process of verbal information, showed stronger activation in regular roads. This subject could have a special verbal memory about this road network during Day 1's learning, as the subjects were not asked to maintain absolutely quiet in the learning. Also, it could be the subject is imaging him/herself walking in that area in an egocentric perspective and updating his/her current location, according to Lawrence's finding based on visually impaired subjects.

Orientation	Regular - Irregular				
Subject	Peak MNI Coordination			Peak Value	Peak MNI Coordination Area
Subject A	66	-22	-6	4.441	Middle Temporal Gyrus
	18	40	22	3.7768	Medial Frontal Gyrus
Subject C	44	6	-20	4.1786	Superior Temporal Gyrus
	48	0	-10	3.656	Superior Temporal Gyrus
Subject E	-24	58	-2	3.8924	Superior Frontal Gyrus
	46	34	26	3.9042	Middle Frontal Gyrus
	36	-58	32	3.7423	Sub-Gyral
	46	-50	48	4.014	Inferior Parietal Lobule
	-22	56	-42	4.4466	*
	38	48	-36	3.8916	

* Blank means undefined area, the followings are the same.

Table 3. Active brain areas in orientation tasks (regular - irregular)

3.2 Shortest-Route-Selection task

As Table 4, which shows the results in Shortest-Route-Selection tasks of irregular road networks – regular road networks (only show + values), shows that there are no unified brain areas that are more active in tasks in irregular road networks. This indicates that subjects had different strategies. However, different brain areas can indicate similar cognition process. Subject A showed more activation in middle occipital gyrus and Subject G showed more activation in superior frontal gyrus. While these two brain areas locate in different lobes, they are both related to visual information, i.e. visual cognition and eye movement control, respectively. This indicates that visual attention to be more complex in irregular road networks. Also, according to Boccia's summary (Boccia, Nemmi et al. 2014), middle occipital gyrus is more active in learning new roads. Therefore, Subject A might have a better memory about regular roads. Also, Subject E showed stronger activation in precentral gyrus, which is related to mental orientation. Similar to Orientation tasks, there were also subjects showing stronger activation in cingulate gyrus (Subject G) and inferior parietal lobule (Subject F), which indicates in irregular road networks, subjects tend to apply an egocentric perspective of view and switch more frequently between ego- and allocentric perspective.

Shortest-Route-Selection	Irregular - Regular				
Subject	Peak MNI Coordination			Peak Value	Peak MNI Coordination Area
Subject A	36	-82	0	4.0512	Middle Occipital Gyrus
	-4	-42	74	3.9033	Postcentral Gyrus
Subject E	64	-16	42	4.1133	Precentral Gyrus
Subject F	-54	-48	52	4.0815	Inferior Parietal Lobule
	-46	-66	50	4.2552	
Subject G	62	-30	-10	4.1009	Middle Temporal Gyrus
	-22	60	18	3.9555	Superior Frontal Gyrus
	-2	-58	28	3.9911	Cingulate Gyrus
	-10	50	46	4.5829	Superior Frontal Gyrus
	-42	52	-18	4.1411	
	-14	-68	64	-3.9744	

Table 4. Active brain areas in shortest-route-selection tasks (irregular - regular)

Table 5 shows the brain areas that are more active in regular road networks compared with irregular ones in Shortest-Route-Selection task (only show + values). Different subjects hardly have any unified or functionally similar activated brain areas. Subject A and F showed stronger activation in middle temporal gyrus, Subject E and F showed stronger activation in precuneus, which are related to distance estimation, and visual spatial picturing and plot memory, respectively. These subjects might have a better memory and maintain better sense of direction in regular road networks.

Shortest-Route-Selection	Regular - Irregular				
Subject	Peak MNI Coordination			Peak Value	Peak MNI Coordination Area
	-42	-62	16	3.8389	Middle Temporal Gyrus
	-56	-56	16	4.0899	Superior Temporal Gyrus
	-44	-48	36	4.3354	Supramarginal Gyrus
	-46	18	42	4.0844	Middle Frontal Gyrus
	-42	6	40	4.0307	Inferior Frontal Gyrus
Subject A	-28	16	62	4.368	Middle Frontal Gyrus
Subject E	-14	-68	64	3.9744	Precuneus
	-22	68	2	4.5276	Superior Frontal Gyrus
	-50	-72	12	4.9878	Middle Temporal Gyrus
	-32	-76	18	4.7807	Middle Temporal Gyrus
	-14	-88	26	3.7641	Cuneus
	-38	-80	30	4.0994	Angular Gyrus
	28	-60	34	4.3939	Sub-Gyral
	8	-86	40	3.6981	Precuneus
	-14	-82	44	3.7341	Precuneus
	8	-80	50	4.6541	Precuneus
	-6	-64	60	4.6156	Precuneus
	2	-50	64	4.6526	Paracentral Lobule
	14	-56	74	3.7577	
	-4	-74	58	4.2978	
	24	-60	68	4.6889	
	-22	-62	68	3.7798	
Subject F	6	-62	66	4.6621	

Table 5. Active brain areas in shortest-route-selection tasks (regular - irregular)

4. Overall Discussion

In this empirical study, we applied fMRI-based experiment to find out the influence of irregular and regular road networks on geospatial cognition during orientation and shortest-route-selection tasks. The results show that the orientation task in irregular road networks requires more attention and might be demanding because more activations of the subjects were observed in middle frontal gyrus, superior frontal gyrus and medial frontal gyrus. For the shortest-route-selection task, some subjects showed better sense of distance and pictorial spatial memory, but there was no united active brain area. In both kinds of tasks, there were some subjects showing stronger activation in cingulate gyrus and inferior parietal lobule in irregular road networks compared with in regular ones, which means in irregular road networks subjects are more likely to use egocentric framework and the switch more frequently between ego- and allocentric perspective.

This study that may cover some difference and influence, this research work can serve as a starting point to explore more detailed influences caused by various road networks in combination with other variates, such as relative density and general orientation.

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