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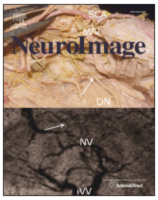

Changes in functional connectivity dynamics associated with vigilance network in taxi drivers

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ABSTRACT

An increasing number of neuroimaging studies have suggested that the fluctuations of low-frequency resting-state functional connectivity (FC) are not noise but are instead linked to the shift between distinct cognitive states. However, there is very limited knowledge about whether and how the fluctuations of FC at rest are influenced by long-term training and experience. Here, we investigated how the dynamics of resting-state FC are linked to driving behavior by comparing 20 licensed taxi drivers with 20 healthy non-drivers using a sliding window approach. We found that the driving experience could be effectively decoded with 90% ($p < 0.001$) accuracy by the amplitude of low-frequency fluctuations in some specific connections, based on a multivariate pattern analysis technique. Interestingly, the majority of these connections fell within a set of distributed regions named "the vigilance network". Moreover, the decreased amplitude of the FC fluctuations within the vigilance network in the drivers was negatively correlated with the number of years that they had driven a taxi. Furthermore, temporally quasi-stable functional connectivity segmentation revealed significant differences between the drivers and non-drivers in the dwell time of specific vigilance-related transient brain states, although the brain's repertoire of functional states was preserved. Overall, these results suggested a significant link between the changes in the time-dependent aspects of resting-state FC within the vigilance network and long-term driving experiences. The results not only improve our understanding of how the brain supports driving behavior but also shed new light on the relationship between the dynamics of functional brain networks and individual behaviors.

1. Introduction

One fundamental issue in cognitive neurosciences concerns how the neural activity of the brain is linked to individual behaviors and further influenced by extensive training or recent experiences. Intrinsic connectivity networks (ICNs), arising from spontaneous low-frequency oscillations of resting-state brains, have been suggested to reflect the underlying functional organization principles in human brains (Damoiseaux et al., 2006; Honey et al., 2009; Sporns, 2014). More importantly, it has been suggested that the resting-state functional connectivity (FC) in some specific regions is modulated by individual behaviors (Hampson et al., 2006), extensive learning (Albert et al., 2009; Tung et al., 2013), experiences (Jeong et al., 2006; Orr et al., 2014), and diseases (Shen et al., 2010). A common assumption used in these studies is the temporal stationarity of FC, where the FC is measured over the entire scan (with a typical duration of 5–10 min). This assumption provides a simple and convenient framework for us to examine large-scale brain networks and explore the correlation between functional and structural connectivity (Honey et al., 2009).

However, a growing body of recent evidence has suggested that the FC of the brain at rest is not static but exhibits complex spontaneous spatiotemporal dynamics with intermittent fluctuations in the connectivity patterns (Calhoun et al., 2014; Chang and Glover, 2010; Hutchison et al., 2013). The low-frequency fluctuations in FC, which could be identified as multiple discrete, reproducible patterns (Allen et al., 2014; Hutchison and Morton, 2015; Yang et al., 2014), have been suggested to be attributed to neural activity, to some extent, and have been linked to changes in cognitive or vigilance states (Betti et al., 2013; Thompson et al., 2013; Wilson et al., 2015). Additionally, some recent reports on disease-related alterations in dynamic FC suggested that the temporal features of FC could serve as a disease biomarker (Jones et al., 2012; Shen et al., 2014). This temporal variability of functional connectivity can even be used to predict an individual's behavior. For example, the individual differences in the variability of functional connectivity exhibit a significant correlation with the tendency to attend to pain (Kucyi et al., 2013) and relate to the degree to which a subject is mind-wandering away from a sensory stimulus (Kucyi and Davis, 2014). In addition, this temporal variability of

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functional connectivity has been empirically demonstrated to be dependent on the structural topology (Shen et al., 2015). These results support the hypothesis that functional network activity on a scale of seconds may contain meaningful information about cognition that may be lost when longer time scales or even entire scans are used. Moreover, the relationship between functional networks and behavior can be better understood using shorter time windows (Thompson et al., 2013). Hence, explorations of the nature of dynamic connectivity and its relationship with individual behaviors have important implications for a more comprehensive understanding of the large-scale functional organization in human brains.

To date, however, there is very limited knowledge about how extensive training or experience is associated with the dynamics in resting-state FC. On a shorter time scale, the activity of resting-state human brains could be clustered into multiple reproducible and transient patterns of connectivity states using a sliding-window approach (Allen et al., 2014); furthermore, the spatiotemporal fluctuation of functional networks reflects a dynamic switch between different FC states. This finding also suggests that the average spatial pattern of FC might not actually resemble a transient state during scanning (Hutchison et al., 2013; Kiviniemi et al., 2011). More importantly, the spatiotemporal properties of these reproducible and transient states on a finer time scale could provide us with some new cues about how the brain supports behavior. Thus, it appears important to investigate the potential link between individual behaviors and the dynamic properties of FC because the intrinsic temporal dynamics may be the basis for an individual's behavior.

In the present study, we sought to investigate the association between temporal variability of dynamic FC and driving behaviors, based on the resting-state fMRI data from 20 licensed taxi drivers and 20 non-drivers. All of the chosen taxi drivers had a consistent level of driving in the environment, i.e., the everyday working hours of the taxi drivers were approximately the same (approximately 8 h a day). Thus, it can be assumed that the number of years as a taxi driver is proportional to the amount of time that our subjects consistently spent performing driving behaviors. Neuroimaging studies have revealed that driving behavior recruits multiple cognitive elements (Calhoun et al., 2002; Chuang et al., 2014; He et al., 2012). Our recent work also demonstrated that driving behavior altered the functional connectivity between the cognitive and sensory ICNs and that the strength of specific connections between the left fronto-parietal and primary visual network was significantly correlated with the number of years as a taxi driver (Wang et al., 2015). Here, we extend these findings to dynamic functional connectivity by hypothesizing that the temporal features of some functional connections were likely to decode or support the decoding of an individual's driving skill. First, we used the 160 previously defined regions of interests (ROIs) (Dosenbach et al., 2010) to construct dynamic graphical representations of brain connectivity within a sliding-time window for each subject. The amplitude of the low-frequency fluctuation of FC (ALFF-FC) was then used to measure the temporal variability of sliced functional connections. Second, using multivariate pattern analysis (MVPA), we identified the functional connections with changes in variability that were the most reliably different between taxi drivers and non-drivers. Finally, the functional connectivity configurations within the sliding windows were temporally divided into quasi-stable states (FC states) via a clustering approach. We also computed the average dwell times in each state, which is defined by the amount of time spent in select functional states. The categories and dwell time of these FC states were further compared between the taxi drivers and non-drivers.

In particular, we are interested in the changes in functional connections within some specific regions related to vigilance, known as "the vigilance network". As a fundamental component of attention, vigilance is the ability to sustain attention over prolonged periods of time. Vigilance is crucial in driving, where humans must continuously monitor and react to rare signals while ignoring irrelevant stimuli. Neuroimaging studies have suggested that a widespread network of regions, including the lateral and medial frontal areas, temporal areas, cuneus and precuneus, insular cortices, and some subcortical regions, engages in vigilance (Breckel et al., 2011). Safe driving requires the ability to concentrate one's attention to various visual or auditory events, to remain vigilant to any dangerous events that potentially threaten safe driving safety, and to make quick cognitive decisions in a complex environment. Thus, we speculate that the long-term driving experience of taxi drivers may alter the temporal features of the functional connections related to vigilance, which likely will provide some insights into the underlying neural substrates of driving behavior. We will test this hypothesis as described below.

2. Materials and methods

2.1. Participants and fMRI data acquisition

Forty right-handed subjects (20 licensed taxi drivers and 20 non-drivers) were included in this study. All of the participants were recruited in Chongqing City, China. The groups of drivers and non-drivers were matched for age, sex, and education level (Table 1). None of the subjects had major head trauma, alcohol or drug dependence, or any neurological disorder. The licensed drivers in this study drive approximately 8 h per day. The mean driving time of the drivers is 11.6 years (range 2–16 years). The subjects of the control group did not have any driving experience, and they traveled by foot or by bus. The subjects in this study were tested with the ethical approval of the Institutional Review Board of Southwest University.

Each subject was instructed to remain awake with their eyes closed and not think of anything in particular during an 8-min resting-state scan with an echo-planar imaging (EPI) sequence. All of the subjects reported that they remained awake for the duration of the experiment. Resting-state fMRI data were collected on a SIEMENS TRIO 3-T MRI scanner in the Key Laboratory of Cognition and Personality (Southwest University), Ministry of Education, China. The imaging parameters were listed as follows: TR = 2000 ms, TE = 30 ms, number of axial slices = 32, slice thickness = 3.0 mm, flip angle = 90°, FOV = 200 × 200 mm^2, and in-plane resolution = 64 × 64. For each subject, 240 volumes were obtained.

2.2. Data preprocessing

The resting-state functional images were preprocessed using the statistical parametric mapping software package SPM8 (http://www.fil.ion.ucl.ac.uk/spm). First, the initial 10 volumes of each subject were discarded due to magnetic saturation effects. The sliding time correction per volume, head motion correction per run, spatial normalization, spatial smoothing, linear detrending, and temporal filtering (0.01–0.08 Hz) were performed in succession. For motion correction, each volume was resliced to the first volume within a run, and the six head motion parameters were estimated. For spatial normalization, the functional images were registered into standard templates on the Montreal Neurological Institute (MNI) space and resampled to a 3 mm isotropic. The spatial smoothing was performed with a Gaussian filter kernel of 6 mm full-width half-maximum (FWHM). The linear detrending preprocessing was to remove the linear signal drift. The final step of

Table 1
The characteristics of the participants recruited in this study.

Variable	Drivers	Non-drivers
Sample size	20	20
Age (years)	39.8 ± 5.5	41.1 ± 5.0
Sex (male/female)	19/1	18/2
Education (years)	9.3 ± 1.6	9.0 ± 1.4
Years of taxi driving	4.6 ± 3.5	
Years of total driving	11.6 ± 4.9	

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