Firing Pattern of Default Mode Brain Network with Spiking Neuron Model

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Abstract. Recently, analyses of fMRI data have revealed functionally connected and interacting spontaneous active regions in the brain, which are referred as "Default Mode Brain Network". The fluctuations on BOLD signals of the default mode brain network have shown spatiotemporally correlated synchronization at a rate lower than 0.1 Hz in contrast to signals under concrete tasks like high frequency rhythms. Here we construct the default mode brain network by functionally connecting a neural network using functional correlation factors. For numerical simulations with Izhikevich's spiking neuron model, the condition on the slow synchronization of this network model is fixed, and the network dynamics is analyzed.

Keywords: spiking neuron model, default mode brain network, spontaneous activity, firing rate, synchronization.

1 Introduction

The functional magnetic resonance imaging (fMRI) has been yielding substantial results for the brain science. The visualization of active regions in the brain by fMRI is expected to ravel not only functions of the brain but also relations between the brain and the mind. For instance, how does one make a choice when two thoughts emerge ? fMRI implied that both regions involved in abstract reasoning and those that process emotions get active in the brain under this situation. Greene and his group found using fMRI that if the dilemma is not so personal, the reasoning part of the brain is dominant when processing a difficult and personal moral dilemma [1].

Thus fMRI makes regions corresponding to any task light up, and also one more possible of fMRI on analyzing the brain is recently presented. It is observation for the slow fluctuations in the blood oxygen level dependent (BOLD) signal in the default or resting state of the brain for dozing situation [2]–[5]. The default or resting state means that someone does not focus on the external environment, namely be in the absence of an explicit task. The fluctuations have shown spatiotemporally correlated synchronization at a rate lower than 0.1 Hz.

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These analyses of fMRI have revealed functionally connected and interacting spontaneous active regions in cerebral cortex, which is so-called "Default Mode Brain Network" and distinct from other systems within the brain. Being the activity in the default, the default mode brain network is a brain system much like the motor or visual systems and/or is associated with the ability of cognitive processing, development, aging, consciousness and psychiatric/neurological diseases. Then, some regions of the brain are in a system that has the spontaneous cognition and other memory-related functions from evidences in brain imaging of fMRI and anatomy [5]. The resting state, but these regions are active, is regarded to be related to the psychological function of the brain such as autobiographical memory. Integration of the neural activities on two states, namely the resting and the task-induced, tells us the entire story of the intrinsic organization of the dynamic networks of the brain that is formulated by anti-correlated signals [2]. Considering the fact that the brain is regarded as a dynamical system, the resting state of the brain is defined as the baseline. Therefore, the resting state is used as a condition of experiments compared with the task positive state, and the knowledge on the default mode brain network from multiple disciplines ranging from psychology to brain imaging technique is important for us to completely understand the brain's function at a systematical level.

2 Default Mode Brain Network and Its Modeling

The default mode brain network has been established as a new field highlighted in recent years though its history is short – just about a decade [5]. Of course, the related fundamentals in neuroscience leading to the advances of the default mode brain network research can be traced to 1970s [5]. In the early era of the fundamental research, the form of the image is rCBF (regional cerebral blood flow) that is obtained by using the nitrous oxide technique. The signals in this kind of images reflect the neural activity of the frontal area of the brain [5]. Later, other brain imaging techniques including PET (positron emission tomography), fMRI and other techniques are used, and the resolution of the obtained images becomes higher.

In informatics, the correlation network of the default mode brain network is verified by the evidences in neuroscience. The graphical representation of the default mode brain network consists of different nodes of the regions of the brain that are functionally connected and is formulated as an interaction of subsystems. This kind of structure is expected to help us to explain how different parts of the brain perform a cooperated function. The intrinsic (spontaneous) activity of the resting state of the brain measured from BOLD signals demonstrates the brain's doing without any input/output. Table 1 is functional connecting core regions suggested as architectonics of the default mode brain network.

Currently, two aspects – the functions of the default mode brain network in neuroscience (e.g., neurophysiology) and pattern analyses of correlated signals (e.g., BOLD) [4] supported by related means of signal processing and data analysis (e.g., handing the noisy case [6]) - are the main streams of the research on

Table 1. Core regions of the default mode brain network. The corresponding brain areas generally imply Brodmann's areas from Refs.[2,5].

Regions	Abbreviation	Corresponding brain areas
Leteral temporal cortex	LTC	21
Medical prefrontal cortex	MPFC	24, 32ac, 10m/10r/10p, 9
Inferior parietal lobule	IPL	39, 40
Posterior cingulate cortex/restrosplenial cortex	PCC/Rsp	23/31, 26,29,30
Parahippocampal cortex	PHC	36
Hippocampal formation	HF	–

the default mode brain network. With the advanced of brain imaging techniques offering satisfactory resolution in space and time, the quantitative analyses of the default mode brain network in spatial and temporal dynamics become possible. For example, the stability of the default mode brain network for aging brain [7] is useful for modeling the temporal dynamics of one. Accordingly, it is a promising theme to explore the complete structure of the default mode brain network.

However, there is a problem in going forward it. It is how we can model a causality network from the correlation network based on theoretical models of nonlinear dynamics. So, we carry out simulation experiments on the default mode network by constructing a functionally connected system composed of eleven nodes with Izhikevich's spiking neuron model in order to solve this question. Basing on the spiking model proposed by Izhikevich [8,9] that explains eight patterns of neuron spikes with four variables and reproduces firing patterns exactly, we construct a functionally connected system composed of eleven nodes that corresponds to the regions of the brain, which is regarded as the default mode brain network here. Simulation experiments are carried out to investigate systematically the default mode brain network of the brain where firing patterns are mapped to neuron assemblies, and we attempt to shed new light on the root of dynamical systems of the brain.

3 Simulation Model and Method

Based on the functionally connected system of the brain in Refs.[2,5], we assume that the cortex region is composed of the neuron assembly formed by placing 160 excitatory neurons and 40 inhibitory neurons in one dimension, and construct a new neural network with the spiking neuron model for the default mode brain network. The ratio of the excitatory neuron's number to the inhibitory one in the region is fixed to follow that of anatomical insight for the human brain. In addition, the neural network takes into account 2 different intrinsic properties as follows:

- Hierarchic neuroanatomical connectivity structure
  - Neuron assembly in each region
    The network is taken to be randomly coupled with the strengths.
  - Collective regions in clusters
    The coupling strength between each region is given as the functional correlation one with the default mode brain network, which is named an *inter*-connection here. On the other hand, we call an *intra*-connection the coupling strength between each neuron.

  The conceptual diagram of new neural network with this hierarchic structure is shown in Figure 1.

- Time delay in the transmission of information
  The delay is simply considered as temporal transmission, and obtained by a common propagation velocity and 3D Euclidean distance between any 2 different regions. Then, we take the velocity as a parameter v, and estimate the distance from the typical locations of the regions in 3D space. Table 2 is the distance calculated using the human data.

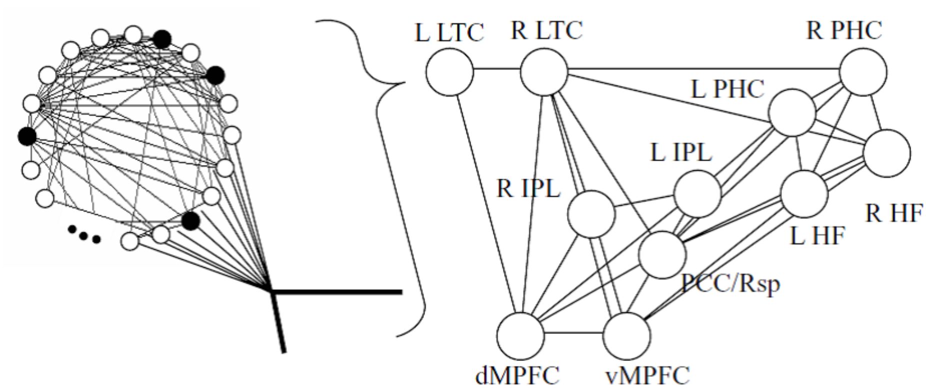

Fig. 1. A network model with the spiking neuron model on the default mode brain network is illustrated. Each region has 200 spiking neuron with intra-connections, and is functionally connected at correlation strengths from anatomical analyses.

Considering these intrinsic properties, the membrane potential of the ith neuron in the M-region with the synaptic current I_{Mi} is given by

$$\frac{dv_{Mi}(t)}{dt} = 0.04\ v_{Mi}(t)^2 + 5\ v_{Mi}(t) + 140 - u_{Mi}(t) + I_{Mi} + \sum_{Mj=\mathrm{Firing}} s_{MiMj} + \alpha \sum_{N(N\neq M)} C_{MN}\ x_N(t - \tau_{MN})\ , \quad (1)$$

$$\frac{du_{Mi}(t)}{dt} = a_{Mi}\ (b_{Mi}\ v_{Mi}(t) - u_{Mi}(t))\ . \quad (2)$$

Table 2. 3D Euclidean distances between each region. The values are obtained by computing on the coordinate system of the Montreal Neurological Institute.

Nodes	L LTC	R LTC	dMPFC	vMPFC	L IPL	R IPL	PCC/Rsp	L PHC	R PHC	L HF	R HF
L LTC	–	120	106	78.1	72.5	126	67.3	36.3	89.6	39.0	82.5
R LTC		–	106	78.1	125.8	72.5	84.7	89.6	36.3	82.5	39.0
dMPFC			–	51.1	134	134	107	103	103	91.5	91.5
vMPFC				–	120	120	88.0	71.9	71.9	51.6	51.6
L IPL					–	88.0	41.4	57.9	91.0	82.2	103
R IPL						–	60.4	91.0	57.9	103	82.2
PCC/Rsp							–	36.4	50.6	55.9	64.0
L PHC								–	56.0	25.1	55.6
R PHC									–	55.6	25.1
L HF										–	44.0
R HF											–

s_{MiMj}, C_{MN}, and α in equation (1) are taken as the strength of intra-, inter-connection, and the parameter of the coupling strength for the inter-connection, respectively. Also, x_N is the firing rate of the region N, and τ_{MN} is the time delay from the region N to M [10]:

$$\tau_{MN} = \frac{L_{MN}}{v} \ , \tag{3}$$

where v and L_{MN} are the velocity as parameter and typical distance listed in Table 2, respectively. For simulation experiments, we use the result of hubs and subsystem within the default mode brain network mapped and estimated from functional connectivity analysis as C_{MN} in equation (1). As a result, our each region now is regarded as in the functional connectivity region in the brain. The values of C_{MN} are listed in Table 3. In addition, other parameters in equations (1)–(2) are listed in Table 4, and s_{MiMj} mentioned between neurons are randomly assigned values between 0 and 0.5 in the case of coupling with an excitatory neuron and between −1 and 0 for an inhibitory neuron.

Analyzing the fluctuations of the synchronization for neuron firing patterns calculated by equations (1)–(2), we define an order parameter for the region M [10]:

$$K_M = \frac{K'_M(t_f) - < K'_M(t_f) >}{< K'_M(t_f) >} \ , \tag{4}$$

where <> denotes the average over time, and

$$K'_M(t_f) = < |\Sigma_{i \in M} F_i(t) - < \Sigma_{i \in M} F_i(t) > | > \ , \tag{5}$$

with $F_i(t)$ representing the neuron firing i in the region M at the time t.

Table 3. Functional correlation strengths of each region within the default mode network [5,11]

Nodes	L LTC	R LTC	dMPFC	vMPFC	L IPL	R IPL	PCC/Rsp	L PHC	R PHC	L HF	R HF
L LTC	1.00	0.41	0.16	0.12	0.14	0.12	0.12	0.11	0.06	0.18	0.14
R LTC		1.00	0.16	0.18	0.07	0.20	0.19	0.08	0.10	0.15	0.17
dMPFC			1.00	0.47	0.22	0.31	0.34	−0.06	−0.10	−0.01	−0.04
vMPFC				1.00	0.27	0.31	0.52	0.11	0.06	0.20	0.16
L IPL					1.00	0.47	0.49	0.25	0.10	0.11	0.06
R IPL						1.00	0.42	0.12	0.05	0.09	0.07
PCC/Rsp							1.00	0.23	0.16	0.26	0.21
L PHC								1.00	0.57	0.31	0.28
R PHC									1.00	0.28	0.28
L HF										1.00	0.61
R HF											1.00

Table 4. Parameter values of the Izhikevich neuron model used in our simulations

Parameters	Excitatory neuron	Inhibitory neuron
Time scale a	0.02	$0.02 \sim 0.10$
Sensitivity b	0.20	$0.20 \sim 0.25$
Resting membrane potential c	$-65 \sim -50$	-65
Inactivity period d	$2 \sim 8$	2

4 Simulation Results and Progress of Research

Using the values of C_{MN} at Table 3, we examined the fluctuation in equation (4) and the power spectrum in the sliding time window of 500 ms shifted by steps of 500 ms for each region. For randomly connected neurons in each region, the result is shown in Figures 2 and 3 in case with the parameter of the coupling strength for the inter-connection $\alpha = 76$ in equation (1) and the velocity $v = 10$ mm/ms in equation (3). We find weakly synchronized firing patterns temporally for each region, and obtain the peak of the power spectrum for the fluctuation with the rate lower than 0.1 Hz. As the resting state is considered as a doze condition without strongly synchronized patterns like the alpha and/or gamma rhythms, one see that our model has correct results for their patterns. By changing the synaptic current I_{Mi} to large values, the firing patterns become to be strongly synchronized both spatially and temporally for each region, but the fluctuation with the rate lower than 0.1 Hz is relatively small.

Now, simulation experiments on the power spectrum of communities consisting of core regions indicated by the strength of the functional correlation are

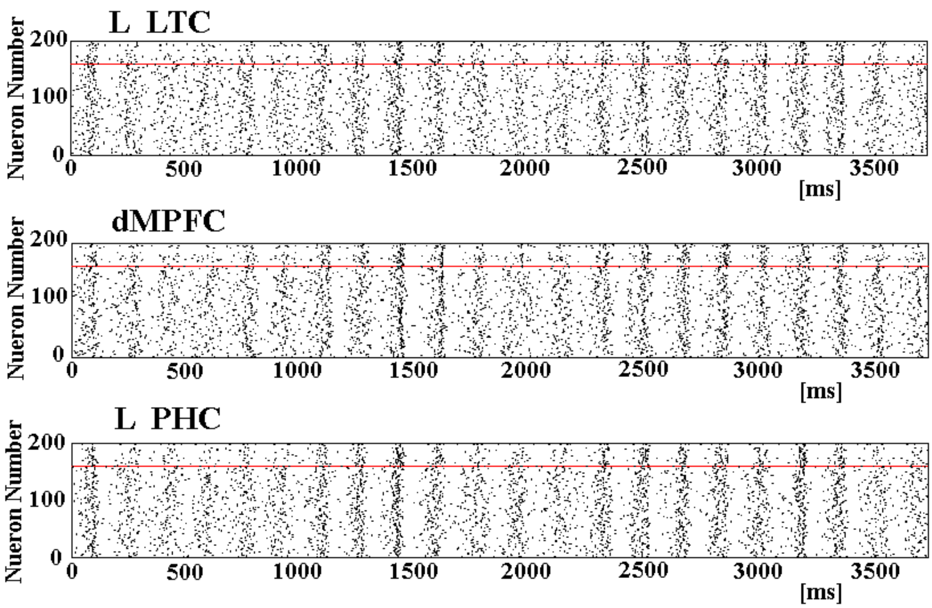

Fig. 2. Simulation results of the raster plots for L LTC, dMPFC and L PHC regions as typical cortices with $\alpha = 76$ and $v = 10$ mm/ms in equations (1)–(3). The firing excitatory (inhibitory) neurons are drawn in area below (above) the line at 160 in each graph.

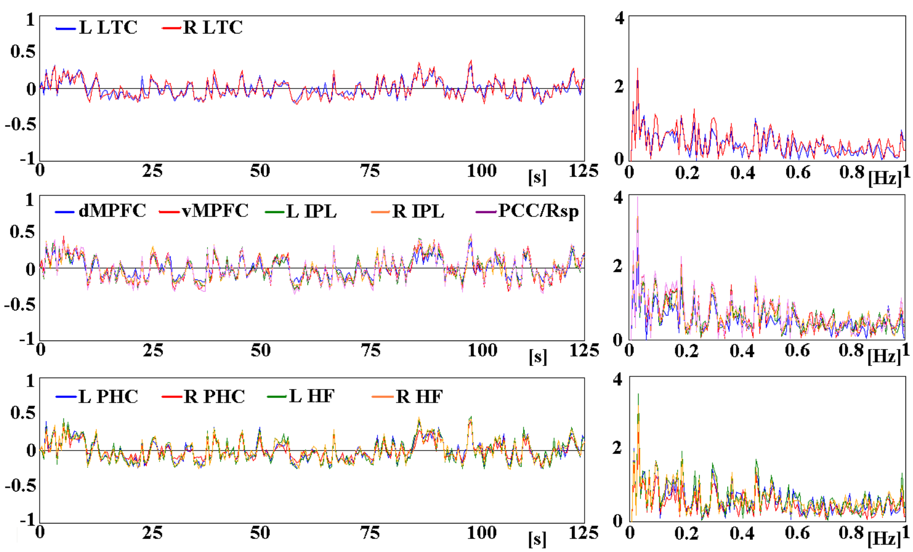

Fig. 3. (Left) Results of the synchronization order parameter K_M in equation (4). (Right) Power spectrum on each region with $\alpha = 76$ and $v = 10$ mm/ms.

simultaneously carried out, because the slow fluctuation of the default mode brain network is not observed at each core region, but at functional collective region constructed by core regions. Also, we are estimating the dependence on the amount of neuron to the power spectrum of the fluctuation.

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