Supporting Information

Organization of state transitions in the resting-state human cerebral cortex

Jiyoung Kang[1], Chongwon Pae[2,3], and Hae-Jeong Park[1,2,3]*

[1]Center for Systems and Translational Brain Sciences, Institute of Human Complexity and Systems Science, System Science Center for Brain and Cognition, Yonsei University, Seoul, Republic of Korea
[2]BK21 PLUS Project for Medical Science, Department of Nuclear Medicine, Department of Radiology, Department of Psychiatry, Yonsei University College of Medicine, Seoul, Republic of Korea
[3]Department of Cognitive Science, Yonsei University, Seoul, Republic of Korea,

Corresponding author: parkhj@yonsei.ac.kr

Contents

S1. Supplementary figures

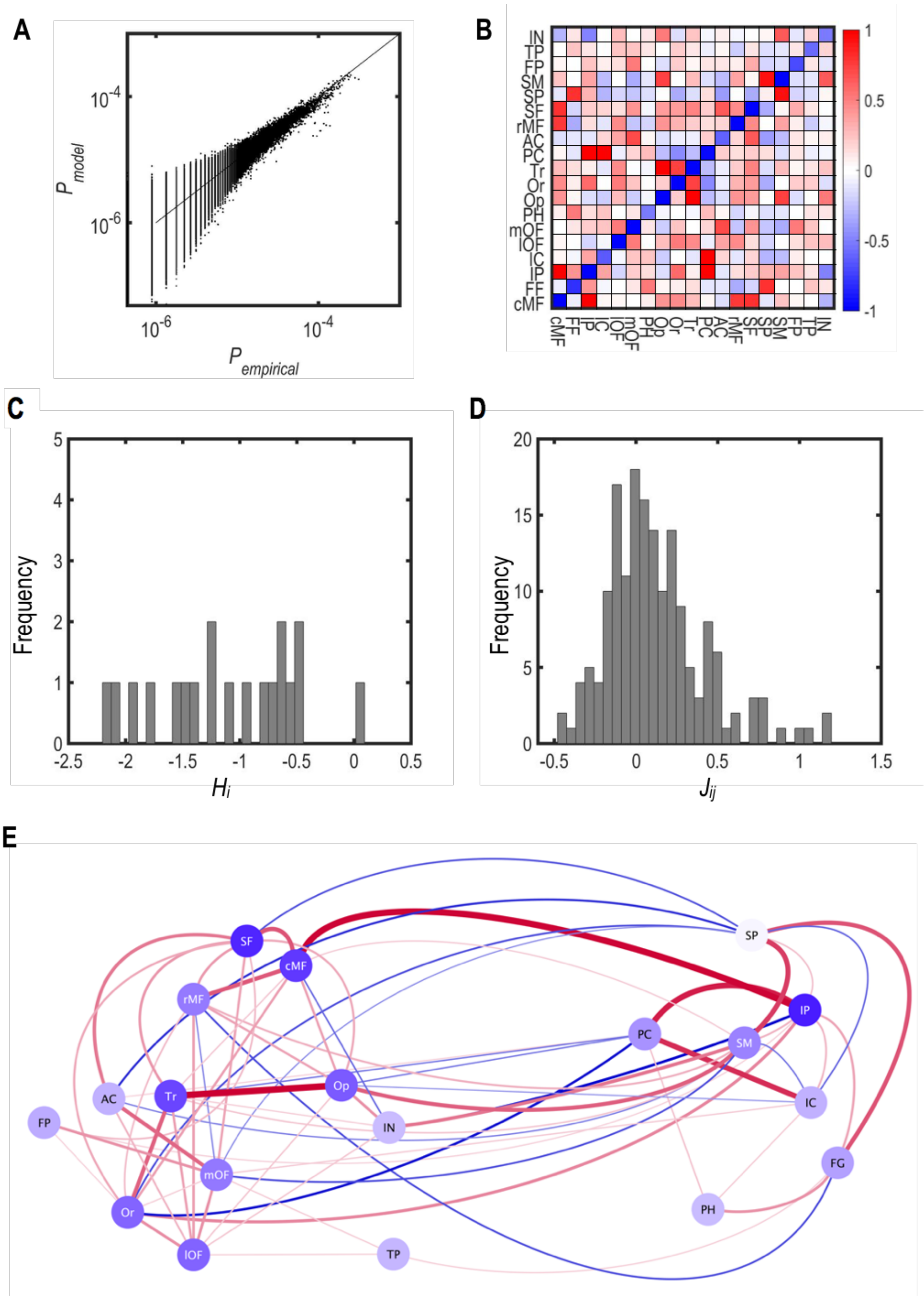

Figure S1. Results of the pairwise MEM for resting state of the cerebral cortex system. (A) The probabilities of the states observed using the constructed MEM were compared with empirical data. (B) Estimated MEM parameters, baseline sensitivity (H_i), and pairwise interaction (J_{ij}) parameters are shown. Diagonal elements represent H_i. Histograms of MEM parameters are shown for H_i and J_{ij} in (C) and (D), respectively. (E) Resting-state cerebral cortex networks estimated by the MEM are summarized. Among all pairwise parameters of MEM J_{ij}, only $|J_{ij}| > 0.2$ were displayed. The thickness of the lines represents the strength of the given interactions. The red and blue lines represent negative and positive J_{ij} parameters, respectively. Most of the ROIs were inactivated by negative H_i values (Figure S1B and S1C). The pairwise interactions, J_{ij}, were distributed among positive and negative values, ranging from -0.4807 to 1.1950 (Figure S1B and S1D). The baseline sensitivities of the inferior parietal lobe, superior frontal gyrus, caudal middle frontal gyrus, and pars-triangularis (H_{IP}, H_{SF}, H_{cMF}, and H_{Tr}) were more negative than those of other regions. Four pairwise interaction parameters, $J_{\mathrm{Op\text{-}Tr}}$, $J_{\mathrm{cMF\text{-}IP}}$, $J_{\mathrm{IP\text{-}PC}}$, and $J_{\mathrm{IC\text{-}PC}}$, were relatively larger than others. Thus, each ROI of the system would be inactivated without pairwise interactions. Estimated strong positive and negative pairwise interactions reflect how two nodes were easily co-activated, and the activation patterns of the local minima (Fig. S1E). The superior parietal (SP), isthmus cingulate (IC) and precuneus (PC) were positively and negatively connected with other ROIs.

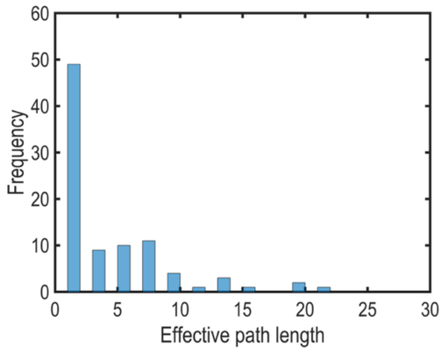

Figure S2. Results of the entire state transition network. Histogram of the effective path length is shown.

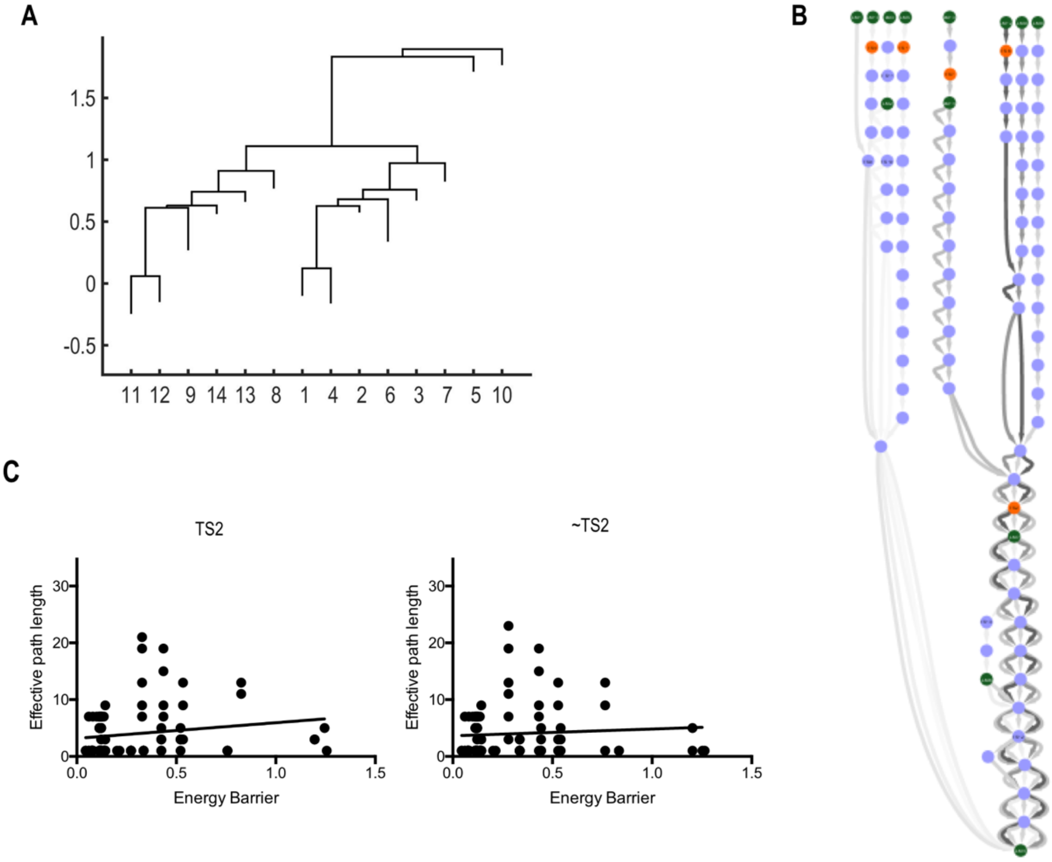

Figure S3. Analysis of state transition network of ~TS2 system. (A) Clustered local minima using energy barriers as the distance metric. (B) The state transition network that relate to transition process to the lowest local minimum is presented. All states which appeared in the state transition process were assigned nodes. Orange, light blue, and green color represent transition, transient, and local minima states, respectively. (C) Both of TS2 and ~TS2 systems did not show any correlation between the energy barrier and effective path lengths.

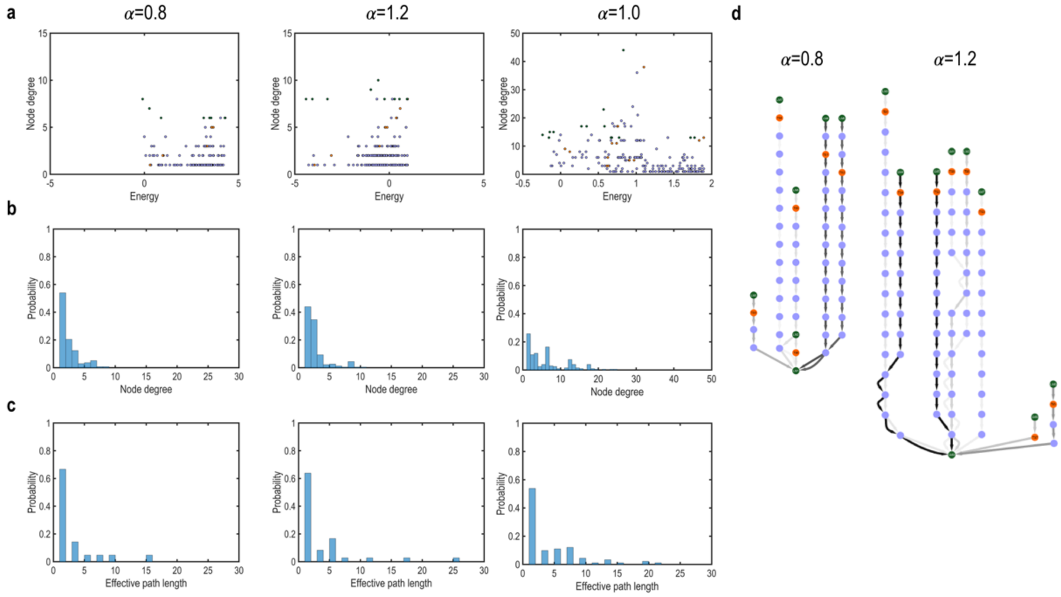

Figure S4. Network properties of the entire state transition networks (ESTNs) for baseline and perturbed systems. (A) Node degree and energies of the nodes in the state transition networks are plotted. (B, C) Histograms for the node degree and effective path length are shown in (B) and (C), respectively. The left and middle panel show results of the perturbed systems, α = 0.8 and 1.2, respectively. The right panel shows results of baseline resting state (α = 1.0). (D) The global minimum focused transition networks (GFTNs) for the perturbed systems (α = 0.8 and 1.2) are shown.

S2. State transition network analysis of the resting state in right-hemisphere

In the main text, cortical regions in the left-hemisphere were mainly investigated. To confirm if brain dynamics in the right-hemisphere contain similar properties, we further constructed the maximum entropy model (MEM) for the right-hemisphere. The activation patterns of rs-fMRI data were reproduced with a high accuracy of fit (r_D = 85.5 %) and reliability (*ER* = 99.9 %) (Figure S5A). Baseline sensitivity parameters H_i and pairwise interaction, J_{ij}, are displayed in Figure S5B. Strong positive correlation was observed between the estimated MEM parameters of the right-hemisphere and the left-hemisphere ($r=0.982$, $p=7.932 \times 10^{-137}$). Although most of MEM parameters of the right-hemisphere were similar to those of the left-hemisphere, several MEM parameters were different; e.g., H_{SF}, H_{rMF}, and $J_{IP\text{-}rMF}$ (Figure S5C).

Analysis of energy landscape identified 18 local minima (having lower energy than their neighbor states) of the right-hemisphere cerebral cortex system at rest. From analysis of the state transition network among full states (STN-FS) and state transition processes (STN-GM) from local minima (LM) toward the global local minimum (LM15), we confirmed that similar properties of state transitions such as existence of hub nodes and multistep process were conserved in the resting-state cerebral cortex system of the right-hemisphere (Figure S6). Activation patterns of local minima and transition rates were similar between the right and left cerebral cortex systems, and clustered (well organized) state transition processes was also identified in the right-hemisphere cerebral cortex system (Figure S7). More specifically, we identified three groups, and similar to the left-hemisphere cerebral cortex system at rest, we found TS1 which appears to mediate transition between two large groups. When we exclude this hub state, its complementary state ~TS1 appeared to serve as a detour for inter-group transitions with similar transition rates (99 %). Thus, "redundant" pathways in inter-group transition processes existed in both the left and right cerebral cortex systems.

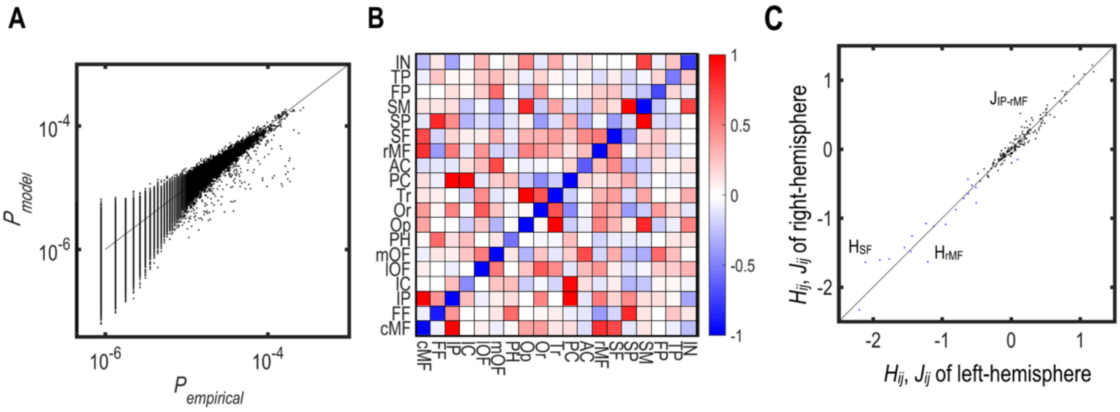

Figure S5. Results of the pairwise MEM for the resting state of the cerebral cortex system of right-hemisphere. (A) The probabilities of the states observed using the constructed MEM were compared with empirical data. (B) Estimated MEM parameters, baseline sensitivity (H_i), and pairwise interaction (J_{ij}) parameters are shown. Diagonal elements represent H_i. (C) Estimated MEM parameters were similar to those of left-hemisphere. (r=0.982, p=7.932 × 10^{-137}). Here, H_i and J_{ij} were colored by blue and black, respectively.

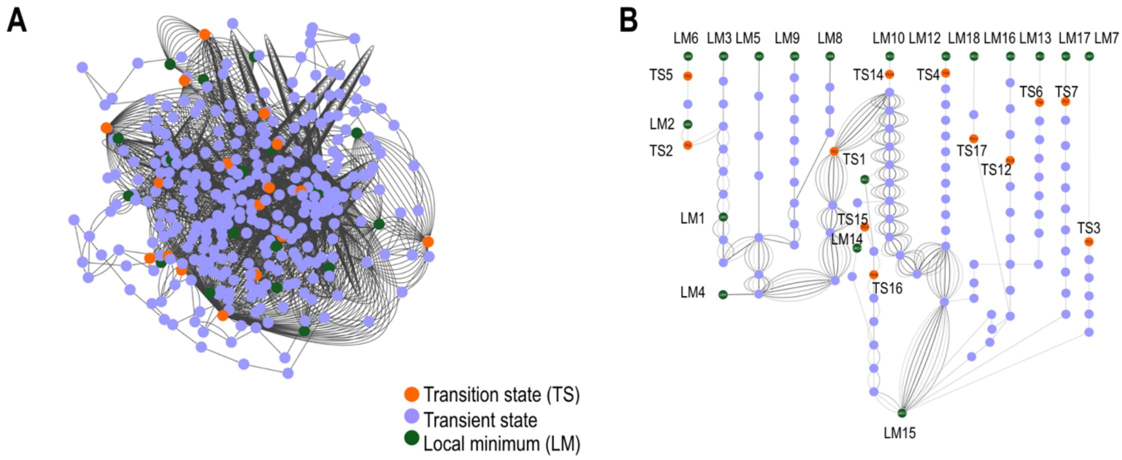

Figure S6. Analysis of the state transition networks (right-hemisphere). (A) The state transition network among full states (STN-FS) of the right-hemisphere is shown. We assigned all states in the state transition process to the nodes. (B) State transition processes (STN-GM) from local minima (LM) toward the global local minimum (LM15) is shown in (B). The green, blue, and orange colors represent local minima, transient, and transition states, respectively.

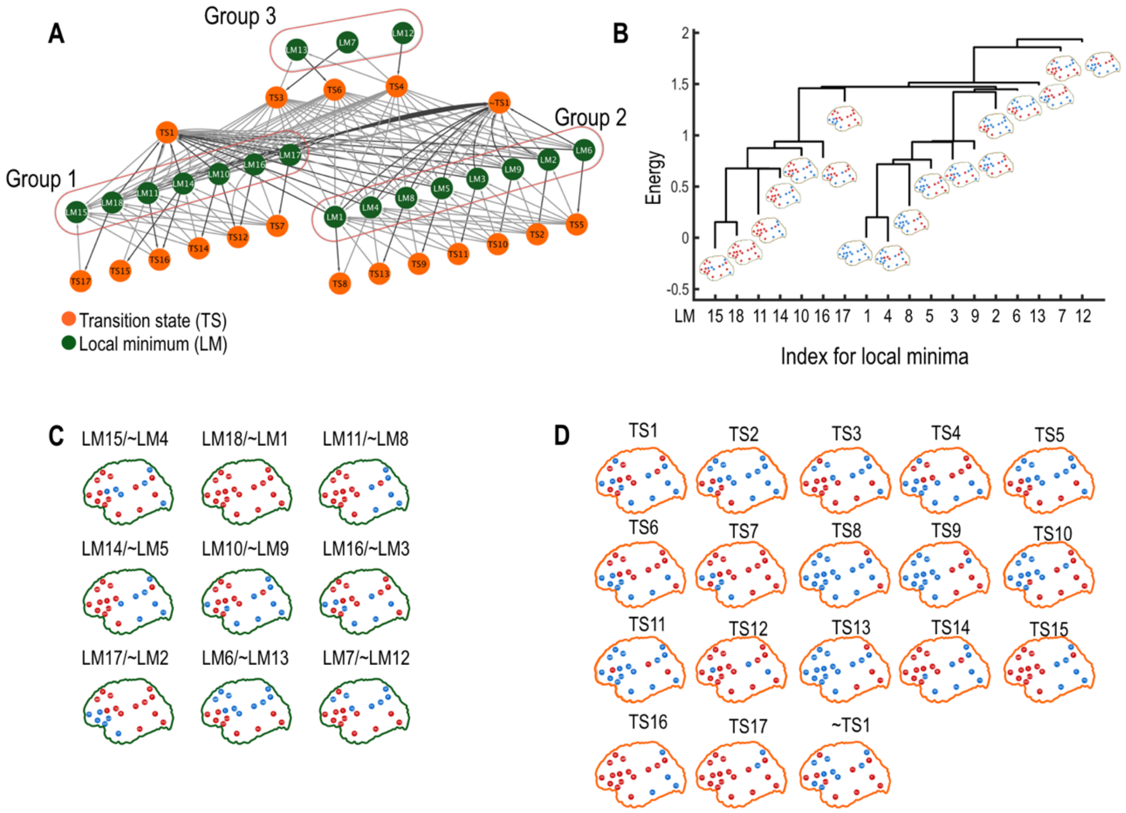

Figure S7. Analysis of the state transition network (STN-LM) composed of rate-determining transition states (TS) and local minima states (LM) (right-hemisphere). (A) The STN-LM is shown. Black and gray colored lines represent in- and out- processes from the state transition states. (B) Local minima (LM) were clustered according to energy barriers. The leaf ends of the dendrogram represent the energy values of the corresponding local minima. (C) Activation patterns of the local minima. The "~" sign represents complementary states. For instance, LM15/~LM4 indicates that LM2 and LM14 are each other's complementary states. (D) Activity patterns of the transition states are shown with TS1 and ~TS1 as major hub transition states. The red and blue dots represent the active and inactive states of the ROIs. The green and orange colors represent local minima and transition states.