Resting State Connectivity of Anterior and Posterior Cingulate Corteces Using Potts Spin Model

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Introduction fMRI studies with complex activation paradigms or unknown brain response patterns (e.g. drug studies, epileptic seizures or analysis of resting-state data) can be analyzed by clustering methods, which often require a prior assumptions, such as the number of expected clusters or an appropriate threshold value, the details which are not known a priori. Here we use a Potts spin model based clustering [1,2] to determine resting state connectivity networks of the anterior (ACC) and posterior (PCC) cingulate corteces. The method makes no assumption of the distribution of the data and is advantageous in the situations when the BOLD response can not be explicitly modeled. Here we demonstrate how the method could be successfully applied to study resting-state connectivity networks.

Theory Consider a data set of N-voxels $\boldsymbol{v_1, \ldots v_N}$, where the interaction, $\boldsymbol{J_{ij}}$, between voxels $\boldsymbol{v_i}$ and $\boldsymbol{v_j}$ is defined as an increasing function of the correlation coefficient. If $\boldsymbol{S = \{ s_1, \ldots, s_N \}}$ is the cluster membership of the data points, then the probability density of the cluster assignment, $\boldsymbol{S}$, at the thermal equilibrium, $\boldsymbol{T}$, is given by the Boltzmann distribution:

$$P(S) = \exp\left(-\frac{H(S)}{T}\right) / \sum_{\tilde{S}} \exp\left(-\frac{H(\tilde{S})}{T}\right)$$

where the Hamiltonian, $\boldsymbol{H(S)}$, specifies the energy of the given system $H(S) = \sum_{(i,j)} J_{ij}(1-\delta_{s_i s_j})$:

To determine the underlying structure of the data one needs to find a group assignment, $\boldsymbol{S}$, which has a high probability at temperature, $\boldsymbol{T}$. This is done by an augmented variable Markov Chain Monte Carlo technique: a Bernoulli variable $\boldsymbol{b_{ij}}$, which may take the value of one ("frozen" bond) whenever voxels $\boldsymbol{v_i}$ and $\boldsymbol{v_j}$ are neighbors *and* belong to the same cluster, and zero otherwise (not frozen bond). Samples from the Potts model are generated by alternating between two steps: (a) Given the cluster configuration, $\boldsymbol{S}$, determine bond, $\boldsymbol{b_{ij}}$, to be frozen $p_{ij} = 1 - \exp(-J_{ij}/T)$ with probability if two points are neighbors and belong to the same cluster; else set $\boldsymbol{b_{ij}}$ to zero. (b) Given the bond configuration, $\boldsymbol{B}$, assign the connected subset – a set of points connected by the frozen bonds – to the same cluster. At any given temperature $\boldsymbol{M}$-simulated samples are collected giving rise to $\boldsymbol{M}$ possible system configurations $\boldsymbol{S_1, \ldots, S_M}$. The probability of two voxels being at the same cluster is estimated as $\hat{\delta}_{ij} = \sum_{S_k, k=1:M} \delta_{ij}^{S_k} / M$, where $\delta_{ij}^{S_k}$ is an indicator of two voxels belonging to the same cluster under system configuration $\boldsymbol{S_k}$. In the Potts spin model we would expect to observe three distinct phases of the system: (1) low temperature phase when all the points form a single cluster; (2) intermediate phase, where strongly coupled interactions are present, but weak interactions are already dissolved by the rising temperature; (3) high temperature phase, where both strong and weak interactions vanished resulting in multiple clusters of small sizes.

Methods fMRI was performed using a commercial 1.5T GE MRI scanner with parameters: TR 0.4s, Flip 50, 4 axial slices, FOV 24x24, BW +/- 62.5 KHz, thick 7mm/2mm, 64x64, 750 time points. Potts model clustering was applied to resting-state data acquired with parameters: 20 axial slices, FOV 24x24, BW +/- 62.5 kHz, TR 2000ms, Flip 82 deg, thick 6mm/1mm, 64x64, 186 time points. Resting state data were collected on 9 healthy adult males. Subjects were instructed to lay still with their eyes closed and refrain from any cognitive activity during the scan. Subjects' motion was assessed using a 3-d registration algorithm in AFNI. Further, only voxels having low-frequency (0.02-0.12Hz) specific correlations of at least 0.3 with 5 or more voxels were retained. The Potts model clustering algorithm was applied with burn-in size of 500 sweeps. The next 500 sweeps were used to determine the cluster assignment.

Results and Conclusion The spikes in the size deviation of the largest cluster (Fig.1) correspond to the changes in the subsequent clusters of smaller sizes. Notice a rapid depletion of the system indicating a short range of temperatures that characterize a stable phase of the system. The transition from the ordered system to the disordered state was rather abrupt in some subjects (subj.2,3,6). Subjects 5, 8 showed volatile changes in the size of the largest cluster at three temperatures before dissolving into randomness. For each subject the temperature corresponding to the last peak of the variation of the size of the 2^{nd} largest cluster was used to determine a stable stage data partition. Group connectivity maps for ACC (Fig.2) show that that at rest it is functionally connected to the bilateral inferior, superior and middle frontal orbital cortex, parahippocampal gyrus, fusiform gyrus, right hippocampus, middle temporal gyrus, thalamus, PCC, superior medial frontal cortex and left postcentral gyrus. PCC (Fig.3) is functionally connected to the thalamus, ACC, left postcentral gyrus, inferior frontal gyrus, hippocampus, orbital frontal gyrus, left fusiform and right parahippocampal gyri. The spectra of the ACC and PCC (Fig.4) look similar and the dominant component of the oscillations corresponds to the low frequency range below 0.12Hz. The magnitude of these oscillations varies with time and shows a strong increase in the last part of the acquisition period.

References [1] Blatt et al (1997) Neural Computation 9, 1805-1842, [2] Murua et.al. Technical Report, University of Washington

Figure 1

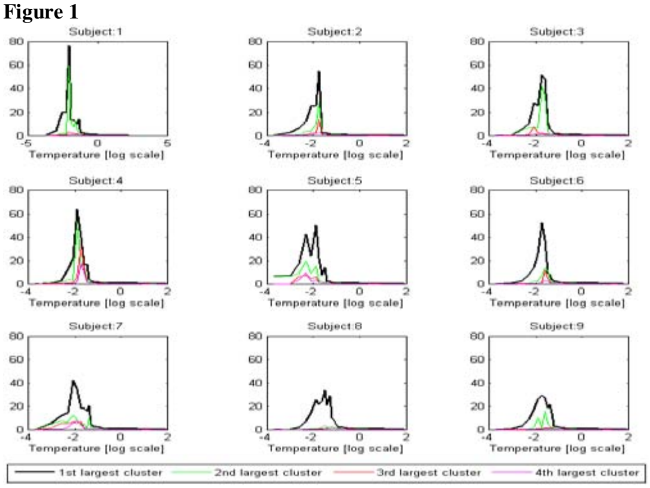

Figure 4

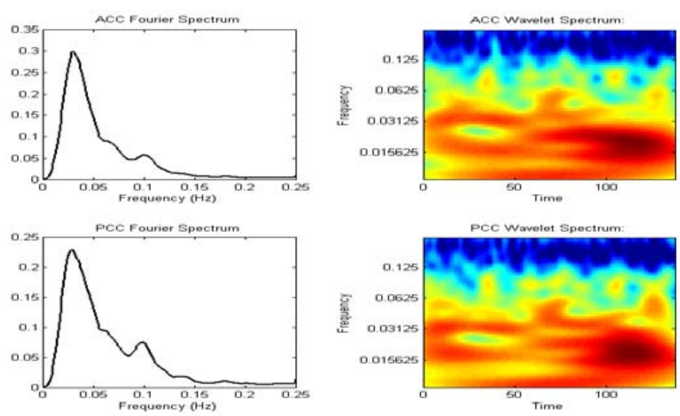

Figure 2

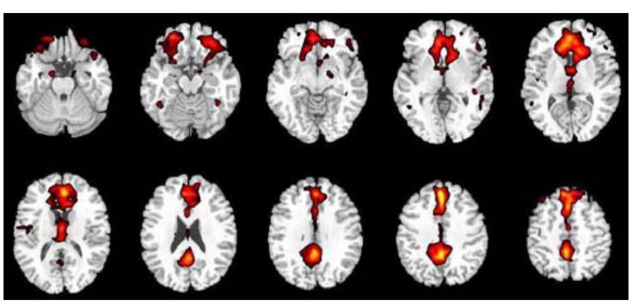

Figure 3