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Thesis Title:	**Understanding the complex dynamics and information processing in the brain network**

ABSTRACT:

Brain is the most complex biological system comprising a large number of interacting neurons whose individual activities are nonlinear and adaptive in nature. In human, for example, brain consists of ≈86 billion neurons, with an average density of ≈30,000 cells mm^{-3}, and each neuron maintains on an average 10,000 synaptic connections. An intricate connection pattern of neurons allows a brain to be organized into hierarchically distributed functionally diverse modules having weak intermodular interactions. This multiscale functional segregation of brain regions increases its adaptivity as well as robustness against external perturbations, with their weak coupling responsible for emergent phenomena. All these characteristics introduce wide timescale separations in neuronal processes, which accounts for the dynamic diversity in neuron coding and decoding processes. It is believed that this complex organization pattern optimizes both the wiring cost and efficiency of neuronal communication.

The present study introduces a novel method to inquire the hierarchical organization in complex brain networks. For this, brain datasets from four different species, namely, *C. elegans*, cat, monkey, and human, were used. Scaling and renormalization theory as well as the *local community paradigm* (LCP) are applied to investigate the system-level organization in these brain networks. Observation includes fractal natures in the evolution of network properties across hierarchical levels, indicating the existence of self-similar organizational rules in brain networks. The findings may reflect to the energy efficient integration of information within and among different levels of organization, enabling functional self-organization in brain networks. The fractal evolution of average network mass, intermodular, and intramodular interaction edges among different levels of organization may further indicate the self-similar distribution of network resources (nodes and edges) among these levels. Another important finding is the decrease in fractal dimensions from lower to higher level species, and it indicates that higher order species such as human brain maintains higher organizational complexity with more ordered and efficient information processing, reflecting their higher cognitive abilities.

Further investigation through LCP method reveals brains' intrinsic ability to maintain compactness of network topology, enabling efficient information processing. This also suggests the existence of intricate hub/hubs manipulation in brain networks. Next, the intricate hub/hubs manipulation can also be understood

from the analysis of hubs and rich clubs. We observe the phenomenon of missing and emergence of leading hubs, unpredictability in the popularity of leading hubs, and their rich-club formation among various levels of each brain network. These properties characterize the absence of a centralized control mechanism in the complex brain functioning, a special feature generally observed in self-organizing complex systems.

We further study the information flow from one organizational level to another. For this, we introduce probability distribution functions of intra- and intermodular edges with respect to the whole network edges (global) and also with respect to the total number of edges in the previous level (local). Interestingly, across different levels these probability functions follow fractal nature, and it may indicate the existence of a fundamental self-similar signal processing in brain networks. Also, the average Hamiltonian function for each organizational level shows self-similar organization behavior, which may indicate the existence of self-similar energy distribution for an efficient complex brain organization. Finally, the distribution of triangular motifs among various levels of each brain network is also found to show fractal nature, which indicates the fundamental regulators are self-similarly distributed among various organizational levels of brain.

In this study, we also investigate the network properties of an autistic brain, and compare it with a control brain of similar phenotypes. LCP-decomposition-plot (LCP-DP) analysis of modules at different organizational levels reveals some degenerate organizational behavior in autistic brain topology. Hubs and rich-club analyses reveal that normalized rich-club coefficient plot of autistic brain network displays a largely distorted pattern, consisting of steady state, monotonically increasing, and a dispersed region, as compared to the control brain. There also reveals an altered hub node population pattern in autistic brain as compared to the control, and proposed that the autistic brain disorder is associated with long-range dysconnectivities of larger hub nodes decreasing their population; however the population of lower degree nodes increases resulting to higher local clustering. These abnormalities may have introduced stresses on the network organization, reflected as inhomogeneous distributions in LCP-DP map.

We then study the stochastic neuron dynamics using Hindmarsh–Rose (HR) single neuron excitable membrane model. Interesting observations include the taming of chaotic neuronal behavior, with the system switching into various orbits differentiated by intermittent, transient chaotic states. The internal noise controlled neuron dynamics exhibit a peculiar type of crises described by repetition of period–chaotic blocks within a particular period. Finally, when two identical HR neurons are allowed to cross-talk through noise-induced synaptic coupling, noise-induced *multisynchrony states* for an optimal range of the internal noise is observed. The observed multisynchrony states may represent the accessible neuron states with cross-talks being favored among those *local synchrony states*.

This study thus highlights some of the basic mechanisms of how brain works at the fundamental level, to address issues on self-organization and other related phenomena. It may also open up new understanding in brain functioning, predicting morphological changes in brain networks due to various brain diseases for possible disease diagnosis and clinical trials.