Abstract

The brain is arguably the most complex system that enables cognition owing to the presence of multiple spatial and temporal scales. The cumulative advances in neuroimaging technologies and experimental and theoretical neuroscience have exerted impetus on brain research. However, only when the research from the neuroscientific community is complemented by the principled approaches by physicists, larger aspects of the brain, and cognition can be understood. The theory of complex networks that leans on the framework of statistical physics and mathematics, and on graph-theoretical concepts from computer science, has seen growing attention from the physics community to understand non-trivial connection structure and its implications on the function of a complex system. Additionally, the framework is generalizable to incorporate characteristics of individual nodes on the top of simple connectivity matrices that describe network structure. The structural descriptors of brain network organization, (for example, the hierarchical structure, modularity, and small worldness) have been directly related to function through correlations with variables describing cognition and behaviour. The theory has also been successful in underpinning structural attributes to altered functional states; for example, the disease states like Alzheimer's, Schizophrenia, and Epilepsy. Moreover, the complex network modelling of the brain can be extended to various neuroimaging modalities such as EEG and fMRI. Another very important pillar that supports research in the brain is that of mathematical modelling and simulations of mechanisms and phenomena in the brain at various levels of the organization. Ranging from the simple model of action potential firing in neurons to sophisticated modelling of thalamocortical columns to understand sleep-wake transitions in animals, the computational neuroscience community has been successful in modelling brain functions at various levels of structural granularity. The neural mass models that capture a mean-field picture of a population of neurons and the synapses connecting them have successfully presented phenomenological descriptions of brain activity such as brain rhythms, synchronization-desynchronization transitions in the brain and sleep stages. The emergence of phenomenons in the brain from the interactions of complex patterns of its sub-systems obviates inherent nonlinearity. Hence, the dynamical systems theory and nonlinear dynamics are inevitable for the modelling and characterization of dynamics in the brain.

This thesis attempts to explore and understand the dynamics of brain activity at the mesoscopic level of brain organization i.e. at the level of brain areas/neuronal ensembles using tools from complex networks and nonlinear dynamics. Specifically, we aim to identify and characterize the complex non-linear dynamical patterns in brain activity and its implications on normal and pathological functioning. We use a plethora of neuro-computational models and use simulations on networks to mirror the dynamics observed in the brain. In light of this goal, we did investigate the collective dynamics of coupled biological oscillators. Each of these oscillators (modelled using the Wilson-Cowan units) representing the mean activity of an ensemble of neurons, were connected to each other in a network framework. In an idealistic network topology, where each of the oscillators was identical in terms of external stimulation and its connectedness to the rest of the network, we find the existence of many complex non-linear patterns each characterized by a different basin of attraction as the coupling strength of these oscillators. Some of these patterns were: Exact synchronization, quasi-periodicity, gradient synchronization and chaos. Apart from the theoretical appeal of these collective oscillator states, these states, and their inter transitions hold significance in the biological aspects of brain functioning. For example, the transition to global synchronization mimics the transitions between interictal and ictal activity in the context of epilepsy. Similarly, transition to de-synchronization with increased coupling can explain the anesthesia-induced loss of consciousness in the brain. We also did a comparative study of variation in synchronization order parameter for the coupled thalamo-cortical oscillators and Kuramoto order parameter (when modelling the nodes as phase oscillators), due to the variation in the network topology. In other words, based on the collective dynamics observed for the two cases, we investigate which one of two scenarios is more apt for studying dynamics in the brain. Besides, we also investigated, which network structures (or connection topologies) support or make the network more prone to the seizure-like phenomenon (corresponding to large scale unwanted synchronization of neurons in the brain) than others. We explored aspects

of synchronization in real brain topologies like the Macaque connectome and its surrogate counterparts. Further, we explored the effects of periodic stimulation on the collective dynamics of coupled oscillators. We find that periodic stimulation of coupled masses can lead them to coherence for a particular range of stimulation frequency, mimicking experimentally observed flickering- stimuli induced epileptic seizures in the human brain. In another neural mass modelling project aimed at modelling spatiotemporal patterns of Spreading Depression, we simulated the mechanism for initiation of Depolarization Block in compartmental neural masses of Hodgkin-Huxley neuron, excitatory neurons, inhibitory neurons. We aim to explore and identify the dynamical changes responsible for the seizure generation and propagation of depolarization block in a network of neural masses.

In our pursuit of exploring and modelling the mesoscopic brain activity, we carried out the analysis of EEG time series data to infer the modular structure of the functional brain networks in different frequency bands. In this work, the EEG time series from the human brain were recorded corresponding to different emotions to infer the specific functional connectivity of brain areas. This functional connectivity between brain areas was, in turn, dictated by the coherence or the amount of synchronization between the time series recorded from the overlying scalp region. Stronger functional connectivity indicates stronger synchronization or coactivity of the brain areas and vice-versa. We then characterized the obtained brain networks using complex network measures to compare and contrast the brain functioning for the perception of different emotions. Further, we obtained the segregation of networks into modules and compared similarities and differences in the modular organization of the emotion networks. We identified the most important nodes or hubs for emotion perception using centrality measures.

In this thesis, we also propose an eigen-spectra based approach to identifying the important structure of complex networks. Such a formalism can be used to obtain a size-reduced representation of large complex networks that have redundant local structures. The subset network, as we show for a plethora of real and simulated networks, can be used to approximate the spectra of the full network; it also has enhanced information flow metrics than the original networks (measured in terms of path length and clustering coefficient). We also show that the subset can successfully be used to identify the modules of the network. Hence, in summary, this approach can be used to enormously reduce the computational burden for operations on large adjacency matrices i.e large complex networks. We provide the implementations of subset selection algorithms on the brain network of Macaque and extract its modular structure.

Keywords : Brain, Complex Networks, Nonlinear Dynamics, EEG, Synchronization, Neural mass models, Phase oscillators, Epilepsy, Spreading Depression, Modular brain network. .