Novel insights into brain organization via graph signal processing

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Overview

This symposium involves novel research in understanding the underpinnings of multi-modal brain signal and imaging data via leveraging principles from the emerging field of graph signal processing (GSP). GSP is promising computational approach that provides a unique set of tools for modeling, analyzing, and interpreting brain functional data. GSP enables representing the observed activity in a space informed by the underlying neuroanatomical or functional connectivity architecture of the brain. Based on this principle, an increasing number of studies are revealing the potentialities of this methodology to uncover still unknown aspects of brain organization and structure-function relationships. The symposium includes four presentations from researchers coming from three continents, namely USA, Australia, and Europe (Germany, Switzerland), at various career stages (PhD candidate, Postdoc, Senior Researcher, and Professor). The works showcase different recent applications of GSP to the brain, namely to: (1) describe structure-function relationships via spectral connectome analysis across different spatial resolutions; (2) illustrate the gradient-shape of structure-function dependencies in the healthy brain and their role as unique signatures of individuals and tasks; (3) describe cortical organization principles via spectral analysis of the functional connectome, i.e. with the newly introduced notion of functional harmonics; (4) distinguish between signal propagation and control on structural connectomes. By presenting this wide range of recently proposed application cases in one integrated session, the objective is to, on the one hand, provide novel perspectives on brain structure-function integration for the field, and on the other hand, outline exciting directions for future work.

Lecture 1: *Spectral connectome analysis across modalities and resolutions: A neuroimaging tool to study the organization of human brain networks*

Sina Mansour Presenter

Understanding how the flow of information over cortical circuitry gives rise to complex human brain functions remains one of the most important challenges in neuroscience. This talk will provide an overview of how spectral analysis of brain networks provides a resolution-independent tool to study the structure-function association. We first provide a brief explanation of how Graph Signal Processing (GSP) methods are used to compute the connectome spectrum from the GSP shift operators. Next, we will explain how spectral analyses aid in modeling structure-function coupling and discuss potential applications of GSP in high-resolution connectomes. The computationally efficient implementations of the aforementioned spectral GSP models make them directly applicable to high-resolution connectivity maps extracted at the resolution of voxels/vertices. These high-resolution maps better reflect the intricate detail of whole-brain mesoscale structural circuitry and can hence provide more realistic models of structure-function coupling. We will cover emerging applications of these high-resolution models in neural field theory and the emergence of graph neural field models.

Lecture 2: *Gradients of structure-function coupling uniquely characterize individuals and tasks*
Maria Giulia Preti Presenter

The structural decoupling index is a novel GSP-based metric to quantify structure-function dependencies in each region of the brain. Via this measure, we showed that structure-function coupling varies in the healthy brain during resting-state following a macroscale cortical gradient spanning from lower level regions to higher-order ones. But how does this relationship change across individuals or when performing specific tasks? In this talk, I will answer these questions by elucidating the value of the structural-decoupling index for fingerprinting, i.e. characterizing different individuals, and task decoding, that is recognizing different tasks.

Lecture 3: *Exploring cortical organization with functional harmonics*
Katharina Glomb Presenter

The interest in graph signal processing is growing in network neuroscience as it provides a set of easy-to-use and powerful tools as well as interpretable results. One such tool is finding the Fourier basis functions of a connectivity graph. In this talk, I will show our work on basis functions - or "functional harmonics" - of fMRI resting state functional connectivity. We found that functional harmonics capture many organizational features of the cortex, spanning from the sub-areal scale, e.g., retinotopic organization of visual cortices, to functional specialization of brain regions and global gradients. I will discuss how in this sense, functional harmonics unify the ideas of a cortical organization best described by parcels vs. gradients.

Lecture 4: *Models of communication and control for brain networks: distinctions, convergence, and future outlook*
Danielle Bassett Presenter

Recent advances in computational models of signal propagation and routing in the human brain have underscored the critical role of white matter structure. A complementary approach has utilized the framework of network control theory to better understand how white matter constrains the manner in which a region or set of regions can direct or control the activity of other regions. Despite the potential for both of these approaches to enhance our understanding of the role of network structure in brain function, little work has sought to understand the relations between them. Here, we seek to explicitly bridge computational models of communication and principles of network control in a conceptual review of the current literature. By drawing comparisons between communication and control models in terms of the level of abstraction, the dynamical complexity, the dependence on network attributes, and the interplay of multiple spatiotemporal scales, we highlight the convergence of and distinctions between the two frameworks. Based on the understanding of the intertwined nature of communication and control in human brain networks, this work provides an integrative perspective for the field and outlines exciting directions for future work.