



ISBI 2020 Tutorial Proposal

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Title

Graph Signal Processing Opens New Perspectives for Human Brain Imaging

Outline

Course Length

1.5 hour theoretical part + 1.5 hour practical laboratory, separated by a thirty-minute coffee break

Tentative syllabus

- Graph Signal Processing (GSP) basics
- Building the structural graph from diffusion-weighted magnetic resonance imaging (MRI) data
- Recording activity time courses with functional MRI
- Combining brain function and structure using GSP
- Introducing the *structural decoupling index*: a local measure of structure-function coupling
- Non-parametric statistical tests: constructing surrogate graph signals with and without knowledge of the underlying graph structure
- Extending GSP metrics to the assessment of dynamic structure-function reconfigurations
- Probing more subtle spatially localized effects with Slepians

Relevance to ISBI audience

By integrating cutting-edge neuroimaging techniques with powerful mathematical tools, graph signal processing applied to human brain imaging provides an innovative and elegant setting to unravel new insights into brain architecture and function and potentially answer several still open questions in the field. This topic would be of particular interest for the ISBI community, including researchers specialized in different imaging and signal processing fields, from more theoretical (signal processing, graph theory, network analysis) to more applied (brain imaging, specific pathologies) ones. In accordance to this, the current tutorial will cover concepts ranging from the main basics of graph signal processing (theory, properties, operations) to its possible useful applications to the brain.

Further, given the novelty of this topic and its rapid expansion, this tutorial will represent an important opportunity for the ISBI crowd to stay up to date with current methodologies.

Description

State-of-the-art magnetic resonance imaging (MRI) provides unprecedented opportunities to study brain structure (anatomy) and function (physiology). Based on such data, graph representations can be built where nodes are associated to brain regions and edge weights to strengths of structural or functional connections^{1,2}. In particular, structural graphs capture major physical white matter pathways, while functional graphs map out statistical interdependencies between pairs of regional activity traces. Network analysis of these graphs has revealed emergent system-level properties of brain structure or function, such as efficiency of communication and modular organization³⁻⁵.

In this tutorial, graph signal processing (GSP) will be presented as a novel framework to integrate brain structure, contained in the structural graph, with brain function, characterized by activity traces that can be considered as time-dependent graph signals⁶. Such a perspective allows to define novel meaningful graph-filtering operations of brain activity that take into account the anatomical backbone. In particular, we will show how activity can be analyzed in terms of being coupled versus decoupled with respect to brain structure (Fig. 1). This method has recently showed for the first time how regions organized in terms of their structure-function coupling form a macrostructural gradient with behavioural relevance, spanning from lower level functions (primary sensory, motor) to higher-level cognitive domains (memory, emotion)⁷. In addition, we will also describe how the derived structure-function relationships can be considered more in depth, in terms of their temporal dynamic properties, and at the finer-grained scale of individual sub-networks.

From the methodological perspective, the well-known Fourier phase randomization method to generate surrogate data can also be adapted to this new setting. We will show how to generate surrogate data of graph signals in this way, which allows a non-parametric evaluation of the statistical significance of the observed measures.

References:

¹ Sporns, O. Networks of the brain. (Cambridge, MA: The MIT Press., 2010).

² Fornito, A., Zalesky, A. & Breakspear, M. Graph analysis of the human connectome: Promise, progress, and pitfalls. *NeuroImage* 80, 426–444 (2013).

³ Bassett, D. S. & Sporns, O. Network neuroscience. *Nat. Neurosci.* 20, 353–364 (2017).

⁴ Sporns, O & Betzel, R.F. Modular Brain Networks. *Annu. Rev. Psychol.* 67, 613-640 (2016).

⁵ Van Den Heuvel, M. P., Mandl, R.C.W., Kahn, R. S., Hulshoff, P., Hilleke, E. Functionally linked resting-state networks reflect the underlying structural connectivity architecture of the human brain. *Hum. Brain Mapp.* 30, 3127-3141 (2009).

⁶ Huang, W., Bolton, T.A.W., Medaglia, J.D., Bassett, D.S., Ribeiro, A., Van De Ville, D. A Graph Signal Processing Perspective on Functional Brain Imaging. *Proceedings of the IEEE*, 106, 868-885 (2018).

⁷ Preti, M.G. & Van De Ville, D. Decoupling of brain function from structure reveals regional behavioral specialization in humans. *Nature Communications*, In press.

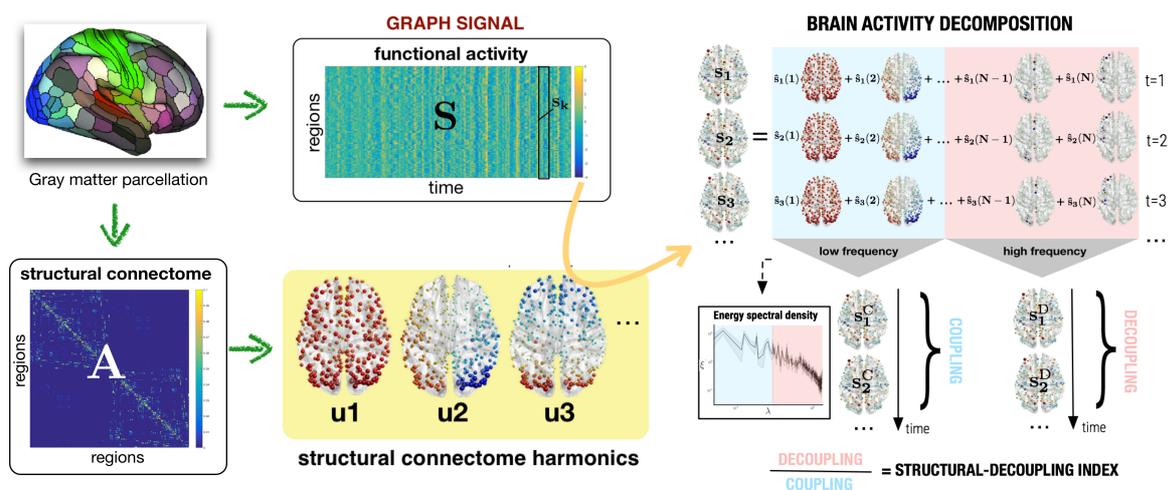


Fig. 1 – Graph Signal Processing framework to integrate brain structure and function. Based on a common gray matter parcellation, a structural connectome (SC) is obtained from diffusion MRI-based tractography and functional signals are recorded with functional MRI. In the GSP framework, the structural connectome is considered as a graph and functional activity patterns at each time point as graph signals. Structural connectome harmonics are obtained as graph Laplacian eigenvectors. The projection of fMRI signals on these basis vectors allows for brain activity decomposition in terms of structural patterns. Then, the split of the spectrum into low and high spatial frequencies allows to identify two portions of the functional signals: one coupled and one decoupled from the structure. The norm of these signals across time yields a regional measure of structure-function coupling, defined as the *structural-decoupling index*.

Expected audience

The expected audience includes engineers, physicists, statisticians, and those interested in acquiring knowledge on the cutting-edge methodologies to study brain connectivity and the several open challenges of the field. Researchers who are focusing on either brain structure or function (with MRI or different techniques) will have the chance to expand

their horizons and learn a new way to merge these two equally important and intrinsically dependent aspects.

Expected audience participation

A practical laboratory covering the main methods introduced in the theoretical part will be held. This will give the opportunity to the audience to implement the step-by-step procedure to apply GSP to the brain. We will be providing both a Matlab and a Python version of the hands-on laboratory. Basic knowledge of Matlab or Python will be enough. All additional explanations will be given during the tutorial.

Coursepacks

All the slides of the tutorial will be made available in electronic format. A practical laboratory will be held with a step-by-step analysis of the methods introduced, based on publicly available datasets. Matlab and Python packages of the practical laboratory as well as its documentation will be made fully available to participants.

Presenters' Biosketch

Maria Giulia Preti

Maria Giulia Preti is a senior scientist at the Signal Processing Core of the Center for Biomedical Imaging (CIBM). She is also affiliated with the Medical Imaging Processing Laboratory (MIPLab), University of Geneva (UNIGE) and École Polytechnique Fédérale de Lausanne (EPFL), at Campus Biotech, Geneva.

She received her Ph.D. in Bioengineering at Politecnico di Milano (Milan, Italy) in 2013, after her M. Sc. (2009) and B. Sc. (2007) in Biomedical Engineering, as well at Politecnico di Milano. During her Ph.D., she focused on advanced techniques of brain magnetic resonance imaging; in particular, she developed a method of groupwise fMRI-guided tractography, which revealed to be useful in the in-vivo investigation of the pathophysiological changes across the evolution of Alzheimer's disease. For this project, she had been collaborating full-time with the hospital Fondazione Don Gnocchi in Milan (Magnetic Resonance Laboratory). In 2011, she was awarded a Progetto Rocca fellowship from the MIT-Italy foundation and spent a visiting research period at the MIT and Harvard Medical School (Boston, USA), under the supervision of Prof. Nikos Makris. Here, she could focus on the anatomical study of specific cerebral fiber bundles.

She has joined the CIBM as a post-doctoral fellow in 2013. Her current research aims at investigating brain functional and structural connectivity, as well as their integration, by developing new methods which build on concepts from network science and (graph) signal processing. In particular, she is working on functional MRI, functional connectivity, functional connectivity dynamics, diffusion tensor imaging and tractography, integration of MRI with other techniques (e.g., EEG), and the application of these methods to several clinical contexts, such as epilepsy, Alzheimer's disease and mild cognitive impairment, multiple sclerosis, attention deficit hyperactivity disorder.

Selected related publications:

- Preti, M.G., Van De Ville, D. Decoupling of brain function from structure reveals regional behavioral specialization in humans, *Nature Communications*, in press.

- Petrovic, M., Bolton, T.A.W., Preti, M.G., Liégeois, R., Van De Ville, D. Guided graph spectral embedding: Application to the C. elegans connectome. *Network Neuroscience*, 3, 807-826 (2019).
- Demesmaeker, R., Preti, M.G., Van De Ville, D. Augmented Slepian: Bandlimited Functions That Counterbalance Energy in Selected Intervals. *IEEE Transactions on Signal Processing*, 66, 4013-4024 (2018).
- Van De Ville, D., Demesmaeker, R., Preti, M.G. When Slepian meets Fiedler: Putting a focus on the graph spectrum. *IEEE Signal Processing Letters*, 24, 1001-1004 (2017).
- Van De Ville, D., Demesmaeker, R., Preti, M.G. Guiding network analysis using graph slepian: an illustration for the C. Elegans connectome. *Wavelets and sparsity XVII*, 10394 (2017).
- Preti, M.G., Van De Ville, D. Graph slepian to probe into large-scale network organization of resting-state functional connectivity. 2017 51st Asilomar Conference on Signals, Systems, and Computers, 1539-1543 (2017).
- Preti, M.G., Bolton, T.A.W., Van De Ville, D. The dynamic functional connectome: State-of-the-art and perspectives. *Neuroimage*, 160, 41-54 (2017).

Thomas A.W. Bolton

Thomas A.W. Bolton is a Ph.D. student in the Medical Imaging Processing Laboratory (MIPLab) at Campus Biotech, Geneva. He is jointly affiliated to the École Polytechnique Fédérale de Lausanne (EPFL) and the University of Geneva (UNIGE).

In his thesis, which revolves around the analysis of functional MRI data, Thomas has been interested in the development of novel mathematical approaches that could help elucidate the neural underpinnings of human behaviour and brain disorders.

In this context, he has explored a variety of methodological avenues, including sliding window-based assessment of dynamic functional connectivity, frame-wise alternatives such as co-activation pattern analysis, temporal modelling by means of hidden Markov models, and multimodal investigations through graph signal processing.

During the course of his Ph.D., Thomas spent a one-month visiting research period at Harvard Medical School (Boston, USA), under the supervision of Prof. Dara Manoach, where he leveraged his technical

developments to study autism spectrum disorders. He has also been involved in other collaborative projects focussing on schizophrenia, bipolar disorders or essential tremor, and conducted another one-month internship at NUS Singapore in Prof. Thomas Yeo's laboratory, where he studied the extent to which different methods suffer from physiology- or motion-based artefacts.

In 2017, Thomas received the OHBM Merit Abstract Award and in 2018, his PhD thesis was awarded the Vasco Sanz Foundation Prize.

Selected related publications:

- Huang, W., Bolton, T.A.W., Medaglia, J.D., Bassett, D.S., Ribeiro, A., Van De Ville, D. A graph signal processing perspective on functional brain imaging. *Proceedings of the IEEE* 106 (5), 868-885 (2018).
- Petrovic, M., Bolton, T.A.W., Preti, M.G., Liégeois, R., Van De Ville, D. Guided graph spectral embedding: Application to the *C. elegans* connectome. *Network Neuroscience*, 3, 807-826 (2019).
- Bolton, T.A.W., Farouj, Y., Inan, M., Van De Ville, D. Structurally-Informed Deconvolution of Functional Magnetic Resonance Imaging Data. 2019 IEEE 16th International Symposium on Biomedical Imaging (ISBI 2019).
- Huang, W., Bolton, T.A.W., Medaglia, J.D., Bassett, D.S., Ribeiro, A., Van De Ville, D. Graph signal processing of human brain imaging data. 2018 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), 980-984.
- Bolton, T.A.W., Farouj, Y., Obertino, S., Van De Ville, D. Graph slepians to strike a balance between local and global network interactions: Application to functional brain imaging. 2018 IEEE 15th International Symposium on Biomedical Imaging (ISBI 2018).
- Preti, M.G., Bolton, T.A.W., Van De Ville, D. The dynamic functional connectome: State-of-the-art and perspectives. *Neuroimage*, 160, 41-54 (2017).