Title

Characterisation of multiscale geometry in brain networks

Job Environment/Context and strength of the position

Complex networks have been increasingly used to analyse and model brain connectivity derived from experimentally obtained data [1]. Topological properties, such as the node centrality, efficiency and modularity have been shown to reveal complementary information on the brain functioning in healthy and pathological conditions. However, what is the latent structure behind the brain network properties is still poorly understood.
Modern dimensionality reduction methods learn nonlinear similarities/proximities (that can be also interpreted as dissimilarities/distances) between points distributed over a hidden manifold in a multidimensional feature space, in order to preserve, embed (map) and visualize them in a low-dimensional reduced space. Such embedding methods can map brain networks in Euclidean spaces, but they are unable to fully explain the structural organization of brain connectivity [2], which motivates the quest for a latent geometry of the brain connectivity. The question of whether it exists a hidden geometry from which real complex networks emerge has attracted the attention of the community lately [3], and is getting more and more ground. The possibility to find an effective congruency between network characteristics and its representation in a latent geometric space offers the possibility to understand the reason behind its structure and function at a more fundamental level, and address the study of complex phenomena taking place in these systems in a novel and promising framework.
This project aims to explore non-Euclidean geometries to represent complex brain networks, and to work in the most appropriate hidden geometric space representation of it to unveil properties of the system in a complementary and coherent way.

Assignment/Mission

The ultimate goal of the PhD project is to develop a statistical framework to extract significant information about brain networks from their projection on an effective geometric (non-Euclidean) space.

Specifically, the PhD thesis project aims at:

- Introducing a new embedding of connectivity graphs on non-Euclidean spaces that explicitly takes into account the multiscale organization of the human brain networks.
- Improving current graph models to increase the congruency between the real brain network and its geometric representation.
- Validating the method in existing brain connectivity datasets (functional or anatomical) of both healthy subjects and epileptic patients
- Testing the approach in new EEG-based experiments involving healthy subjects during a cognitive task (Motor-Imagery BCI)

Main activities

- Geometric embedding of complex brain networks

The main activity consists in conceiving and designing a new graph embedding method suitable to characterize brain networks under different scenarios (healthy subjects at resting and during a cognitive task, and epileptic patients). Starting from the state-of- the-art, a graph embedding, based on non-Euclidean distances, that accounts for the topological properties of real brain networks (e.g., nodes, groups of nodes, entire network) will be developed. The developed method will be first validated on synthetic networks generated from known models and then tested on actual brain networks derived from functional and anatomical brain networks. The main objective is the characterisation of the different brain networks (healthy subjects vs patients; or healthy subjects at rest vs cognitive task) by the application of the developed embedding graph method.

- Characterisation of multiscale connectivity

Brain networks possess a rich architecture organized over multiple scales linked to one another (from single nodes to groups or clusters). The characterization of this multiscale property in complex systems is commonly addressed using the renormalization technique of statistical physics. Nevertheless, the presence of correlations between different scales in complex networks limits, however, the application of renormalization procedures directly on the graph or the associated connectivity matrix. Models of complex networks based on non-Euclidean distances can predict, however, the multiscale properties of brain networks, including self-similarity [4].

This PhD thesis will finally identify and characterise the multiscale architecture of human brain networks, e.g. similar organization of short- and long-range connections between different brain regions over many resolution scales. A particular attention will be devoted to the development of a model to reproduce this multiscale geometry of the brain networks. Monte Carlo sampling and Maximum likelihood estimation (maximizing the likelihood for the observed network to be reproduced by the model) will be used to assess the model.

Results evaluation and report

The obtained results will be evaluated with respect to those obtained with standard approaches and interpreted from a methodological and neuroscience perspective. This procedure will allow to emphasize the strong aspects and identify the weak points that can be addressed in the future, and those that must to be solved in the course of the project. All the conducted research activity will be reported and shared with the PI's team and published in written documents and/or presented in appropriate international conferences.

Local environment and resources

This project will be realized in the team "Excitabilité cellulaire et dynamiques des réseaux neuronaux" at the Institut du Cerveau (ICM) in Paris. The team has a privileged position within a unique scientific and technological environment with a comprehensive neuroimaging core facility (eg, M/EEG, fMRI, DTI) including a powerful centralized cluster computer system to realize big-data analysis and simulations. The application of complex network theory to study brain networks derived from neuroimaging data has been a major research direction in the team in the last years.

All the neuroimaging data needed to validate the methodology are already available in the framework of different past and current research projects granted to the PI's team.

Required skills

The ideal candidate should have a solid background in statistical physics, graph theory, good mathematical abstraction and data analysis skills, as well as programming (C++, Python, MATLAB). The knowledge of neuroimaging techniques and data processing is welcome but not necessary. The ability and willingness to learn will do equally well.

Contact (PI supervisor)

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References

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[2] Allard A, Serrano MÁ (2020) Navigable maps of structural brain networks across species. PLoS Comput Biol 16(2): e1007584.
[3] Boguñá, M., Bonamassa, I., De Domenico, M. *et al.* Network geometry. *Nat Rev Phys* **3,** 114–135 (2021)
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