Graph-Based Machine Learning for Enhancing Neuroimaging Data Representation and Analysis

1. Description of the PhD thesis project

1.1 Objectives of the project based on the current state of the art

In neuroscience, characterizing the shape of the brain is a key issue in understanding its organization and its dysfunctions in psychiatric and neurological diseases. For this purpose, non-invasive brain imaging techniques, and in particular Magnetic Resonance Imaging (MRI), offer unparalleled opportunities to identify markers of these pathologies, such as for example cortical folding abnormalities as described in [1].

We have recently identified a new set of features for characterizing cortical folding, the sulcal pits, and developed a method for automatic extraction of these points from anatomical MRI scans [2]. We then proposed to model cortical folding patterns using graphs, defined a graph kernel that allows us to compare the patterns modeled, and demonstrated the relevance of these approaches by integrating them in a brain morphometric method based on machine learning [3]. This approach is illustrated on Fig.1. Recently, we started to explore the potential of Graph Neural Networks (GCN, GAT) to learn a representation space in which basic individual characteristics such as the sex can be predicted, with promising results [4].

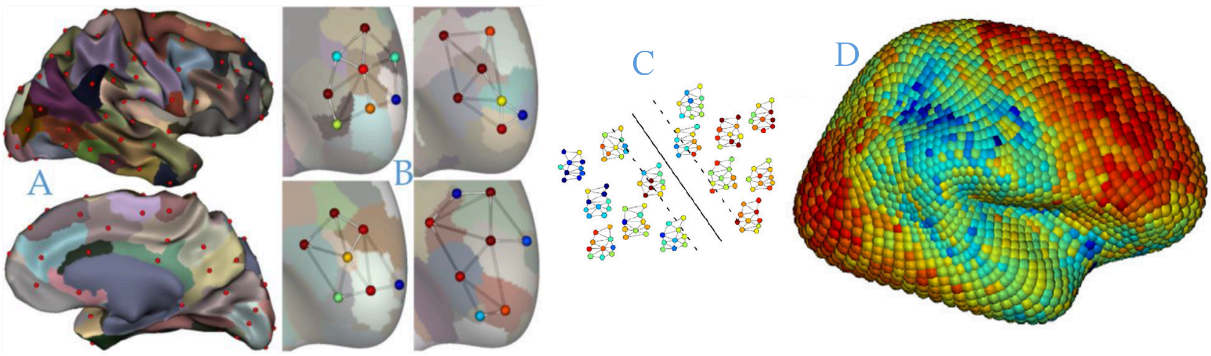

Figure 1 (adapted from [3]) : illustration of the modeling of cortical folding patterns as attributed graphs (A,B) used for a classification task (C) allowing to visualize the differences in the shape of the cortex between two populations of subjects (D).

The aim of this PhD project is to build upon recent research from our teams by developing innovative machine learning models for these graphs, which are capable of (i) discerning specific traits of individuals, such as gender or pathology, and (ii) embedding principles of fairness into the models to guarantee resilience against variations in data acquisition and the inherent diversity of brain structures. This PhD can be built upon advances obtained on Graph Neural Networks, on both convolution [5] and pooling [6] steps.

1.2 Methodology and Work plan

The proposed PhD research program aims to develop innovative graph machine learning (GML) techniques to enhance the representation and analysis of brain imaging data derived from Magnetic Resonance Imaging. The PhD candidate will have access to large datasets such as http://www.humanconnectomeproject.org/ with top-quality MRI from 1200 individuals, and https://www.ukbiobank.ac.uk/ with multimodal MRI from >10000 individuals. The novel GML methods will target the following specific challenges in neuroimaging data analysis:

Research Questions:

1. ***Hierarchical Information Analysis in Brain Graphs:*** *How can graph machine learning models be designed to effectively capture and utilize hierarchical information in brain graphs, for improved representation and analysis of cortical folding patterns?*
2. ***Robustness to variations in MRI acquisition:*** *Can a GML model trained on brain data from one acquisition center generalize effectively to data from different centers, thereby demonstrating robustness to acquisition-related biases and enhancing reproducibility of neuroimaging studies? This research question aims to study the possibility of applying transfer learning in the context of GML.*
3. ***Local Variation Identification for Cognitive Functions:*** *How can GML approaches be employed to identify and analyze local variations in brain anatomy, and what insights can these variations provide regarding cognitive functions and neurological conditions?*

This PhD research program is part of the ANR project FAMOUS, focusing on fair machine learning. Fairness refers here to the biases (in the data and/or induced), while being interested in the interpretability of the models to help their certification. As such, the PhD candidate will benefit from regular interactions with the other research teams involved in this project: LITIS, LIS, INT, Laboratoire Hubert Curien and EURONOVA.

1.3 Supervisor and research group description

The PhD candidate will be located at INSA Rouen, in LITIS laboratory. The project will be co-supervised by Benoit Gaüzère, Guillaume Auzias, Sylvain Takerkart and Paul Honeine. This project lies at the crossroad between their respective domains of expertise. In addition, the PhD candidate will benefit from the joint efforts from each of their research teams:

B. Gaüzère and P. Honeine are members of the "Apprentissage" (Machine Learning) group of LITIS lab. The ML group aims to contribute to machine learning in various fields such as optimization, transfer learning, and trustworthy AI. It has a strong expertise in Graph Machine Learning, and specially in Graph Neural Networks, on both theoretical and practical aspects. The LITIS lab is composed of 90 permanent researchers, with 19 members in the "Apprentissage" group with 20 PhD students.

G.Auzias and S. Takerkart are members of the MeCA team from the Institute for Neurosciences of La Timone (INT). MeCA is a computational anatomy and methods team with a solid experience in developing methods for surface-based analysis of cortical morphometry. The INT is one of the top French neuroscience research institutes with 150 staff members gathered in 10 inter-disciplinary teams examining different aspects of the cerebral organization. It is located on the medical campus of Aix-Marseille University.

2. Related publications

[1] A. Lefrere, G.Auzias et al., "Global and Local Cortical Folding Alterations Are Associated with Neurodevelopmental Subtype in Bipolar Disorders: A Sulcal Pits Analysis," Journal of Affective Disorders 325 (March 15, 2023): 224–30, https://doi.org/10.1016/j.jad.2022.12.156.

[2] G. Auzias, L. Brun, C. Deruelle, and O. Coulon, 'Deep sulcal landmarks: Algorithmic and conceptual improvements in the definition and extraction of sulcal pits', NeuroImage, vol. 111, pp. 12–25, May 2015.

[3] S. Takerkart, G. Auzias, L. Brun, and O. Coulon, 'Structural graph-based morphometry: A multiscale searchlight framework based on sulcal pits', Medical Image Analysis, vol. 35, pp. 32–45, Jan. 2017.

[4] R. Yadav, F.-X Dupé, S. Takerkart, G. Auzias, "Geometric Deep Learning for Sulcal Graphs," in IEEE International Symposium on Biomedical Imaging, 2024.

[5] M. Balcilar, P. Héroux, B. Gaüzère,P. Vasseur, S. Adam and P. Honeine, "Breaking the Limits of Message Passing Graph Neural Networks" Proceedings of the 38th International Conference on Machine Learning, 2021. Available from https://proceedings.mlr.press/v139/balcilar21a.html.

[6] S. Stanovic, B. Gaüzère, , L. Brun, "Maximal independent sets for pooling in graph neural networks", In International Workshop on Graph-Based Representations in Pattern Recognition, pp. 113-124, August 2023.

3. Expected profile of the candidate

We are seeking a PhD candidate who meets the following requirements:

1) Master degree in data science, computer engineering or a similar field;
2) Proficient with computer programming (Python will be our language of choice);
3) Good knowledge and/or experience in machine learning / data science.

Experience with graph structures would be a plus. Prior experience in neuroscience is not a requirement, but interest in the field and high motivation are of course necessary. Good reading/writing/communication skills in English are also essential.

4. How to apply

Send resume, academic results, and links to code or/and scientific & technical papers to the scientific contacts below. For a better processing of your application, please add the word [FAMOUS] in the subject of the email.

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