1. PHD PROJECT DESCRIPTION (4000 characters max., including the aims and work plan, all in English)

Project title: Dynamics of attractor neural networks

1.1. Project goals

The challenge that we would like to address is to investigate dynamics of attractor neural network models that explain experimental observations. Activation of specific subnetworks on connectome structures should lead to attractor states of neural networks that correspond to the EEG/MEG microstates. Building such biologically-oriented neural models would be an important step towards understanding, optimizing and even repairing brain processes. Non-linear methods of analysis of brain signals are a new approach to understanding of neurodynamics. Our recent results show that there is a chance for real-time EEG-based neurofeedback that could revolutionize treatment of many mental disorders. This project has both potentially very important implications for basic understanding of the brain and medical applications.

1.2. Outline

One of the priority areas of the European Commission is application of AI in medicine, especially the use of methods developed in physics of complex systems, machine learning, image and signal analysis to diagnosis of brain disorders. High-definition measurement of EEG creates large amounts of data and is difficult to analyze, requiring sophisticated computational methods to simulate propagation of electric potentials and magnetic fields through different types of brain tissue. Decomposition of brain activity into a series of quasi-stable microstates (lasting 60-150 ms) that can be identified in EEG/MEG signals has an important diagnostic value in neuropsychiatry. Another promising attempt to understand brain dynamics has been based on fMRI. Tensor diffusion imaging (DTI) shows anatomical connections between different regions of the brain. Network neuroscience is using this data together with functional correlations to create graphs representing information flow. This approach can explain many phenomena, including mental disorders, intelligence, working memory and decision making. fMRI provides information about spatial distribution of active brain regions with accuracy of 1-2 mm, but temporal resolution does not exceed 1 Hz. This means that one brain scan is averaging signals of about 10 microstates. On the other hand temporal resolution of EEG is excellent, up to 1 ms, but spatial resolution is of the order of centimeters. fMRI is very useful not only to recognize various problems with brain connectome structure but also information flow, that is determined by very complex biophysical processes responsible for neural activations (Yahata, N., Kasai, K., Kawato, 2017).
Localization of active structures gives also a chance for therapeutic neurofeedback interventions. Real-time fMRI (rt-fMRI) based on source localization or monitoring of functional connectivity is very effective in changing behavior. Neurofeedback based on EEG signal analysis is not working as well as rt-fMRI. EEG is much more cost-effective and practical, but requires source reconstruction and localization to extract information about localized brain activity. Development of new non-linear methods of recurrence analysis of EEG microstates is of great importance. Ultimately we would like to decompose brain signals into activity of specific subnetworks with groups of neurons in well-defined anatomical locations.
We have recently developed a Matlab/Python Toolbox SupFunSim for simulations of propagation of electric potentials through various brain tissues, new method for solving inverse problems using

minimum-variance pseudo-unbiased reduced-rank approach, and are able to perform source-level directed connectivity analysis, using partial directed coherence (PDC) and directed transfer function (DTF) measures to see information flow between different brain regions. We have been analyzing data from our own experiments, analyzing complexity of signals, and data from the Human Connectome Project to see how well this approach is able to reconstruct activity of brain subnetworks from EEG signals. The goal is to derived functional networks similar as can be obtained from fMRI analysis. Non-linear recurrence analysis methods can capture dynamics of microstates transitions and has already been used in a few papers for diagnosis of mental disorders with excellent results.

1.3. Work plan

Depending on the skills of PhD candidate, the work may be more focused on computational simulations using such systems as Emergent, or The Virtual Brain, or more of neuroimaging signal analysis, EEG/MEG and fMRI. This field is changing very quickly, therefore it is not possible to make detailed plans.

1) Learning basics: signal processing methods, machine learning.
2) Learning advanced methods of EEG/MEG and fMRI analysis.
3) Analysis of complexity of EEG signals acquired from our own experiments on fluid Intelligence, and public databases such as the Human Connectome Project, using nonlinear Recurrent Quantification Analysis, Multidimensional Empirical Mode Decomposition and other non-linear methods.
4) Application of brain fingerprinting methods based on non-linear methods of analysis for diagnosis of various mental disorders using large databases of EEG and FMRI recordings.
5) Work on real-time methods for identification of brain subnetworks based on non-linear dynamics.
6) Application of new methods of brain fingerprinting for clinical diagnosis, in collaboration with psychiatrists and clinical psychologists.

1.4. Literature

Bosl, W. J., Tager-Flusberg, H., & Nelson, C. A. (2018). EEG Analytics for Early Detection of Autism Spectrum Disorder: A data-driven approach. Scientific Reports, 8(1), 6828. https://doi.org/10.1038/s41598-018-24318-x

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Yahata, N., Kasai, K., & Kawato, M. (2017). Computational neuroscience approach to biomarkers and treatments for mental disorders. Psychiatry and Clinical Neurosciences, 71(4), 215–237. https://doi.org/10.1111/pcn.12502

Rykaczewski, Krzysztof; Nikadon, Jan; Duch, Włodzisław; Piotrowski, Tomasz. (2020) SupFunSim: spatial filtering toolbox for EEG. Neuroinformatics (IF 5.1), accepted 4/2020, see also bioRxiv preprint doi: