RESEARCH CENTRE

Inria Center
at Université Côte d'Azur

2022
ACTIVITY REPORT

Team
ATHENA

Computational Imaging of the Central Nervous System

Inria teams are typically groups of researchers working on the definition of a common project, and objectives, with the goal to arrive at the creation of a project-team. Such project-teams may include other partners (universities or research institutions)

DOMAIN

Digital Health, Biology and Earth

THEME

Computational Neuroscience and Medicine

Inria

Contents

Team ATHENA

Creation of the Team: 2022 December 01

Keywords

Computer sciences and digital sciences

A3.4. – Machine learning and statistics

A6.1. – Methods in mathematical modeling

A6.3. – Computation-data interaction

A9. – Artificial intelligence

A9.2. – Machine learning

A9.3. – Signal analysis

A9.7. – AI algorithmics

Other research topics and application domains

B1. – Life sciences

B1.2. – Neuroscience and cognitive science

B1.2.1. – Understanding and simulation of the brain and the nervous system

B1.2.2. – Cognitive science

B1.2.3. – Computational neurosciences

B2.2.2. – Nervous system and endocrinology

B2.2.6. – Neurodegenerative diseases

B2.5.1. – Sensorimotor disabilities

B2.6.1. – Brain imaging

1 Team members, visitors, external collaborators

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- Rachid Deriche [Team leader, INRIA, Senior Researcher, HDR]
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Interns and Apprentices

- Aymene Bouayed [Aix Marseille Université, Intern, from Feb 2022 until Aug 2022]
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2 Overall objectives

2.1 Presentation

The main objective of ATHENA is to develop rigorous mathematical models and computational tools for analyzing and modeling the complex Central Nervous System structure and function. These models and tools will help to better understand the structure and the functioning of the human brain and address pressing and challenging clinical and neuroscience questions. Exploring new directions to solve these challenging problems will push forward the state-of-the-art in Structural and Functional Computational Brain Connectivity Mapping.

The relationship between brain structure and function is fundamental in neuroscience. Developing computational models and techniques that recover the structural and functional connectivities of the brain in vivo is thus of utmost importance: it will definitely improve the understanding of the brain and its mechanisms. On the basis of our expertise and contributions to the field of computational neuroimaging and in order to have an impact on this field, our research focusses mainly on the structural and functional Imaging of the brain with a particular emphasis on signal and image recording from diffusion Magnetic Resonance Imaging (dMRI), Magneto-Encephalography (MEG) and Electro-Encephalography (EEG).

In order to further increase the impact of our research, we also aim to push our contributions towards some applications related to brain diseases with characteristic abnormalities in the micro-structure of brain tissues that are not apparent and cannot be revealed reliably by standard imaging techniques. Diffusion MRI, a non invasive imaging modality based on the measurement of the random thermal movement (diffusion) of water molecules within samples can make visible these co-lateral damages to the fibers of the brain white matter and can also help in the development of new biomarkers related to the progression of certain types of neurodegenerative disease. Diffusion MRI is the imaging modality that we will primarly consider to recover the structural brain connectivity.

Connectivity represents the network infrastructure of the brain. Electric activity corresponds to communications over this network. MEG and EEG (jointly as M/EEG), two non-invasive techniques, reveal part of the cortical electric activity and are instrumental in better understanding the brain functional connectivity and in diagnosing diseases linked to anomalous brain function - that in some cases structural or other functional MR images do not reveal. MEG and EEG are the imaging modalities that we will primarly consider to recover the functional brain connectivity.

In some CNS injuries (medullar injuries, strokes, AMS), the peripheral nervous system may not be able to execute commands that are issued by the brain. Brain Computer Interfaces (BCI) use brain signals such as measured through EEG, and translate in real-time the electrical activity of the brain in commands to control external devices. While BCI is advocated as a means to communicate and help restore mobility or autonomy for very severe cases of disabled patients, it is also a new tool for interactively probing and training the human brain.

These considerations support the need to do research on new models and computational tools to analyse brain signals and imaging data. Our main objective is to push forward the state-of-the-art in Structural and Functional Computational Brain Connectivity Mapping to better understand the structure and function of the brain.

In order to tackle these long term and challenging objectives, our strategy is based on the following road map:

- Develop rigorous mathematical and computational tools for the analysis and interpretation of Diffusion MRI and M/EEG data.
- Improve acquisition and processing techniques and push forward the state-of-the-art in Computational brain imaging.
- Use our expertise to address with collaborators clinical and neuroscience questions.

This is implemented through:

- Publications in international conferences and journals dedicated to promoting advances in computational methods for Diffusion MRI and M/EEG analysis and/or use of Diffusion MRI and M/EEG in clinical and neuroscience applications.
- A dense network of collaborations with national as well as international neuroimaging laboratories through which we have access equipment and data and with whom we will jointly contribute to solve common crucial problems of interest.
- Software packages developed to be used in a first stage by our national and international collaborators and then made available to other partners.

3 Research program

3.1 Computational diffusion MRI

Diffusion MRI (dMRI) provides a non-invasive way of estimating in-vivo CNS fiber structures using the average random thermal movement (diffusion) of water molecules as a probe. It's a relatively recent field of research with a history of roughly three decades. It was introduced in the mid 80's by Le Bihan et al [59], Merboldt et al [64] and Taylor et al [78]. As of today, it is the unique non-invasive technique capable of describing the neural connectivity in vivo by quantifying the anisotropic diffusion of water molecules in biological tissues.

Diffusion Tensor Imaging & High Angular Resolution Diffusion Imaging In dMRI, the acquisition and reconstruction of the diffusion signal allows for the reconstruction of the water molecules displacement probability, known as the Ensemble Average Propagator (EAP) [77, 42]. Historically, the first model in dMRI is the 2nd order diffusion tensor (DTI) [39, 38] which assumes the EAP to be Gaussian centered at the origin. DTI (Diffusion Tensor Imaging) has now proved to be extremely useful to study the normal and pathological human brain [60, 50]. It has led to many applications in clinical diagnosis of neurological diseases and disorder, neurosciences applications in assessing connectivity of different brain regions, and more recently, therapeutic applications, primarily in neurosurgical planning. An important and very successful application of diffusion MRI has been brain ischemia, following the discovery that water diffusion drops immediately after the onset of an ischemic event, when brain cells undergo swelling through cytotoxic edema.

The increasing clinical importance of diffusion imaging has driven our interest to develop new processing tools for Diffusion Tensor MRI. Because of the complexity of the data, this imaging modality raises a large amount of mathematical and computational challenges. We have therefore developed original and efficient algorithms relying on Riemannian geometry, differential geometry, partial differential equations and front propagation techniques to correctly and efficiently estimate, regularize, segment and process Diffusion Tensor MRI (DT-MRI) (see [62] and [61]).

In DTI, the Gaussian assumption over-simplifies the diffusion of water molecules. While it is adequate for voxels in which there is only a single fiber orientation (or none), it breaks for voxels in which there are more complex internal structures and limitates the ability of the DTI to describe complex, singular and intricate fiber configurations (U-shape, kissing or crossing fibers). To overcome this limitation, so-called Diffusion Spectrum Imaging (DSI) [81] and High Angular Resolution Diffusion Imaging (HARDI) methods such as Q-ball imaging [79] and other multi-tensors and compartment models [74, 76, 57, 56, 71] were developed to resolve the orientationnality of more complicated fiber bundle configurations.

Q-Ball imaging (QBI) has been proven very successful in resolving multiple intravoxel fiber orientations in MR images, thanks to its ability to reconstruct the Orientation Distribution Function (ODF, the probability of diffusion in a given direction). These tools play a central role in our work related to the development of a robust and linear spherical harmonic estimation of the HARDI signal and to our development of a regularized, fast and robust analytical QBI solution that outperforms the state-of-the-art ODF numerical technique developed by Tuch [79]. Those contributions are fundamental and have already started to impact on the Diffusion MRI, HARDI and Q-Ball Imaging community [46]. They are at the core of our probabilistic and deterministic tractography algorithms devised to best exploit the full distribution of the fiber ODF (see [47, 4, 48, 5]).

Beyond DTI with high order tensors High Order Tensors (HOT) models to estimate the diffusion function while overcoming the shortcomings of the 2nd order tensor model have also been proposed such as the Generalized Diffusion Tensor Imaging (G-DTI) model developed by Ozarslan et al [69, 70] or 4th order Tensor Model [37]. For more details, we refer the reader to our articles in [54, 74] where we review HOT models and to our articles in [61], co-authored with some of our close collaborators, where we review recent mathematical models and computational methods for the processing of Diffusion Magnetic Resonance Images, including state-of-the-art reconstruction of diffusion models, cerebral white matter connectivity analysis, and segmentation techniques. We also worked on Diffusion Kurtosis Imaging (DKI), of great interest for the company OLEA MEDICAL. Indeed, DKI is fastly gaining popularity in the domain for characterizing the diffusion propagator or EAP by its deviation from Gaussianity. Hence it is an important clinical tool for characterizing the white-matter's integrity with biomarkers derived from the 3D 4th order kurtosis tensor (KT) [55].

All these powerful techniques are of utmost importance to acquire a better understanding of the CNS mechanisms and have helped to efficiently tackle and solve a number of important and challenging problems [56, 57]. They have also opened up a landscape of extremely exciting research fields for medicine and neuroscience. Hence, due to the complexity of the CNS data and as the magnetic field strength of scanners increases, as the strength and speed of gradients increase and as new acquisition techniques appear [3], these imaging modalities raise a large amount of mathematical and computational challenges at the core of the research we develop at ATHENA [52, 74].

Improving dMRI acquisitions One of the most important challenges in diffusion imaging is to improve acquisition schemes and analyse approaches to optimally acquire and accurately represent diffusion profiles in a clinically feasible scanning time. Indeed, a very important and open problem in Diffusion MRI is related to the fact that HARDI scans generally require many times more diffusion gradient than traditional diffusion MRI scan times. This comes at the price of longer scans, which can be problematic for children and people with certain diseases. Patients are usually unable to tolerate long scans and excessive motion of the patient during the acquisition process can force a scan to be aborted or produce useless diffusion MRI images. We have developed novel methods for the acquisition and the processing of diffusion magnetic resonance images, to efficiently provide, with just few measurements, new insights into the structure and anatomy of the brain white matter in vivo.

First, we contributed developing real-time Q-Ball Imaging reconstruction algorithm based on the Kalman filter [45]. Then, we started to explore the utility of Compressive Sensing methods to enable faster acquisition of dMRI data by reducing the number of measurements, while maintaining a high quality for the results. Compressed Sensing (CS) is a relatively recent technique which has been proved to accurately reconstruct sparse signals from undersampled measurements acquired below the Shannon-Nyquist rate [65].

We have also contributed to the reconstruction important features of the diffusion signal as the orientation distribution function and the ensemble average propagator, with a special focus on clinical setting in particular for single and multiple Q-shell experiments. Compressive sensing as well as the parametric reconstruction of the diffusion signal in a continuous basis of functions such as the Spherical Polar Fourier basis, have been proved through our contributions to be very useful for deriving simple and analytical closed formulae for many important dMRI features, which can be estimated via a reduced number of measurements [65, 43, 44].

We have also contributed to design optimal acquisition schemes for single and multiple Q-shell experiments. In particular, the method proposed in [3] helps generate sampling schemes with optimal angular coverage for multi-shell acquisitions. The cost function we proposed is an extension of the electrostatic repulsion to multi-shell and can be used to create acquisition schemes with incremental angular distribution, compatible with prematurely stopped scans. Compared to more commonly used radial sampling, our method improves the angular resolution, as well as fiber crossing discrimination. The optimal sampling schemes, freely available for download, have been selected for use in the HCP (Human Connectome Project).

We think that such kind of contributions open new perspectives for dMRI applications including, for example, tractography where the improved characterization of the fiber orientations is likely to greatly and quickly help tracking through regions with and/or without crossing fibers [53].

dMRI modelling, tissue microstructures features recovery & applications The dMRI signal is highly complex, hence, the mathematical tools required for processing it have to be commensurate in their complexity. Overall, these last years have seen an explosion of intensive scientific research which has vastly improved and literally changed the face of dMRI. In terms of dMRI models, two trends are clearly visible today: the parametric approaches which attempt to build models of the tissue to explain the signal based on model-parameters such as CHARMED [33], AxCaliber [34] and NODDI [82] to cite but a few, and the non-parametric approaches, which attempt to describe the signal in useful but generic functional bases such as the Spherical Polar Fourier (SPF) basis [35, 36], the Solid Harmonic (SoH) basis [49], the Simple Harmonic Oscillator based Reconstruction and Estimation (SHORE) basis [67] and more recent Mean Apparent Propagator or MAP-MRI basis [68].

We propose to investigate the feasibility of using our new models and methods to measure extremely important biological tissue microstructure quantities such as axonal radius and density in white matter. These parameters could indeed provide new insight to better understand the brain's architecture and more importantly could also provide new imaging bio-markers to characterize certain neurodegenerative diseases. This challenging scientific problem, when solved, will lead to direct measurements of important microstructural features that will be integrated in our analysis to provide much greater insight into disease mechanisms, recovery and development. These new microstructural parameters will open the road to go far beyond the limitations of the more simple bio-markers derived from DTI that are clinically used to this date – such as MD (Mean Diffusivity) and FA (Fractional Anisotropy) which are known to be extremely

sensitive to confounding factors such as partial volume and axonal dispersion, non-specific and not able to capture any subtle effects that might be early indicators of diseases [8].

Towards microstructural based tractography In order to go far beyond traditional fiber-tracking techniques, we believe that first order information, i.e. fiber orientations, has to be superseeded by second and third order information, such as microstructure details, to improve tractography. However, many of these higher order information methods are relatively new or unexplored and tractography algorithms based on these high order based methods have to be conceived and designed. In this aim, we propose to work with multiple-shells to reconstruct the Ensemble Average Propagator (EAP), which represents the whole 3D diffusion process and use the possibility it offers to deduce valuable insights on the microstructural properties of the white matter. Indeed, from a reconstructed EAP one can compute the angular features of the diffusion in an diffusion Orientation Distribution Function (ODF), providing insight in axon orientation, calculate properties of the entire diffusion in a voxel such as the Mean Squared Diffusivity (MSD) and Return-To-Origin Probability (RTOP), or come forth with bio-markers detailing diffusion along a particular white matter bundle direction such as the Return-to-Axis or Return-to-Plane Probability (RTAP or RTPP). This opens the way to a ground-breaking computational and unified framework for tractography based on EAP and microstructure features [10]. Using additional a priori anatomical and/or functional information, we could also constrain the tractography algorithm to start and terminate the streamlines only at valid processing areas of the brain.

This development of a computational and unified framework for tractography, based on EAP, microstructure and a priori anatomical and/or functional features, will open new perspectives in tractography, paving the way to a new generation of realistic and biologically plausible algorithms able to deal with intricate configurations of white matter fibers and to provide an exquisite and intrinsic brain connectivity quantification.

Going beyond the state-of-the-art dMRI Although great improvements in dMRI modelling have been made during the last years, major problems are still unsolved and improvements are still required to better acquire dMRI data, better understand the biophysics of the signal formation, go beyond classical second order tensors invariants and recover high order invariants, recover robust and intrinsic microstructure features, identify bio-physically important bio-markers, improve tractography and in fine contribute to reconstruct the complete map of the cerebral connections, the connectome, as well as to better understand brain structure and function.

Therefore, there is still considerable room for improvement when it comes to the concepts and tools able to efficiently acquire, process and analyze the complex structure of dMRI data. Develop groundbreaking dMRI tools and models for brain connectomics is one of the major objective we would like to achieve in order to take dMRI from the benchside to the bedside and lead to a decisive advance and breakthrough in this field.

3.2 MEG and EEG

Electroencephalography (EEG) and Magnetoencephalography (MEG) are two non-invasive techniques for measuring (part of) the electrical activity of the brain. While EEG is an old technique (Hans Berger, a German neuropsychiatrist, measured the first human EEG in 1929), MEG is a rather new one: the first measurements of the magnetic field generated by the electrophysiological activity of the brain were made in 1968 at MIT by D. Cohen. Nowadays, EEG is relatively inexpensive and is routinely used to detect and qualify neural activities (epilepsy detection and characterisation, neural disorder qualification, BCI, ...). MEG is, comparatively, much more expensive as SQUIDS (Superconducting QUantum Interference Device) only operate under very challenging conditions (at liquid helium temperature) and as a specially shielded room must be used to separate the signal of interest from the ambient noise. However, as it reveals a complementary vision to that of EEG and as it is less sensitive to the head structure, it also bears great hopes and an increasing number of MEG machines are being installed throughout the world. Inria and ODYSSÉE/ATHENA have participated in the acquisition of one such machine installed in the hospital "La Timone" in Marseille.

MEG and EEG can be measured simultaneously (M/EEG) and reveal complementary properties of the electrical fields. The two techniques have temporal resolutions of about the millisecond, which is the typical granularity of the measurable electrical phenomena that arise within the brain. This high temporal resolution makes MEG and EEG attractive for the functional study of the brain. The spatial resolution, on the contrary, is somewhat poor as only a few hundred data points can be acquired simultaneously (about 300-400 for MEG and up to 256 for EEG). MEG and EEG are somewhat complementary with fMRI (Functional MRI) and SPECT (Single-Photon Emission Computed Tomography) in that those provide a very good spatial resolution but a rather poor temporal resolution (of the order of a second for fMRI and a minute for SPECT). Also, contrarily to fMRI, which "only" measures an haemodynamic response linked to the metabolic demand, MEG and EEG measure a direct consequence of the electrical activity of the brain: it is acknowledged that the signals measured by MEG and EEG correspond to the variations of the post-synaptic potentials of the pyramidal cells in the cortex. Pyramidal neurons compose approximately 80% of the neurons of the cortex, and it requires at least about 50,000 active such neurons to generate some measurable signal.

While the few hundred temporal curves obtained using M/EEG have a clear clinical interest, they only provide partial information on the localisation of the sources of the activity (as the measurements are made on or outside of the head). Thus the practical use of M/EEG data raises various problems that are at the core of the ATHENA research in this topic:

- First, as acquisition is continuous and is run at a rate up to 1kHz, the amount of data generated by each experiment is huge. Data selection and reduction (finding relevant time blocks or frequency bands) and pre-processing (removing artifacts, enhancing the signal to noise ratio, ...) are largely done manually at present. Making a better and more systematic use of the measurements is an important step to optimally exploit the M/EEG data [2].

- With a proper model of the head and of the sources of brain electromagnetic activity, it is possible to simulate the electrical propagation and reconstruct sources that can explain the measured signal. Proposing better models [58, 12] and means to calibrate them [80] so as to have better reconstructions are other important aims of our work.

- Finally, we wish to exploit the temporal resolution of M/EEG and to apply the various methods we have developed to better understand some aspects of the brain functioning, and/or to extract more subtle information out of the measurements. This is of interest not only as a cognitive goal, but it also serves the purpose of validating our algorithms and can lead to the use of such methods in the field of Brain Computer Interfaces. To be able to conduct such kind of experiments, an EEG lab has been set up at ATHENA.

3.3 Combined M/EEG and dMRI

dMRI provides a global and systematic view of the long-range structural connectivity within the whole brain. In particular, it allows the recovery of the fiber structure of the white matter which can be considered as the wiring connections between distant cortical areas. These white matter based tractograms are analyzed, e.g. to explore the differences in structural connectivity between pathological and normal populations. Moreover, as a by-product, the tractograms can be processed to reveal the nodes of the brain networks, i.e. by segregating together gray matter that share similar connections to the rest of the white matter. But dMRI does not provide information on:

- the cortico-cortical pathways (not passing through white matter) and to some extent, on the short-range connections in the white matter,

- the actual use of connections over time during a given brain activity.

On the opposite, M/EEG measures brain activation over time and provides, after source reconstruction (solving the so-called inverse problem of source reconstruction), time courses of the activity of the cortical areas. Unfortunately, deep brain structures have very little contribution to M/EEG measurements and are thus difficult to analyze. Consequently, M/EEG reveals information about the nodes of the network, but in a more blurry (because of the inverse problem) and fragmented view than dMRI (since it can

only reveal brain areas measurable in M/EEG whose activity varies during the experimental protocol). Given its very high temporal resolution, the signal of reconstructed sources can be processed to reveal the functional connectivity between the nodes [75].

While dMRI and M/EEG have been the object of considerable research separately, there have been very few studies on combining the information they provide. Some existing studies deal with the localization of abnormal MEG signals, particularly in the case of epilepsy, and on studying the white matter fibers near the detected abnormal source [63, 66], but to our knowledge there are very few studies merging data coming both from M/EEG and dMRI at the analysis level [73, 51, 40, 72].

Combining the structural and functional information provided by dMRI and M/EEG is a difficult problem as the spatial and temporal resolutions of the two types of measures are extremely different. Still, combining the measurements obtained by these two types of techniques has the great potential of providing a detailed view both in space and time of the functioning brain at a macroscopic level. Consequently, it is a timely and extremely important objective to develop innovative computational tools and models that advance the dMRI and M/EEG state-of-the-art and combine these imaging modalities to build a comprehensive dynamical structural-functional brain connectivity network to be exploited in brain connectivities diseases.

The CoBCoM ERC project aimed to develop a joint dynamical structural-functional brain connectivity network built on advanced and integrated dMRI and M/EEG ground-breaking methods. To this end, CoBCoM develops new generation of computational dMRI and M/EEG models and methods for identifying and characterizing the connectivities on which the joint network is built. The CoBCoM URL summarizes the contributions and publications, some of which given also via Videos Lectures.

The 3IA UCA Chair AI-based Computational Brain Connectomics project aims to reconstruct and analyse the network of neural connections of the brain, called the connectome via a computational brain connectomics framework based on ground-breaking AI algorithms and machine learning tools to gain insight into brain architecture, functioning and neurodegenerative diseases. The avalanche of big data required to reconstruct the connectome and the study of the high complexity of structural and functional interactions within the connectome clearly position brain connectomics as a big data problem where AI & machine learning in particular, represent a very promising trend, as recently demonstrated in computer vision and in some biomedical image data-driven analysis. Partly related to the ERC Advanced Grant CoBCoM, this project aims to construct networks specifically built on new generation of AI algorithms and machine learning tools to reconstruct structural and functional connectomes using advanced and integrated diffusion MRI, Electro and Magneto-Encephalography (EEG & MEG) methods.

Capitalizing on the strengths of dMRI & M/EEG and building on the bio-physical and mathematical foundations of our models, CoBCoM and the 3IA UCA Chair AI-based Computational Brain Connectomics contribute to create a joint and solid network which will be exploited to identify and characterize white matter abnormalities in some high-impact brain diseases such as Multiple Sclerosis (MS), Epilepsy and mild Traumatic Brain Injury (mTBI).

4 Application domains

4.1 Applications of diffusion MRI

Clinical domain: Diagnosis of neurological disorder

Various examples of CNS diseases as Alzheimer's and Parkinson's diseases and others like multiple sclerosis, traumatic brain injury and schizophrenia have characteristic abnormalities in the microstructure of brain tissues that are not apparent and cannot be revealed reliably by standard imaging techniques. Diffusion MRI can make visible these co-lateral damages to the fibers of the CNS white matter that connect different brain regions.

4.2 Applications of M/EEG

Clinical domain: Diagnosis of neurological disorders

The dream of all M/EEG researchers is to alleviate the need for invasive recordings (electrocorticograms or intracerebral electrodes), which are often necessary prior to brain surgery, in order to precisely locate both pathological and vital functional areas. We are involved in this quest, particularly through our collaborations with the La Timone hospital in Marseille.
Subtopics include:

- Diagnosis of neurological disorders such as epilepsy, schizophrenia, tinnitus, ...
- Presurgical planning of brain surgery.
- Collaboration with the *Institut de Neurosciences des Systèmes* in Marseille on these topics.

Cognitive research

- Aims at better understanding the brain spatio-temporal organisation.
- Collaboration with laboratories of cognitive neuroscience in order to develop methods that suit their needs for sophisticated data analysis.

Brain Computer Interfaces (BCI) aim to allow direct control of external devices using brain signals such as measured through EEG. In our project, BCI can be seen as an application of EEG processing techniques, but also as an object of fundamental and applied research as they open the way for more dynamical and active brain cognitive protocols.

We develop a research collaboration with the eemagine/ANT-Neuro company. We collaborate with Nice University Hospital on the usage of BCI-based communication for ALS[1] patients.

5 Highlights of the year

The ATHENA team reached the maximum longevity of an Inria Project-Team of 12 years in 2022. Thus, despite a very positive final evaluation, it was ended at December 31st, 2022. It therefore seems appropriate to summarize some of its activity in a few words. Overall, since its inception on July 2010 and up to December 2022, a total of 29 PhD's students have defended their thesis, 115 journal papers have been published, and 233 conference articles have been presented.

The CRONOS project-team, which members are Théodore Papadopoulo (as team leader), Samuel Deslauriers-Gauthier, and Rachid Deriche (emeritus) started on December, 1st, 2022, and took over ATHENA to go further into computational modelling of brain dynamical networks.

6 New software and platforms

6.1 New software

6.1.1 OpenMEEG

Keywords: Health, Neuroimaging, Medical imaging

Scientific Description: OpenMEEG provides a symmetric boundary element method (BEM) implementation for solving the forward problem of electromagnetic propagation over heterogeneous media made of several domains of homogeneous and isotropic conductivities. OpenMEEG works for the quasistatic regime (frequencies < 100Hz and medium diameter < 1m).

Functional Description: OpenMEEG provides state-of-the art tools for modelling bio-electromagnetic propagation in the quasi-static regime. It is based on the symmetric BEM for the EEG/MEG forward problem, with a distributed source model. OpenMEEG has also been used to model the forward problem of ECoG, for modelling nerves or the cochlea. OpenMEEG is a free, open software written in C++ with python bindings. OpenMEEG is used through a command line interface, but is also interfaced in graphical interfaces such as BrainStorm, FieldTrip or SPM.

[1] Nice University Hospital hosts a regional reference center for patients suffering from Amyotrophic Lateral Sclerosis

Release Contributions: OpenMEEG has had a large update including notably the parallelisation of some operators and bug corrections. The new version allows in addition the use of non-nested domains.

News of the Year: The python interface of OpenMEEG has been improved and now allows to pass python data structures (meshes, conductivities) to characterize the gain matrices to be calculated without going through files. This is done to ease a future integration of OpenMEEG in MNE-python. A code factorization also took place to allow in the long term to facilitate the integration in OpenMEEG of the work of K. Maksymenko on the efficient calculation of gain matrices for several conductivity values. This work has not yet been released.

URL: http://openmeeg.github.io/

Publications: inria-00467061v2, inria-00584205v1, hal-01278377v1

Contact: Théodore Papadopoulo

Participants: Alexandre Gramfort, Emmanuel Olivi, Geoffray Adde, Jan Kybic, Kai Dang, Maureen Clerc Gallagher, Perrine Landreau, Renaud Keriven, Théodore Papadopoulo

6.1.2 BCI-VIZAPP

Name: BCI visual applications

Keywords: Health, Brain-Computer Interface, GUI (Graphical User Interface)

Scientific Description: Bci-Vizapp is a library that allows (in interaction with OpenViBE) to build BCI (Brain Computer Interfaces) applications based on the P300 speller principle. Bci-Vizapp provides a library that allows you to create the BCI's stimulation part as part of the Qt toolkit. Being able to use a standard toolkit to make BCI applications is a strong Bci-Vizapp originality. Indeed, in general the use of such toolkits is prohibited by the need for a very precise control of the display timings, which generally eliminates high-level graphic toolkits such as Qt.

Functional Description: BCI-VIZAPP includes a virtual keyboard for typing text, a photodiode monitoring application for checking timing issues. It communicates with the OpenViBE acquisition server for signal acquisition and with the OpenViBE designer for signal processing. The configuration is performed through a wizard.

This software is a new version following the CoAdapt P300 stimulator software.

News of the Year: Bci-Vizapp is undergoing a deep transmutation following, among other things, the impulse of the SED of Inria Sophia Antipolis Méditerranée in the ADT BciBrowser. Signal processing which was once based only on OpenViBE can now be done internally by the software. This has led to the development of different substitutable "backends" which can do this processing. In 2022, this software has finalized the change to a new database format that logs all parameters to ease the reproducibility of results. It also gained a possibility to replay old P300 datasets to reproduce results and evaluate performance changes in various conditions (software changes, electrode selection, ...). Tools to deal with dry electrodes EEG caps were also added and will be used in a forthcoming P300 speller acquisition campaign. This software basis has also received improvements from Côme Le Breton to implement a neurofeedback protocol aiming at doing a study on epileptic patient with Hospital La Timone in Marseille.

Contact: Théodore Papadopoulo

Participants: Nathanaël Foy, Romain Lacroix, Maureen Clerc Gallagher, Théodore Papadopoulo, Yang Ji, Come Le Breton

6.1.3 A4D fMRI

Name: Anisotropic 4D filtering of functional MRI

Keywords: FMRI, Denoising, Anisotropic

Scientific Description: Based on the idea that large image variations should be preserved as they occur during brain activations, whereas small variations considered as noise should be removed, the A4D-fMRI applies an anisotropic regularization, thus recovering the location and the duration of brain activations.

Functional Description: A4D-fMRI provides a simple command line that takes as input an fMRI image in Nifti format and denoises it. The output is saved in a new Nifti file.

Release Contributions: This is the first version of the software which implements the A4D-fMRI algorighm. It allows the denoising of arbitrary fMRI acquisition with only a few parameters to set. Two implementations are provided, one relying only on numpy and one on tensorflow.

News of the Year: This is the first version of the software which implements the A4D-fMRI algorighm. It allows the denoising of arbitrary fMRI acquisition with only a few parameters to set. Two implementations are provided, one relying only on numpy and one on tensorflow.

Publication: 03629113

Authors: Isa Costantini, Samuel Deslauriers-Gauthier

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7 New results

7.1 Computational Diffusion MRI

A Riemannian revisiting of structure–function mapping based on eigenmodes

Participants: Samuel Deslauriers-Gauthier, Mauro Zucchelli, Hiba Laghrissi, Rachid Deriche.

Understanding the link between brain structure and function may not only improve our knowledge of brain organization, but also lead to better quantification of pathology. To quantify this link, recent studies have attempted to predict the brain's functional connectivity from its structural connectivity. However, functional connectivity matrices live in the Riemannian manifold of the symmetric positive definite space and a specific attention must be paid to operate on this appropriate space. In this work we investigated the implications of using a distance based on an affine invariant Riemannian metric in the context of structure–function mapping. Specifically, we revisit previously proposed structure–function mappings based on eigendecomposition and test them on 100 healthy subjects from the Human Connectome Project using this adapted notion of distance. First, we show that using this Riemannian distance significantly alters the notion of similarity between subjects from a functional point of view. We also show that using this distance improves the correlation between the structural and functional similarity of different subjects. Finally, by using a distance appropriate to this manifold, we demonstrate the importance of mapping function from structure under the Riemannian manifold and show in particular that it is possible to outperform the group average and the so–called glass ceiling on the performance of mappings based on eigenmodes.

This work has been published in [15].

CNN and diffusion MRI's 4th degree rotational invariants for Alzheimer's disease identification

Participants: Aymene Mohammed Bouayed, Samuel Deslauriers-Gauthier, Mauro Zucchelli, Rachid Deriche.

Recently, a general analytical formula to extract all the Rotation Invariant Features (RIFs) of the diffusion Magnetic Resonance Imaging (dMRI) signal was proposed. The features extracted using this formula represent a generalisation of the usual second degree RIFs such as the mean diffusivity. In this work, we study the usefulness of all the 12 algebraically independent RIFs extracted from 4th degree spherical harmonics that model the dMRI signal per voxel in the context of Alzheimer Disease (AD) identification. To do so, and since we are working with imbalanced data sets, we first introduce a non-linear metric to evaluate the performance of the models, the (B-score). This proposed metric allows high score only when both classes are distinguished correctly. We use the proposed metric in conjunction with a deep Convolutional Neural Network that operates on subject slices to identify if a subject has AD or not. We find that micro-structure information communicated by RIFs is indeed useful to AD identification and that not all RIFs are equivalently useful. We also identify the two best RIF combinations for the ADNI-SIEMENS and the ADNI-GE medical data sets respectively. The combination of these RIFs achieves a classification B-score of 73.62% and 72.31% on the previous data sets respectively. We note the importance of combining high degree RIFs with low degree ones to improve the classification performance.

This work has been published in [20].

DORIS: A diffusion MRI-based 10 tissue class deep learning segmentation algorithm tailored to improve anatomically-constrained tractography

Participants: Guillaume Theaud *(Université de Sherbrooke)*, Manon Edde *(Université de Sherbrooke)*, Mathieu Dumont *(Imeka Solutions, Sherbrooke)*, Clement Zotti *(Imeka Solutions, Sherbrooke)*, Mauro Zucchelli, Samuel Deslauriers-Gauthier, Pierre-Marc Jodoin *(Université de Sherbrooke)*, Maxime Descoteaux *(Université de Sherbrooke)*, Rachid Deriche.

Modern tractography algorithms such as anatomically-constrained tractography (ACT) are based on segmentation maps of white matter (WM), gray matter (GM), and cerebrospinal fluid (CSF). These maps are generally estimated from a T1-weighted (T1w) image and then registered in diffusion weighted images (DWI) space. Registration of T1w to diffusion space and partial volume estimation are challenging and rarely voxel-perfect. Diffusion-based segmentation would, thus, potentially allow not to have higher quality anatomical priors injected in the tractography process. On the other hand, even if FA-based tractography is possible without T1 registration, the literature shows that this technique suffers from multiple issues such as holes in the tracking mask and a high proportion of generated broken and anatomically implausible streamlines. Therefore, there is an important need for a tissue segmentation algorithm that works directly in the native diffusion space. We propose DORIS, a DWI-based deep learning segmentation algorithm. DORIS outputs 10 different tissue classes including WM, GM, CSF, ventricles, and 6 other subcortical structures (putamen, pallidum, hippocampus, caudate, amygdala, and thalamus). DORIS was trained and validated on a wide range of subjects, including 1,000 individuals from 22 to 90 years old from clinical and research DWI acquisitions, from 5 public databases. In the absence of a "true" ground truth in diffusion space, DORIS used a silver standard strategy from Freesurfer output registered onto the DWI. This strategy is extensively evaluated and discussed in the current study. Segmentation maps provided by DORIS are quantitatively compared to Freesurfer and FSL-fast and the impacts on tractography are evaluated. Overall, we show that DORIS is fast, accurate, and reproducible and that DORIS-based tractograms produce bundles with a longer mean length and fewer anatomically implausible streamlines.

This work has been published in [18].

Localization of brain microstructure changes associated with Alzheimer's disease using class activation maps

Participants: Aymene Mohammed Bouayed, Samuel Deslauriers-Gauthier, Rachid Deriche.

Recently, we have proposed a general analytical formula to extract all of the 4th order Rotation Invariant Features (RIFs) from diffusion Magnetic Resonance Imaging (dMRI) data. These invariants have been shown to be linked to the underling brain microstructure and were recently used to identify Alzheimer Disease (AD) patients. While these features indeed contain information that is useful to the identification of AD, the classification is based on the analysis of the whole brain volume and does not pinpoint local changes associated with AD. In this work, we propose to use explainable AI tools, namely Class Activation Maps (CAMs), to localize brain microstructure changes associated with AD.

This work has been published in [27].

Hyperbolic model captures temporal small worldness of brain dynamics

Participants: Aurora Rossi *(COATI, Inria)*, Pierluigi Crescenzi *(COATI, Inria)*, Samuel Deslaurier-Gauthier, Emanuele Natale *(COATI, Inria)*.

Brain activity can be represented as a complex network This work is about looking for the best model that simulates the functional connectivity of the brain and can be used as a null model. We show that the Hyperbolic model not only is close to real data but it has the same behaviour.

This work has been published in [31]

Rotation invariant features for Alzheimer's disease identification using convolutional neural networks

Participants: Aymene Mohammed Bouayed, Samuel Deslauriers-Gauthier, Rachid Deriche.

Rotation Invariant Features (RIFs) extracted from dMRI scans represent a generalisation of the usually used 2nd order invariants such as Fractional Anisotropy (FA) and Mean Diffusivity (MD). This work studies the usefulness all of the 12 algebraically independent RIFs extracted from 4th order Spherical Harmonics in the context of Alzheimer Disease (AD) identification. To do so, we introduce a fair metric (B-score) that we use to evaluate the proposed deep Convolutional Neural Network (Subject CNN) which operates on subject slices to classify the whole subject while avoiding over-fitting. On the ADNI-SIEMENS1 data set that contains 46 AD and 352 Normal Connectivity (NC) subjects respectively, we observe that the 12 algebraically independent 4th order RIFs are not equivalently useful to the classification task. A particular combination of a low degree RIF with a high degree one achieves the best performance of 82.67% B-score and 84.88% accuracy on this data set. Also, the generated 3D Class Activation Maps (CAMs) show that to classify a subject as AD or NC the model focuses on the value of the RIFs in the white matter around the ventricul

This work has been published in [28].

Graph alignment exploiting the spatial organisation improves the similarity of brain networks

Participants: Anna Calissano *(Epione inria)*, Samuel Deslauriers-Gauthier, Xavier Pennec *(Epione, Inria)*, Theo Papadopoulo.

Every brain is unique, having its structural and functional organisation shaped by both genetic and environmental factors over the course of its development. Brain image studies tend to produce results by averaging across a group of subjects, under a common assumption that it is possible to subdivide the cortex into homogeneous areas while maintaining a correspondence across subjects. This paper questions such assumption: can the structural and functional properties of a specific region of an atlas be assumed to be the same across subjects? This question is addressed by looking at the network representation of the brain, with nodes corresponding to brain regions and edges to their structural relationships. We perform graph matching on a set of control patients and on parcellations of different granularity to understand which is the connectivity misalignment between regions. The graph matching is unsupervised and reveals interesting insight on local misalignment of brain regions across subjects

This work has been published in [25].

A revisiting of structure-function mapping using graph convolutional networks

Participants: Sarah Mouffok, Samuel Deslauriers-Gauthier, Rachid Deriche.

Being able to infer the function of a brain given the knowledge of its structure is valuable in order to understand the impact of structural alterations caused by injuries and/or diseases on the function of the brain. Indeed, devising a mapping from brain structural connectivity (SC) to brain functional connectivity (FC) is motivated by the thought that structure is the physical support on which function operates. Consequently, using supervised learning, we attempt to predict a subject's FC matrix from their SC matrix. This work has been performed within the framework of Mouffok's internship's and extends our previous work in which an auto-encoder architecture is used to perform the aforementioned task. We have extended our previous work and altered the GCN architecture in multiple ways. First, using separate weight sets for the second-order Chebyshev polynomial leads to small improvements in performances as quantified by the MSE, and a non-negligible increase in Pearson correlation. Second, this separation of weight sets enabled the usage of higher Chebyshev polynomial orders. Increasing the order of the Chebyshev polynomial does not increase performances. However, through the observation of the first order Chebyshev Polynomial that makes no use of SC information and still yields good results, we found out that the estimations of the network were in fact very close to the FC matrix estimated by the reference estimator, both in MSE and Pearson Correlation, leading to the conclusion that the network is converging towards the mean. Moreover, using the Affine Invariant Riemannian Metric on Symmetric Positive Definite matrices does not lead to an estimation of the Frechet Mean, but it does output estimations that are correlated to the real functional connectivity almost as much as the mean's correlation to real functional connectivity. The current architecture does not seem to be appropriate for this loss, as the loss seems to reach a local minimal value early on in the learning.

This work has been published in [26].

7.2 Unveiling brain activity using M/EEG and its applications to Brain Computer Interfaces

Embedding neurophysiological signals

Participants: Pierre Guetschel *(University of Freiburg)*, Théodore Papadopoulo, Michael Tangermann *(University of Freiburg)*.

Neurophysiological time-series recordings of brain activity like the electroencephalogram (EEG) or local field potentials can be decoded by machine learning models in order to either control an application, e.g., for communication or rehabilitation after stroke, or to passively monitor the ongoing brain state of the subject, e.g., in a demanding work environment. A typical decoding challenge faced by a brain-computer interface (BCI) is the small dataset size compared to other domains of machine learning like computer vision or natural language processing. The possibilities to tackle classification or regression problems in BCI are to either train a regular model on the available small training data sets or through transfer learning, which utilizes data from other sessions, subjects, or even datasets to train a model. Transfer learning is non-trivial because of the non-stationary of EEG signals between subjects but also within subjects. This variability calls for explicit calibration phases at the start of every session, before BCI applications can be used online. In this study, we present arguments to BCI researchers to encourage the use of embeddings for EEG decoding. In particular, we introduce a simple domain adaptation technique involving both deep learning (when learning the embeddings from the source data) and classical machine learning (for fast calibration on the target data). This technique allows us to learn embeddings across subjects, which deliver a generalized data representation. These can then be fed into subject-specific classifiers in order to minimize their need for calibration data. We conducted offline experiments on the 14 subjects of the High Gamma EEG-BCI Dataset [1]. Embedding functions were obtained by training EEGNet [2] using a leave-one-subject-out (LOSO) protocol, and the embedding vectors were classified by the logistic regression algorithm. Our pipeline was compared to two baseline approaches: EEGNet without subject-specific calibration and the standard FBCSP pipeline in a within-subject training. We observed that the representations learned by the embedding functions were indeed non-stationary across subjects, justifying the need for an additional subject-specific calibration. We also observed that the subject-specific calibration indeed improved the score. Finally, our data suggest, that building upon embeddings requires fewer individual calibration data than the FBCSP baseline to reach satisfactory scores.

This work has been published in [19].

Current distribution of distributed all-polar cochlear implant stimulation mode measured in-situ

Participants: Pierre Stahl *(Oticon Medical)*, Kai Dang, Clair Vandersteen *(Nice University Hospital)*, Nicolas Guevara *(Nice University Hospital)*, Maureen Clerc.

Oticon Medical cochlear implants use a stimulation mode called Distributed All-Polar (DAP) that connects all non-stimulating available intracochlear electrodes and an extracochlear reference electrode. It results in a complex distribution of current that is yet undescribed. The present study aims at providing a first characterization of this current distribution. A Neuro Zti was modified to allow the measurement of current returning to each electrode during a DAP stimulation and was implanted in an ex-vivo human head. Maps of distributed current were then created for different stimulation conditions with different charge levels. Results show that, on average, about 20% of current returns to the extracochlear reference electrode, while the remaining 80% is distributed between intracochlear electrodes. The position of the stimulating electrode changed this ratio, and about 10% more current to the extracochlear return in case of the first 3 basal electrodes than for apical and mid position electrodes was observed. Increasing the charge level led to small but significant change in the ratio, and about 4% more current to the extracochlear return was measured when increasing the charge level from 11.7 to 70 nC. Further research is needed to show if DAP yields better speech understanding than other stimulation modes.

This work has been published in [17].

Auditory attention analysis during music listening: Making the link between machine learning, electrophysiology and cognition

Participants: Joan Belo, Maureen Clerc, Daniele Schon *(CNRS, INS, Aix-Marseille Université)*.

This part describes the work performed within the framework of Joan Belo's PhD defended on Dec. 5th, 2022.

The ability to focus attention on a particular sound in a noisy environment is crucial for day-to-day life. But this ability is undermined in people with cochlear implants. One solution to this problem would be to create a new type of device that could selectively amplify the source of interest. This could be achieved by using a recent method called Auditory Attention Detection, which allows to detect which source within a set of multiple concurrent sources an individual is attending to, based solely on brain activity. However, the performance of this technique varies greatly from one individual to another, partly because of physiological factors but possibly also because of cognitive and behavioral ones. The aim of this PhD work is therefore to investigate how specific cognitive and behavioral factors may influence the performance of auditory attention detection and more specifically in a natural music listening context.

This work has been published in [21].

Usability of phase synchrony neuromarkers in neurofeedback protocols for epileptic seizures reduction

Participants: Côme Le Breton, Théodore Papadopoulo, Maureen Clerc.

This part describes the work performed within the framework of Côme Lebreton's PhD defended on Oct. 18th, 2022. A video of the PhD defense is available via the following YouTube link

The brain is an organ that oversees many vital functions. Despite its fascinating complexity associated to its incredible consistency, failures can occur and have severe consequences such as in epilepsy disorders. Major functions in the brain are enabled through the oscillatory activity of neuronal assemblies. These oscillations occur at different rhythms, over different regions, depending on the mental task. They can be described by two quantities: their amplitude and their phase. In particular, the phase characterizes over time the oscillatory pattern of a neuronal assembly. Phase synchrony measures the similarity between two oscillations by capturing the stability of a phase relationship between neuronal assembly activities and informs on a functional relationship between these assemblies. While synchronization between the oscillatory activities of brain regions is presented as a necessary coordinator between brain areas, its excess, such as in epilepsy, causes dramatic outcomes, indicating that a balance is necessary. For these reasons and others detailed in this manuscript, this work focuses on the real-time modulation of phase synchrony between distinct brain areas by means of electroencephalography (EEG) to offer new treatment opportunities for certain epileptic disorders.

In a first contribution, focusing on the retrieval of the phase from EEG signals, the Morlet wavelet transforms of sinusoids, weighted sums of sinusoids, oscillating bursts and overlapping oscillating bursts are formally derived. Simplifications are proposed to allow for compact expressions of the phase.Their properties and parameters are discussed.These derivations notably show that for close frequency components with similar energy the phase is not trustworthy.They also show that for too close bursts, the phase cannot be reliably recovered. Nonetheless, in reasonable and practical conditions, the recovery based on the Morlet Wavelet transform of the properties of alpha bursts (amplitude and phase) is attempted and provides satisfactory preliminary results on selected real data. The second contribution is an attempt to reproduce a study showing the potential of phase synchrony in differentiating between epileptic and healthy brains with statistical improvements to handle highly correlated data, inherent to EEG and phase synchrony measures. Original strategies to correct for the biases are proposed and detailed. Contrarily to what was published, the mean phase coherence is shown to be generally higher in temporal lobe epilepsy patients than in controls. While adapting the statistical analysis moderated the results, it did not overturn the conclusions. In a third contribution, an EEG dataset of resting states and simple tasks was acquired on healthy subjects to search for trainable phase synchrony neuromarkers. The study of bare phase

differences along the anteroposterior axis showed that there exists predominant phase differences in the alpha frequency band, notably during eyes closed resting state. These phase differences, which are different from one subject to the other, are stable across recordings over long periods. A simple model of two sources is proposed to account for this finding and lead to reconsider some properties of phase synchrony measures. Ultimately, while the real-time modulation of a phase synchrony marker was not achieved, especially because the identi

cation of such a marker was demonstrated non-trivial, the various contributions lay more foundations to the search for phase-based neural markers. Primarily through the development of theoretical but also software contributions. These software contributions are part of an ongoing research protocol with hospital La Timone in Marseille.

This work has been published in [23].

7.3 Combined fMRI, M/EEG and dMRI and its applications

An anisotropic 4D filtering approach to recover brain activation from paradigm-free functional MRI data

Participants: Isa Costantini, , Samuel Deslauriers-Gauthier, , Rachid Deriche.

Context: Functional Magnetic Resonance Imaging (fMRI) is a non-invasive imaging technique that provides an indirect view into brain activity via the blood oxygen level dependent (BOLD) response. In particular, resting-state fMRI poses challenges to the recovery of brain activity without prior knowledge on the experimental paradigm, as it is the case for task fMRI. Conventional methods to infer brain activity from the fMRI signals, for example, the general linear model (GLM), require the knowledge of the experimental paradigm to define regressors and estimate the contribution of each voxel's time course to the task. To overcome this limitation, approaches to deconvolve the BOLD response and recover the underlying neural activations without a priori information on the task have been proposed. State-of-the-art techniques, and in particular the total activation (TA), formulate the deconvolution as an optimization problem with decoupled spatial and temporal regularization and an optimization strategy that alternates between the constraints.

Approach: In this work, we propose a paradigm-free regularization algorithm named Anisotropic 4D-fMRI (A4D-fMRI) that is applied on the 4D fMRI image, acting simultaneously in the 3D space and 1D time dimensions. Based on the idea that large image variations should be preserved as they occur during brain activations, whereas small variations considered as noise should be removed, the A4D-fMRI applies an anisotropic regularization, thus recovering the location and the duration of brain activations.

Results: Using the experimental paradigm as ground truth, the A4D-fMRI is validated on synthetic and real task-fMRI data from 51 subjects, and its performance is compared to the TA. Results show higher correlations of the recovered time courses with the ground truth compared to the TA and lower computational times. In addition, we show that the A4D-fMRI recovers activity that agrees with the GLM, without requiring or using any knowledge of the experimental paradigm.

This work has been published in [14].

Reconstruction of cortical activity from MEG data using brain networks and transmission delays estimated from dMRI

Participants: Ivana Kojčić, Théodore Papadopoulo, Rachid Deriche, Samuel Deslauriers-Gauthier.

This part describes the work performed within the framework of Ivana Kojčić's PhD defended on Nov. 18th, 2022.

White matter fibers transfer information between brain regions with delays that are observable with magnetoencephalography and electroencephalography (M/EEG) due to their millisecond temporal resolution. We can represent the brain as a graph where nodes are the cortical sources or areas and edges are the physical connections between them: either local (between adjacent vertices on the cortical mesh) or nonlocal (long-range white matter fibers). Long-range anatomical connections can be obtained with diffusion MRI (dMRI) tractography which yields a set of streamlines representing white matter fiber bundles. Given the streamlines' lengths and the information conduction speed, transmission delays can be estimated for each connection. dMRI can thus give an insight into interaction delays of the macroscopic brain network. Localizing and recovering electrical activity of the brain from M/EEG measurements is known as the M/EEG inverse problem. Generally, there are more unknowns (brain sources) than the number of sensors, so the solution is non-unique and the problem ill-posed. To obtain a unique solution, prior constraints on the characteristics of source distributions are needed. Traditional linear inverse methods deploy different constraints which can favour solutions with minimum norm, impose smoothness constraints in space and/or time along the cortical surface, etc. Yet, structural connectivity is rarely considered and transmission delays almost always neglected.

The first contribution of this thesis consists of a multimodal preprocessing pipeline used to integrate structural MRI, dMRI and MEG data into a same framework, and of a simulation procedure of source-level brain activity that was used as a synthetic dataset to validate the proposed reconstruction approaches. In the second contribution, we proposed a new framework to solve the M/EEG inverse problem called Connectivity-Informed M/EEG Inverse Problem (CIMIP), where prior transmission delays supported by dMRI were included to enforce temporal smoothness between time courses of connected sources. This was done by incorporating a Laplacian operator into the regularization, that operates on a timedependent connectivity graph. Nonetheless, some limitations of the CIMIP approach arised, mainly due to the nature of the Laplacian, which acts on the whole graph, favours smooth solutions across all connections, for all delays, and it is agnostic to directionality.

In this thesis, we aimed to investigate patterns of brain activity during visuomotor tasks, during which only a few regions typically get significantly activated, as shown by previous studies. This led us to our third contribution, an extension of the CIMIP approach that addresses the aforementioned limitations, named CIMIP_OML (Optimal Masked Laplacian). We restricted the full source space network (the whole cortical mesh) to a network of regions of interest and tried to find how the information is transferred between its nodes. To describe the interactions between nodes in a directed graph, we used the concept of network motifs. We proposed an algorithm that (1) searches for an optimal network motif – an optimal pattern of interaction between different regions and (2) reconstructs source activity given the found motif.

Promising results are shown for both simulated and real MEG data for a visuomotor task and compared with 3 different state-of-the-art reconstruction methods. To conclude, we tackled a difficult problem of exploiting delays supported by dMRI for the reconstruction of brain activity, while also considering the directionality in the information transfer, and provided new insights into the complex patterns of brain activity.

This work has been published in [22].

Domain specific convolutional neural networks for dMRI and M/EEG signal analysis

Participants: Sara Sedlar, Théodore Papadopoulo, Samuel Deslauriers-Gauthier, Rachid Deriche.

This part describes the work performed within the framework of Sara Sedlar's PhD defended on Dec. 22nd, 2022.

The analysis of neuroimaging data is essential for the interpretation of the functional or structural characteristics of the human brain. New machine learning algorithms usually require a high amount of data often infeasible to acquire in clinical and practical conditions. This requirement is a consequence of significant data variability arising from numerous factors (various recording procedures, subjects and sessions, presence of high levels of noise). To address this problem, in this thesis, we have investigated

and proposed convolutional machine learning models adapted to the properties and well grounded assumptions about the acquired data. Therefore, the models are endowed with valuable knowledge and consequently more efficiently learn to perform certain inferences. In particular, we have studied models for the analysis of non-invasive and in-vivo structural and functional neuroimaging data, namely diffusion Magnetic Resonance Imaging (dMRI) and magneto- and electroencephalography (M/EEG) signals.

Diffusion MRI is a nuclear imaging modality which captures micro-structural properties of the examined tissue. As q-space sampling has been the most widely used high angular resolution diffusion imaging protocol (HARDI) over the last decade, we have studied spherical rotation equivariant convolutional neural networks (CNNs) for dMRI local modeling. As a first contribution, we have proposed a spherical U-net for the estimation of fiber orientation distribution functions (fODFs) with convolutions and non-linearities realized in the spectral and signal domains, respectively. To avoid aliasing, our second contribution proposes a Fourier domain CNN for micro-structure parameter estimation, where non-linearities are defined in the spectral domain.

M/EEG are functional imaging techniques which measure magnetic field strength and electric field potential caused by neural electric activities in the cerebral cortex. Measured signals can be explained by Maxwell's equations with quasi-static approximations. Consequently, we can assume that cortical brain activities spread instantaneously and linearly over the measuring sensors, thus a multivariate M/EEG signal can be represented as a sum of rank-1 multivariate signals corresponding to individual sources in the cortex and noise. Considering this assumption, the second part of the thesis firstly investigates an M/EEG spatial and temporal dictionary learning approach with an L0 constraint. A second contribution is a CNN classifier with rank-1 spatio-temporal kernels regularized in the spectral domain, where the spatial components of the kernels are represented in terms of spherical harmonics basis, while the temporal components are represented in terms of discrete cosine basis

Forward modelling of M/EEG: Towards a new automatic head and brain tissue segmentation system

Participants: Ludovic Corcos, Samuel Deslauriers-Gauthier, Theo Papadopoulo.

Magnetoencephalography and electroencephalography (together M/EEG) are imaging modalities that allow the non-invasive measurement of the magnetic field and the electric potential generated by cortical activity. Inferring which brain areas generated the observed M/EEG measurements is not a trivial task and is referred to as the inverse problem. A common way to solve the problem is to assume than brain sources act like current dipoles in a volume conductor, in this case the head whose geometry can be obtained from magnetic resonance imaging (MRI). The relationship between brain sources and M/EEG measurements can therefore be modeled, a process called the solving forward problem. This process can be seen as injecting anatomical priors into the inverse problem. However, extracting the anatomical information from MRI needed to solve the forward problem is lengthy and tedious with existing tools. In this work, we present the first step in the creation of an automated pipeline to generate a volume conductor model from T1 and T2 images.

This work has been published in [30].

Autoregressive models for M/EEG signal analysis

Participants: Agathe Senellart, Igor Carrara, Côme Le Breton, Théodore Papadopoulo.

Electroencephalotherapy (EEG) is a widely used and inexpensive modality that serves as a support not only for experiments aimed at understanding the functioning of the brain when it performs certain tasks, but also for the characterization of certain pathologies (such as epilepsy) or the development

of brain-computer interfaces. But EEG signals are complex and difficult to characterize, in particular because of their variability, whether in the same subject through the repetition of the same experiment or a fortiori when one wants to carry out multi-subject analyses. They therefore require the use of specific and adapted signal processing methods. In a recent approach [41], sources were modeled as an auto-regressive model which explains a portion of a signal. This approach works at the level of the source space (i.e. the cortex), which requires modeling of the head and makes it quite expensive. However, EEG measurements can be considered as a linear mixture of sources and therefore it is possible to estimate an auto-regressive model directly at the measurement level. The objectives of this work is to explore the possibility of exploiting EEG/MEG auto-regressive models to extract as much information as possible without requiring the complex head modelling required for source reconstruction.

This work has been presented in [29]. Two journal papers are in preparation.

A shallow convolutional neural network with rank-1 Fourier domain weights for brain signal classification

Participants: Sara Sedlar, Samuel Deslauriers-Gauthier, Rachid Deriche, Théodore Papadopoulo.

Electro- and magneto-encephalography (MEG) signals are measured by sensors placed on the scalp (EEG) or slightly above it (MEG). Such measurements can be represented as linear combinations of source signals occurring in different cortical regions and are characterized by a high temporal, but low spatial resolution. Depending on the performed task, the signals exhibit different temporal and spatial patterns. These signals are affected by a significant amount of noise coming from measuring devices or from the subject itself and suffer from high intra- and inter-subject variability which make their analysis quite challenging. Deep learning approaches have been successfully used in different domains of medical signal analysis. However, they often require large amounts of data, otherwise they either suffer from over-fitting or exhibit poor generalization power. In this work, we propose a rank-1 convolutional neural network (CNN) with Fourier domain kernels for MEEG signal classification. Since the spread of the source signals across sensors is instantaneous and linear, we have used rank-1 trainable kernels in our model, where both spatial and temporal components are represented in Fourier domain, which acts as a regularization space. Assuming that the head can be modeled by a sphere, spatial kernels are represented in the basis of spherical harmonics. This representation is less sensitive to the spatial distribution of sensors which varies between subjects and sessions. In order to constrain temporal kernels to focus on feature extraction from certain frequency range, they are represented as linear combinations of discrete cosine coefficients. The model is compared with the state-of-the-art CNN models on the passive brain computer interface problem of mental workload classification from EEG signals and motor-task MEG signal classification. We have shown that our model can achieve state-of-the art performance with significantly lower number of parameters and achieve improvement when the number of available training subjects is smaller. Given this and its speed both during train and test phase, it is well suited for portable devices in brain computer interfaces.

This work has been published in [32].

Identifying subcortical connectivity during brain tumor surgery: A multimodal study

Participants: Fabien Almairac, Petru Isan, Marie Onno, Théodore Papadopoulo, Lydiane Mondot, Stéphane Chanalet, Charlotte Fernandez, Maureen Clerc, Rachid Deriche, Denys Fontaine, Patryk Filipiak.

Bipolar direct electrical stimulation (DES) of an awake patient is the reference technique for identifying brain structures to achieve maximal safe tumor resection. Unfortunately, DES cannot be performed in all cases. Alternative surgical tools are therefore needed to aid identification of subcortical connectivity

during brain tumor removal. Moreover, although functional responses to DES are well documented, its electrophysiological effect on brain networks is poorly known. In this study, we sought to (i) evaluate the combined use of electrocorticography (ECoG) and tractography for identification of white matter (WM) tracts under the functional control of DES, and (ii) provide clues to the electrophysiological effects of bipolar stimulation on neural pathways. We included 12 brain tumor patients with a mean age of 38 years [20-59] (five women, six lesions on the left side) who had had a functional brain mapping under awake craniotomy. After tumor resection, 14 ECoG electrodes (one strip of six, and two strips of four electrodes) were positioned along the cortical terminations of the associative tracts of interest previously reconstructed with probabilistic tractography. Electrophysiological recordings of subcortical evoked potentials (SCEPs) were acquired during bipolar stimulation of functional sites of the WM identified during the awake phase of a surgery. Correlations between the obtained structural and electrophysiological data were measured subject to verification with the functional neurocognitive responses induced by DES. SCEPs were observed in 11 out of 12 patients in response to the stimulation of functional sites of the white matter. In one patient, subcortical stimulation elicited neither functional nor electrophysiological response. On average, 4.26 cortical electrodes [1-9] recorded SCEPs, usually located close to the subcortical stimulation site (mean Euclidean distance = 32.22 ±9.65 mm). The median length of the stimulated fibers from the subcortical site to the "activated" electrodes was 43.24 ±19.55 mm, belonging to tracts of median lengths of 89.84 ±24.65 mm. The electrophysiological (delay, amplitude, and speed of propagation) and structural (number and lengths of streamlines, and mean fractional anisotropy) measures were significantly correlated. SCEPs were elicited with bipolar stimulation on various associative WM tracts. In our experimental settings, their propagation was essentially limited to a subpart of the bundles, suggesting a selectivity of action of the DES on the brain networks. Correlations between functional, structural, and electrophysiological biomarkers portend the combined use of evoked potentials and tractography as a potential intraoperative tool to achieve maximum safe resection in brain tumor surgery.

This work has been submitted to the journal Brain and is currently under evaluation.

8 Bilateral contracts and grants with industry

8.1 Bilateral Grants with Industry

Participants: Théodore Papadopoulo.

A BPI grant proposal has been obtained in 2022 with the startup Mag4Health (other partners are CNRS and INSERM). This company develops a new MEG machine working with optically pumped magnetometers (magnetic sensors), which potentially means lower costs and better measurements. ATHENA is in charge of developing a real time interface for signal visualization, source reconstruction and epileptic spikes detection. The initial funding is for 2 years, but an extension is already expected.

9 Partnerships and cooperations

9.1 International initiatives

9.1.1 Associate Teams in the framework of an Inria International Lab or in the framework of an Inria International Program

An associate team proposal was submitted by S. Deslauriers-Gauthier within the framework of Inria London Programme in collaboration with Dario Farina of Imperial College London. The nature and objective of this proposal is to increase the bandwidth between the EEG and EMG communities and promote a mutually beneficial exchange of methodology and knowledge. The Athena team has a longstanding history in forward modelling and inverse problem in electroencephalography and magnetoencephalography. The Imperial College London team has extensive expertise in the processing and analysis of EMG signals for neurorehabilitation and the control of movements. By collaborating via the associated team, the two research labs will rapidly move forward both the EMG and the EEG communities.

9.2 National initiatives

3IA UCA Chair : AI-Based Computational Brain Connectomics

Participants: Rachid Deriche (P.I), Samuel Deslauriers-Gauthier, Théodore Papadopoulo, Sara Sedlar, Mauro Zucchelli.

Start date: October, 2019 **Duration:** *48 months.*

This project aims to reconstruct and analyse the network of neural connections of the brain, called the connectome via a computational brain connectomics framework based on ground-breaking AI algorithms and machine learning tools to gain insight into brain architecture, functioning and neurodegenerative diseases.

The avalanche of big data required to reconstruct the connectome and the study of the high complexity of structural and functional interactions within the connectome clearly position brain connectomics as a big data problem where AI & machine learning in particular, represent a very promising trend, as recently demonstrated in computer vision and in some biomedical image data-driven analysis. Partly related to the ERC AdG CoBCoM, the computational brain connectomics framework we develop in this project will construct networks specifically built on new generation of AI algorithms and machine learning tools to reconstruct a structural and functional connectome using advanced and integrated dMRI, EEG & MEG methods. This project completes CoBCoM by specifically investigating the AI added value in brain mapping, opens also exciting prospects and paves the way to translate the large amounts of high dimensional heterogeneous and complex brain data into knowledge for better contribute to neurodegenerative diseases detection and diagnosis.

EPIFEED

Participants: Angela Marchi, Côme Le Breton, Fabrice Bartolomei, Théodore Papadopoulo, Christian Bénar, Jean-Michel Badier, Julien Wintz.

Start date: February 2023 **Duration:** *24 months.*

Electroencephalography (EEG) Neurofeedback (NFB) is a potential treatment for drug resistant epileptic patients (DREP). NFB training helps to self-regulate specific activities of the brain. This technique is interesting for different neuropathologies, and it is known to reduce the frequency of epileptic seizures by modulating the amplitude of slow cortical rhythms in DREP. An increase in cerebral synchrony during the interictal and ictal period in DREP is well known, so we propose here an innovative NFB method based on the real-time acquisition of synchrony, with as objective measures of treatment success the frequency (and severity) and psychiatric comorbidities. This works aims at leveraging the work done in the Ph.D. thesis of C. Le Breton for a study of the utility of NFB for epileptic patients.

ConnectTC

Participants: Fabien Almairac, Petru Isan, Théodore Papadopoulo.

Start date: July 2019 **Duration:** *60 months*

This grant was obtained from Nice Pasteur hospital to do a multimodal study of the connectome of patients suffering from a brain glioma during awake brain surgery. It aims at better understanding the effects of bipolar direct electrical stimulation (DES) that is used during surgery to delineate the resection region. This study combines ECoG measurements (measured during DES) and white matter fiber tracts obtained with diffusion MRI to better understand how DES operates in the patient brain (which areas are stimulated and how the local stimulation is propagated to other brain areas). The goal is to acquire data on at least 30 participants. It has been extended to at least summer 2024 due to difficulties which arose in obtaining this number of subjects (Covid, ...).

Auditory attention analysis during music listening

Participants: Maureen Clerc, Joan Belo, Oticon Medical.

The Ph.D, of Joan Belo is funded by this joint grant from Oticon Medical and Region Provence Alpes Côtes d'Azur. The goal of the project is to better understand the link between the decoding of auditory attention during naturalistic music listening using recent EEG methods known as Auditory Attention Detection and several cognitive functions and behavioral indicators that are important for listening in complex auditory situation, such as working memory or mind wandering. This is done with the aim of improving the efficiency of next generation cochlear implants by taking into account the individual cognitive aspects.

10 Dissemination

10.1 Promoting scientific activities

Participants: Rachid Deriche, Théodore Papadopoulo, Samuel Deslauriers-Gauthier.

10.1.1 Scientific events: selection

Reviewer

- R. Deriche served several international conferences (ISBI, MICCAI, ISMRM, ...) and international workshops (CD-MRI MICCAI, MFCA).
- S. Deslauriers-Gauthier served several international conferences (ISBI, MICCAI) and international workshops (CD-MRI MICCAI).
- T. Papadopoulo served several international conferences (ISBI, ICIP).

Member of the conference program committees

- T. Papadopoulo was in the scientific committee of GRETSI 2022.

10.1.2 Journal

Member of the editorial boards

- R. Deriche is member of the Editorial Board of the Journal of Neural Engineering, editorial board member at Springer for the book series entitled Computational Imaging and Vision and member of the Editorial Board of the Medical Image Analysis Journal
- S. Deslauriers-Gauthier served as Guest Editor for the special issue on Advances in Brain Functional and Structural Networks Modeling via Graph Theory of the journal Frontiers in Neuroscience.
- T. Papadopoulo serves as Associate Editor in Frontiers: Brain Imaging Methods and as Review Editor for Frontiers: Artificial Intelligence in Radiology.

Reviewer - reviewing activities

- R. Deriche serves several international journals (NeuroImage, IEEE Transactions on Medical Imaging, Magnetic Resonance in Medicine, Medical Image Analysis Journal,Journal of Neural Engineering ...).
- S. Deslauriers-Gauthier serves several international journals (NeuroImage, IEEE Transactions on Biomedical Engineering, Journal of Neural Engineering, Medical Image Analysis, Science Advances).
- T. Papadopoulo served several international journals (Computers and Mathematics with Applications, Frontiers in Neurosciences, Frontiers in Neural Circuits, IEEE Transactions on Biomedical Engineering, NeuroImage, NeuroImage Reports, Physics & Medicine in Biology, Scientific Reports).

10.1.3 Invited talks

- R. Deriche gave a keynote speech at Abu-Dhabi AI Connect - 12-13 Dec. 2022 Abu-Dhabi (EAU).

10.1.4 Scientific expertise

- R. Deriche served several national and international institutions in reviewing applications : 3IA UCA Chairs, ERC AdG and StG Grants, Swiss National Science Foundation, EPFL, the Netherlands Organisation for Scientific Research (NWO).
- S. Deslauriers-Gauthier reviewed funding applications for the Fonds de recherche Nature et technologie du Québec.
- S. Deslauriers-Gauthier reviewed funding applications for the ANR Jeunes Chercheuses et Jeunes Chercheurs.
- T. Papadopoulo served in reviewing applications for the Neuromod institute of Université Côte d'Azur.
- T. Papadopoulo served in reviewing for several internal programs of Université Côte d'Azur (see membership in academic council below).
- T. Papadopoulo was member of the INSERM committee responsible for the selection of INSERM program of collaborative research in health (MESSIDORE).
- T. Papadopoulo served as a reviewer for the European call FET-OPEN.

10.1.5 Research administration

- T. Papadopoulo is elected member in the academic council of Côte d'Azur University.
- T. Papadopoulo is the head of the Technological Development Committee of Inria Sophia Antipolis Méditerranée.
- T. Papadopoulo is a member of the Neuromod scientific council and represents Neuromod in the EUR Healthy (EUR: Universitary Research School).

10.2 Teaching - Supervision - Juries

10.2.1 Teaching

- Master: T. Papadopoulo, *Inverse problems for brain functional imaging*, 24 ETD, M2, Mathématiques, Vision et Apprentissage, ENS Cachan, France.
- Master: T. Papadopoulo, *Functional Brain Imaging*, 10 ETD, M1,M2 in the MSc Mod4NeuCog of Université Côte d'Azur.
- Master: S. Deslauriers-Gauthier, *Functional Brain Imaging*, 10 ETD, M1,M2 in the MSc Mod4NeuCog of Université Côte d'Azur.

10.2.2 Supervision

- PhD defended on Dec. 22nd, 2022: Sara Sedlar, "Domain specific convolutional neural networks for dMRI and M/EEG signal analysis", Université Côte d'Azur, started October 2018. Supervisors: Théodore Papadopoulo and Samuel Deslauriers-Gauthier
- PhD defended on Nov. 18th, 2022: Ivana Kojcic, "Reconstruction of cortical activity from MEG data using brain networks and transmission delays estimated from dMRI", Université Côte d'Azur, started October 2018. Supervisors: Théodore Papadopoulo and Samuel Deslauriers-Gauthier.
- PhD defended on Oct. 18th, 2022: Côme Le Breton, "Non invasive analysis of epileptogenetic networks and their response to neurofeedback", started June 2019. Supervisors: Maureen Clerc and Théodore Papadopoulo.
- PhD defended on Dec. 5th, 2022: Joan Belo, "Auditory attention analysis during music listening - Making the link between machine learning, electrophysiology and cognition", started June 2019. Supervisors: Maureen Clerc and Daniele Schön.
- PhD in progress: I. Carrara, "Auto-regressive models for MEG/EEG processing", started in Oct. 2021. Supervisor: Théodore Papadopoulo.
- PhD in progress: Y. Aeschlimann, started in Oct. 2022. Supervisors: Samuel Deslauriers-Gauthier, Théodore Papadopoulo.

10.2.3 Juries

- T. Papadopoulo participated in the jury of C. Le Breton at Université Côte d'Azur on Oct. 18th, 2022.
- R. Deriche, S. Deslaurier-Gauthier and T. Papadopoulo participated in the PhD Jury of I. Kojcic at Université Côte d'Azur on Nov. 18th, 2022.
- R. Deriche, S. Deslaurier-Gauthier and T. Papadopoulo participated in the PhD Jury of S. Sedlar at Université Côte d'Azur on Dec. 22nd, 2022.

10.3 Popularization

- T. Papadopoulo and C. Le Breton presented the P300 Speller at the inauguration of TerraNumerica in June 2022.

11 Scientific production

11.1 Major publications

[1] B. Belaoucha and T. Papadopoulo. 'Structural connectivity to reconstruct brain activation and effective connectivity between brain regions'. In: *Journal of Neural Engineering* 17.3 (1st June 2020), p. 035006. DOI: 10.1088/1741-2552/ab8b2b. URL: https://hal.inria.fr/hal-02945585.

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[3] E. Caruyer, C. Lenglet, G. Sapiro and R. Deriche. 'Design of multishell sampling schemes with uniform coverage in diffusion MRI'. In: *Magnetic Resonance in Medicine* 69.6 (June 2013), pp. 1534–1540. DOI: 10.1002/mrm.24736. URL: http://hal.inria.fr/hal-00821688/.

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[6] S. Deslauriers-Gauthier, J.-M. Lina, R. Butler, K. Whittingstall, P.-M. Bernier, R. Deriche and M. Descoteaux. 'White Matter Information Flow Mapping from Diffusion MRI and EEG'. In: *NeuroImage* (July 2019). DOI: 10.1016/j.neuroimage.2019.116017. URL: https://hal.inria.fr/hal-02187859.

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[9] M. Frigo, E. Cruciani, D. Coudert, R. Deriche, S. Deslauriers-Gauthier and E. Natale. 'Network alignment and similarity reveal atlas-based topological differences in structural connectomes'. In: *Network Neuroscience* (20th May 2021). DOI: 10.1162/netn_a_00199. URL: https://hal.archives-ouvertes.fr/hal-03033777.

[10] G. Girard, A. Daducci, L. Petit, J.-P. Thiran, K. Whittingstall, R. Deriche, D. Wassermann and M. Descoteaux. 'AxTract: Toward microstructure informed tractography'. In: *Human Brain Mapping* 38.11 (Nov. 2017), pp. 5485–5500. DOI: 10.1002/hbm.23741. URL: http://onlinelibrary.wiley.com/doi/10.1002/hbm.23741/abstract.

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11.2 Publications of the year

International journals

[14] I. Costantini, R. Deriche and S. Deslauriers-Gauthier. 'An Anisotropic 4D Filtering Approach to Recover Brain Activation From Paradigm-Free Functional MRI Data'. In: *Frontiers in Neuroimaging* 1 (2022), p. 815423. DOI: 10.3389/fnimg.2022.815423. URL: https://hal.archives-ouvertes.fr/hal-03629113.

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International peer-reviewed conferences

[19] P. Guetschel, T. Papadopoulo and M. Tangermann. 'Embedding neurophysiological signals'. In: Proceedings of the IEEE MetroXRAINE conference. Roma, Italy, 26th Oct. 2022. URL: https://hal.inria.fr/hal-03878615.

Conferences without proceedings

[20] A. M. Bouayed, S. Deslauriers-Gauthier, M. Zucchelli and R. Deriche. 'CNN and diffusion MRI's 4th degree rotational invariants for Alzheimer's disease identification'. In: International Workshop on Learning with Imbalanced Domains: Theory and Applications. Grenoble, France, 23rd Sept. 2022. URL: https://hal.science/hal-03740103.

Doctoral dissertations and habilitation theses

[21] J. Belo. 'Auditory attention analysis during music listening - Making the link between machine learning, electrophysiology and cognition'. Université Côte D'Azur, 5th Dec. 2022. URL: https://hal.science/tel-03941659.

[22] I. Kojčić. 'Reconstruction of cortical activity from MEG data using brain networks and transmission delays estimated from dMRI'. Université Côte d'Azur, 18th Nov. 2022. URL: https://hal.inria.fr/tel-03944354.

[23] C. Le Breton. 'Usability of phase synchrony neuromarkers in neurofeedback protocols for epileptic seizures reduction'. Université Côte d'Azur, 18th Oct. 2022. URL: https://theses.hal.science/tel-03946762.

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Reports & preprints

[25] A. Calissano, T. Papadopoulo, X. Pennec and S. Deslauriers-Gauthier. *Graph Alignment Exploiting the Spatial Organisation Improves the Similarity of Brain Networks*. 22nd Dec. 2022. URL: https://hal.inria.fr/hal-03910761.

[26] S. Mouffok. *A revisiting of structure-function mapping using Graph Convolutional Networks*. 1st Sept. 2022. URL: https://hal.archives-ouvertes.fr/hal-03766992.

Other scientific publications

[27] A. M. Bouayed, S. Deslauriers-Gauthier and R. Deriche. 'Localization of Brain Microstructure Changes Associated with Alzheimer's Disease using Class Activation Maps'. In: Soph.I.A Summit 2022 : fifth edition of the international AI conference. Sophia Antipolis, France, 23rd Nov. 2022. URL: https://hal.inria.fr/hal-03879975.

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[32] S. Sedlar, S. Deslauriers-Gauthier, R. Deriche and T. Papadopoulo. 'Shallow convolutional neural network with rank-1 Fourier domain weights for brain signal classification'. In: Proceedings of SophIA 2022. Sophia Antipolis, France, 23rd Nov. 2022. URL: https://hal.inria.fr/hal-03878709.

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