

2025 Activity Report

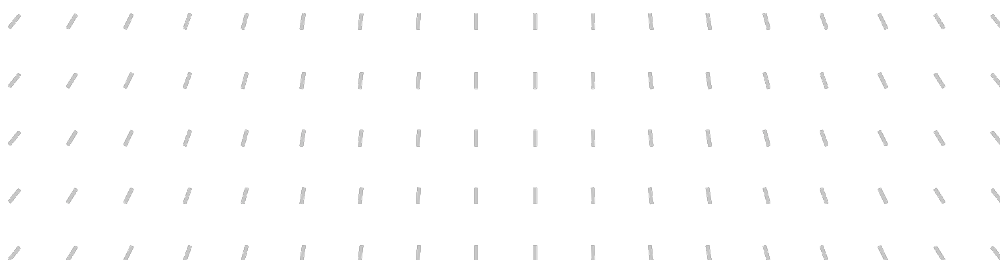
RESEARCH CENTRE: Inria Centre at Université Côte d'Azur


Project-Team

CRONOS

Computational modelling of brain dynamical
networks





Project-Team CRONOS

Creation of the Project-Team: 2022 December 01

Each year, Inria research teams publish an Activity Report presenting their work and results over the reporting period. These reports follow a common structure, with some optional sections depending on the specific team. They typically begin by outlining the overall objectives and research programme, including the main research themes, goals, and methodological approaches. They also describe the application domains targeted by the team, highlighting the scientific or societal contexts in which their work is situated. The reports then present the highlights of the year, covering major scientific achievements, software developments, or teaching contributions. When relevant, they include sections on software, platforms, and open data, detailing the tools developed and how they are shared. A substantial part is dedicated to new results, where scientific contributions are described in detail, often with subsections specifying participants and associated keywords. Finally, the Activity Report addresses funding, contracts, partnerships, and collaborations at various levels, from industrial agreements to international cooperations. It also covers dissemination and teaching activities, such as participation in scientific events, outreach, and supervision. The document concludes with a presentation of scientific production, including major publications and those produced during the year.

Keywords

Computer sciences and digital sciences

- A5.1.4. – Brain-computer interfaces, physiological computing
- A5.9.2. – Estimation, modeling
- A5.9.3. – Reconstruction, enhancement
- A6.1. – Methods in mathematical modeling
- A6.2. – Scientific computing, Numerical Analysis & Optimization
- A6.3. – Computation-data interaction
 - A6.3.1. – Inverse problems
 - A6.3.2. – Data assimilation
 - A6.3.3. – Data processing
 - A6.3.4. – Model reduction
 - A6.3.5. – Uncertainty Quantification
- A9.2. – Machine learning
- A9.3. – Signal processing

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
 - B2.2.6. – Neurodegenerative diseases
 - B2.5.1. – Sensorimotor disabilities
 - B2.6.1. – Brain imaging

Contents

Project-Team CRONOS	1
1 Team members, visitors, external collaborators	5
2 Overall objectives	6
2.1 Main Research hypotheses	7
2.1.1 Brain Signal Modeling	7
2.1.2 Network Modeling	7
3 Research program	7
3.1 Sensor level: the first window on brain dynamics	8
3.1.1 Automating the detection of brain state changes from the acquired data	8
3.1.2 Better modeling of the spatio-temporal variability of brain signals	8
3.1.3 Adapting to new sensor modalities	9
3.2 Source level: the integration space	9
3.2.1 Source modeling: anatomical, temporal, and numerical constraints	9
3.2.2 Unified network models explaining various brain measurements	10
3.2.3 Global inverse problem using all measurements altogether	10
3.3 Group level: understanding variability to constrain network properties	10
3.3.1 Matching individual subject models	11
3.3.2 Statistics over brain networks	11
4 Application domains	11
4.1 Clinical applications	11
4.2 Brain Computer Interfaces (BCI)	12
5 Latest software developments, platforms, open data	12
5.1 Latest software developments	12
5.1.1 BCI-VIZAPP	12
5.1.2 Tractography.jl	12
5.1.3 tractography	13
5.1.4 BifurcationKit	13
5.1.5 SynapseElife	14
5.1.6 OpenMEEG	14
6 New results	14
6.1 Sensor Level: Brain Signal Modeling (see Section 3.1)	14
6.1.1 Electrophysiology and BCI	14
6.1.2 Diffusion MRI	16
6.2 Source Level: Brain Dynamic Network Modeling (see Section 3.2)	16
6.2.1 Understanding Brain Functional Connectivity	16
6.2.2 Dynamical models towards Whole Brain Models	18
6.2.3 Clinical applications	20
6.3 Group Level (see Section 3.3)	22
6.4 Other Results	22
7 Bilateral contracts and grants with industry	24
7.1 Bilateral contracts with industry	24
7.2 Bilateral Grants with Industry	24

8 Partnerships and cooperations	24
8.1 International initiatives	24
8.1.1 Associate Teams in the framework of an Inria International Lab or in the framework of an Inria International Program	25
8.2 International research visitors	25
8.2.1 Visits of international scientists	25
8.3 National initiatives	25
8.4 Regional initiatives	27
9 Dissemination	28
9.1 Promoting scientific activities	29
9.1.1 Scientific events: organisation	29
9.1.2 Journal	29
9.1.3 Invited talks	29
9.1.4 Leadership within the scientific community	30
9.1.5 Scientific expertise	30
9.1.6 Research administration	30
9.2 Teaching - Supervision - Juries - Educational and pedagogical outreach	30
9.2.1 Teaching	30
9.2.2 Supervision	31
9.2.3 Juries	32
9.3 Popularization	32
9.3.1 Specific official responsibilities in science outreach structures	32
9.3.2 Participation in Live events	33
10 Scientific production	33
10.1 Major publications	33
10.2 Publications of the year	34
10.3 Cited publications	36

1 Team members, visitors, external collaborators

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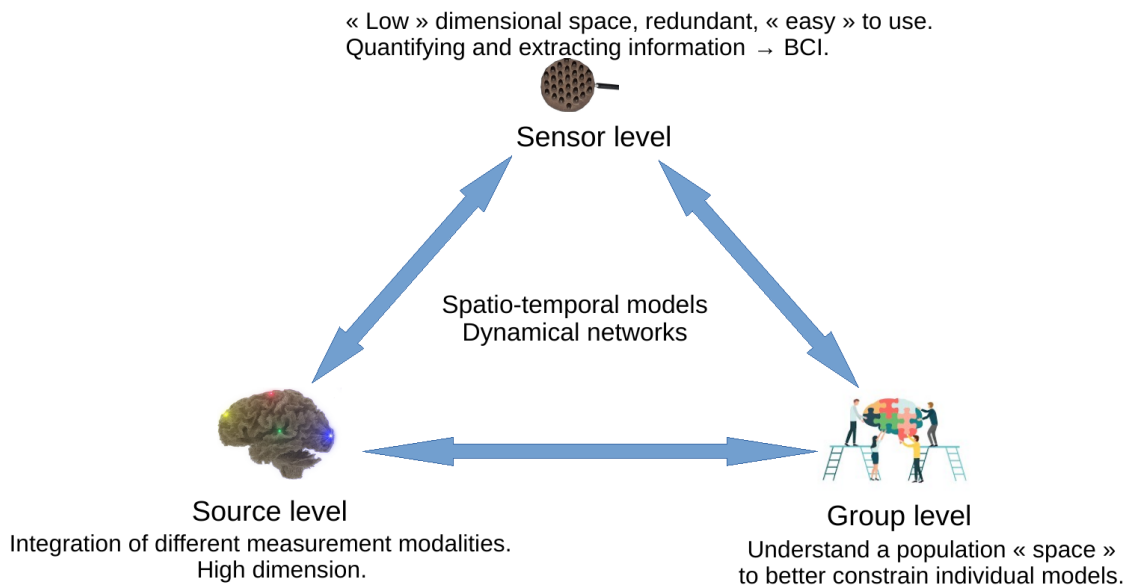


Figure 1: Research axes and their interactions

2 Overall objectives

The objective of CRONOS is to develop models, algorithms, and software to estimate, understand, and quantify the whole brain dynamics. We will achieve this objective by modeling the macroscopic architecture and connectivity of the brain at three complexity levels: source, sensor, and group (see Figure 1). These three levels, detailed in Section 3, will be studied through the unifying representation of dynamic networks.

CRONOS aims at pushing forward the state-of-the-art in computational brain imaging by developing computational tools to integrate the dynamic and partial information provided by each measurement modality (fMRI, dMRI, EEG, MEG, . . .)¹ into a consistent global dynamic network model.

Developing the computational models, algorithms, and software to estimate, understand, and quantify the brain's dynamical networks is a mathematical and computational challenge. Starting from several specific partial models of the brain, the overall goal is to assimilate in a single global numerical model the diversity of observations provided by non-invasive imaging. Indeed, the observations provided by various modalities are based on very different physical and biological principles. They thus reveal very different but complementary aspects of the brain, including its structural organization, electrical activity, and hemodynamic response. In addition, because of the varied nature of the physical principles used for imaging, different modalities also have drastically different spatial and temporal resolutions making their unification challenging. Some examples of sub-objectives we develop are:

- Go beyond the hypothesis that brain networks are static over a given period of time.
- Study the possibility of estimating brain functional areas simultaneously with the networks.
- Study the impact on the reconstructed networks of various models of activity transfer between brain areas.
- Develop a complete modeling of time delays involved by long range connections.
- Develop *network based* regularization methods in estimating brain activity.
- Go from subject specific studies to group level studies and increase the level of abstraction implied by the use of brain networks to open research perspectives in identifying network characteristics and invariances.

¹MR: magnetic resonance, fMRI: functional magnetic resonance imaging, dMRI: diffusion magnetic resonance imaging, EEG: electroencephalography, MEG: magnetoencephalography.

- Study the impact of the model imperfections on the obtained results.

Finally, the software implementing our models and algorithms must be accessible to non-technical users. They must therefore provide a level of abstraction, ease of use, and interpretability suitable for neuroscientists, cognitivicians, and clinicians.

2.1 Main Research hypotheses

To achieve our goals, we decided to make some hypotheses on the way brain signals and networks are modeled.

2.1.1 Brain Signal Modeling

To model brain signals, we adopt a signal processing perspective, i.e. consider that at the macroscopic scale we look at signals, general signal modeling approaches are sufficient for the goal of describing brain dynamics. This contrasts with many other teams, which often follow a more constructivist approach, where brain signal models are derived from a computational neuroscience perspective, i.e. emerge from a mathematical modeling of neurons, axons and dendrites or assemblies of those (spiking neurons, neural mass models, . . .). Our approach gives more freedom to model signals and allows for descriptions with a very limited number of parameters at the cost of losing some connection with the microscopic reality. Additionally, the reduced number of parameters simplifies the problem of parameter identification. Depending on the type of modeling, we may use rather simple phenomenological descriptions (e.g. a region is activated or not) or more or less complicated signal models (sampled signals with no specific temporal models, various multivariate autoregressive (AR) models, integro-differential equations, . . .). Generally speaking, the more we will be interested in dynamic properties of the signals, the more we will need sophisticated signal models.

2.1.2 Network Modeling

Classical – deterministic – networks only strictly exist at the microscopic level where neurons are connected together through axons. For usual neural systems, such networks are huge, currently unavailable and too complex for a macroscopic view of the brain. At such a scale, networks are of stochastic nature. Both nodes and edges are only defined probabilistically. We allow ourselves to work either directly with these probabilistic networks or with deterministic networks obtained by thresholding the probabilistic ones, in which case it is important to pay attention to the amount of approximation and bias introduced by the thresholding operation. It is important to note that, while deterministic networks have received a lot of attention, the domain of stochastic networks or its transfer to computational neurosciences is still in its infancy.

3 Research program

As described in Section 2 and Figure 1, the research program of CRONOS is organized in 3 main axes corresponding to different levels of complexity:

- The *Sensor* level aims at extracting information directly from sensor data, without necessarily using the underlying brain anatomy. It can be thought of as a projection of the underlying brain networks onto a low dimensional space thus allowing computationally efficient processing and analysis. This provides a first window for observing and estimating brain dynamics. This sensor space is particularly convenient for the estimation of properties that are projection invariants (e.g. number of sources, state changes, . . .). It is also the level that is most suitable for real time applications, such as brain-computer interfaces (BCI).
- The *Source* level aims at measurement integration into a unified and high dimensional spatio-temporal space, i.e. a computational representation of dynamic brain networks. This is the level that is understood by neuroscientists, cognitivicians, and clinicians, and therefore has an essential role to play in the visualization of brain activities.

- The *Group* level aims at providing tools to constrain the search space of the two previous levels. This is the natural space to develop statistical models and tests of the functioning of the brain. It is the level that allows the study of inter-subject variability of brain activity and the development of data driven priors. In particular, the topic of making statistics over noisy networks is a challenging task for this level.

These three levels closely interact with each other, as depicted by Fig. 1, towards the ultimate goal of non-invasively and continuously localizing brain activity in the form of brain networks.

3.1 Sensor level: the first window on brain dynamics

Sensor level mostly concerns MEG and EEG measurements. These serve 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). As an inexpensive modality, EEG is also widely used for the development of brain-computer interfaces. EEG and MEG are characterized by a high temporal resolution (up to 1000Hz or more), by a poor spatial resolution (measurable events involve several centimeters-square portions of the cortex) and by a rather poor signal-to-noise ratio (SNR)². For both EEG and MEG, the obtained measurements are linear mixtures of the “true” electrical sources that are at a distance of the sensors. MEG and EEG temporal resolution characteristics allow them to reveal changes in the dynamic of the brain activity. This “sensor space” has two main advantages: 1) its relatively small dimension (from a few to several hundreds sensors) compared to that of the “source space” (tens of thousands of degrees of freedom) and 2) its ease-of-use³. It is thus opportune to extract as much information as possible from this lower dimensional space, which already contains all the dynamical information of the functioning brain available from these modalities. This involves a better understanding of the invariants between source and sensor levels, which can lead to better BCI classification algorithms. The BCI field not only clearly is an applicative domain that will benefit from this research, but will also help in validation of algorithms and methods. Our ambition is also to study how BCI-like techniques can be used for constraining the reconstruction of brain networks, for detecting some brain events in real time for clinical applications or for creating improved cognitive protocols using real time responses to dynamically adapt stimulations.

This axis relies on three major ideas, which are necessary steps towards the ultimate goal of using MEG or EEG systems to non-invasively and continuously localize brain activity in the form of brain networks (i.e. without averaging multiple trials signals).

3.1.1 Automating the detection of brain state changes from the acquired data

Experimental practice in MEG, EEG, and BCI shows that very valuable information can be obtained directly from the “sensor space”. This encompasses estimating the number [39] or the time courses of sources [35, 34] or the detection of changes in the brain dynamical activity. This type of information can be an indication of a “brain state change”. In particular, automating the detection of changes in brain states would allow the splitting of the incoming functional data into segments in which the brain network can be considered as stationary. During such stationary segments of data, the sources and their locations remain fixed, which offers a means to regularize the solution of the inverse problem of source reconstruction. Furthermore, any improvement on EEG signal classification has direct applications for BCI. One approach that we explore is the use of autoregressive spatio-temporal models or lagged correlation measurements as a means to improve classification of MEG/EEG signals. These autoregressive spatio-temporal models constitute a possible first step towards using more sophisticated causality modeling.

3.1.2 Better modeling of the spatio-temporal variability of brain signals

Hand in hand with the previous sub-goal is the need to better understand the spatio-temporal variability of brain signals. This variability originates from several factors ranging from the intrinsic variability of the

²The SNR further depends on several factors such as the technology used in the sensor (dry/wet, active/passive electrodes, ...), on the quality of the amplifier, on the quality of the setup, . . .

³Going to source space requires to create a head model which, for better efficiency, requires to be adapted to the subject. In turn, this means acquiring MR data and apply complex processes to it.

brain sources (even in a same subject) to important differences in the spatial organization of the cortex across subjects or to variations in the way sensors are setup by experimenters. Thus, variability occurs not only across subjects, but also across sessions or even trials for a same subject.

The most common approach developed to cope with the noisy MEG and EEG signals is commonly referred to as evoked potentials: the signal is “clocked” on some stimulus or reaction of the subject and the low amplitude signals – almost completely hidden by background activity – are then averaged over multiple repetitions (trials) of the experiment to improve the SNR. But, because of variability, such an averaging distorts the overall activity and hides specific activities such as high frequency components. It is thus advisable to improve models so that they can “work” in single event mode (i.e. without averaging). Relying on multiple trials to obtain better statistical models of individual signals (with techniques such as dictionary learning, autoregressive models, deep-neural networks, . . .) would be an important improvement over the current state-of-the-art as it would provide a more objective and systematic way of characterizing single trial data. Events will be extracted separately for each trial without relying on averaging, but with the knowledge of the “group” model (see Section 3.3). This will allow the study of the variability of brain activity across trials (attention, habituation are e.g. known to change the activity). This is a difficult long term challenge with possible short-middle term advances for some specific cases such as epileptic spikes. This research path is grounded by some of our previous work [2, 6]. Understanding variability is particularly important for BCI as it is often necessary to “learn” a classifier to detect the subject’s brain state with a limited dataset (because of time constraint). At the sensor level, spatial patterns of activity are often described by covariance/correlation matrices. Using Riemannian metric over the space of symmetric definite positive matrices is a powerful technique that has been used these last years by the BCI community [32]. Extending and improving these techniques as well as finding proper low dimensional spaces that characterize brain activity are other research paths we will follow.

3.1.3 Adapting to new sensor modalities

During the last few years, tremendous improvements have been made on means to acquire functional brain data. Yet, novelty in this domain continues and new sensors are regularly proposed. These sensors can offer more accurate measurements with improved SNR and/or some ease-of-use improvements. For example, the use of room temperature MEG sensors (such as those developed by [Mag4Health](#) – see Section 7.2) promise improvements in both aspects. EEG dry electrodes hold the promises to simplify the setup of BCI systems, but are difficult to master. MR machines are also more and more powerful with either higher fields (better signal quality and/or better spatial resolution) or, on the contrary, lower fields (easier to use and better contrasts in some cases). It is important to continually adapt processing methods to exploit the specificities of these new sensors as they become available to the community.

3.2 Source level: the integration space

MR images of the brain offer different views of its organization and function via dMRI tractography and fMRI connectivity. When combined with MEG and EEG, we obtain complementary, but highly heterogeneous perspectives on brain networks and their dynamics. The natural space to integrate this complex information is the space of brain sources, allowing a unified model of imaging data. This axis is built over our past research (in the former team *ATHENA*) in modeling the propagation of the electromagnetic field from brain sources to sensors [7], brain structural connectivity [4] or mapping different brain imaging modalities [5]. Our plan for fusing the data originating from different modalities into a single network based model can be described in 3 sub-topics.

3.2.1 Source modeling: anatomical, temporal, and numerical constraints

Brain sources refer to regions of interests whose properties link brain activity to the observed measurements. For example, in EEG, brain sources can be modeled as dipoles representing the superposition of many synchronous and parallel neurons. The combination of the electric fields generated by these dipoles gives rise to the potential differences measured at the surface of the scalp in EEG. The magnetic fields generated by these same dipoles give rise to MEG signals. Regardless of the modality, the task of recovering brain sources from imaging data is an inverse problem. This inverse problem is ill-posed, either because of the

limited number of sensors (EEG and MEG), because of poor signal to noise ratio (EEG, MEG, fMRI), or because of the limited spatial (dMRI, EEG, MEG) or temporal resolution (fMRI, dMRI). To recover a unique and stable solution, simple mathematical (i.e. not fully grounded by biology) criteria such as minimum norm or sparsity are used to constrain the source space. However, these regularization approaches do not correspond to any specific anatomical or physiological properties of the brain and are therefore quite arbitrary. The challenge we address here is to increase the amount of subject specific anatomical and physiological constraints taken into account for the recovery of brain activity from non-invasive imaging. More specifically, we will investigate how brain networks, and in particular their associated delays, can be used to constrain the inverse problem. Previous work has already shown the potential of temporal regularization based on brain connectivity [4], but the topic remains largely open to identifying new models grounded in physiological data. Another difficulty is the dynamic aspect of brain networks: we first assume that a stationary brain state has been identified (e.g. using methods from Section 3.1). Eventually (as a long term objective), transitions between stationary brain state models could be directly modeled in the networks themselves and estimated from the data. The validation of the proposed models is both challenging and essential and will be explored with our clinical partners (see Section 8). Finally, non-traditional imaging modalities will also be considered. For example, accurate modeling of electromyography, in collaboration with **Neurodec**, can provide important timing information of sources.

3.2.2 Unified network models explaining various brain measurements

In the previous section, brain activity is estimated from one modality using information from the others as constraints or priors. This obviously favors one modality over the others and propagates errors of processing pipelines via the constraints. This *modus operandi*, while suboptimal, is historically justified: analysis pipelines have been developed independently for each modality by different communities. Given the complementary nature of the different modalities, it seems relevant to instead construct one global pipeline encompassing all brain measurement modalities into a single unified framework. With brain networks arising as a central concept in the neuroscientific community, we propose to make it the basis of such a global model. Doing so will enable the recovery of brain network dynamics from non-invasive multi-modal data, an important open problem in neuroscience. To achieve this objective, we propose to devise forward models describing the link between brain networks and each of the various imaging modalities. Specifically, effort is needed to evaluate different formalisms describing brain networks that differ in the way nodes and their interactions are defined. For example, we investigate the relationship between electrical (EEG/MEG), architectural (dMRI) and metabolic (fMRI) activities. Separated models – either electric or hemodynamic – have been proposed for some time, but coupling them is an important challenge all the more that the role of some neural constituents (such as glia) is currently not well understood. Such models have already been – at least partly as in [33] – devised. The main challenge is to define one that is sufficiently simple and well spatialized (in particular to incorporate connectivity) in order to be useful for our purpose. We will also consider electromyography in this context, extending brain networks to the peripheral nervous system.

3.2.3 Global inverse problem using all measurements altogether

Models established in the previous section can be used in a global inverse problem involving all the measurements modalities to recover the specific brain network involved in a task. In all cases, we need to solve an inverse problem over a complex network model with a sparse prior as we need to find “simple” networks that can explain our data. Depending on the way networks are modeled, some difficulties may arise. For example, the model defined in [36, 37] leads to combinatorial explosion when used for source localization. Finding appropriate models that facilitate the resolution of this inverse problem may require some iterations between this sub-task and the previous one.

3.3 Group level: understanding variability to constrain network properties

Given the high intra- or inter-subject variability of brain activity, it is particularly interesting to be able to characterize the part of the activity that remains invariant (over time for one subject or across different subjects). This will allow a better understanding of brain processes as well as a better understanding of their variability across time or subjects. It also opens the possibility to constrain network models to reduce their

complexity and improve their identifiability. The following description mostly refers to group statistics at the source level, but similar techniques are also relevant for the sensor level axis (see Section 3.1). This axis is a long term research effort as it builds upon previous axes.

3.3.1 Matching individual subject models

Reconstructions obtained in Section 3.2 will certainly differ even for different measurement sessions obtained with a same subject. An important problem to solve is the matching of instances of such reconstructions (whether they consist in brain networks or spatio-temporal autoregressive models). In general, the relative positions of functional brain areas are fairly well known. However, temporal variations (lag, duration) in these models make the matching problem rather complicated. Finding and using some invariants of the models is one path to find a good compromise that would allow for enough flexibility in the matching process while avoiding the combinatorial complexity that e.g. graph matching problems usually exhibit. Another – long term – possibility would be to directly solve “group problems”, but this would complexify even more the modeling problem and might have the same drawbacks as averaging if not properly done (i.e. hiding some activity or the intrinsic variability of the studied phenomenon).

3.3.2 Statistics over brain networks

Once the matching of single subject models has been solved, statistics will be necessary to assess the significance of the various model elements (e.g. in the case of dynamic network models, brain areas and their connections). Such statistics can also be used as a basis to derive “group statistical models” describing a family of task-related models that can in turn be used to constrain models used in Section 3.2 and, through a forward model to reduce the dimension of the search space at sensor level (see Section 3.1). The BCI community is still divided on the actual benefits in terms of accuracy on using the source space (v.s. the sensor space) for classifying brain signals. The statistical tools developed in this sub-axis may help to address this problem.

4 Application domains

4.1 Clinical applications

CRONOS research has a strong clinical potential impact for brain diseases like epilepsy, brain cancer surgery, phantom pains, traumatic brain injuries, anoxia and disorders of consciousness. We closely work with several hospital teams and research groups ([Pasteur hospital in Nice](#), [La Timone hospital in Marseille](#), [CRNL – Centre de Recherche en Neurosciences in Lyon](#) and the [Toulouse Neuroimaging center](#)) towards exporting our research in their medical contexts. Example of applications are:

- Better understanding brain stimulation used in awake brain surgery and its relation with brain anatomy and in particular fibers as measured by dMRI.
- Real time detection of epileptic spikes from new generation MEG data and the visualization of their associated brain sources in real time.
- Use of BCI (see Section 4.2) for helping disabled people to communicate (e.g. for patients suffering from Amyotrophic Lateral Sclerosis) or for helping epileptic patients to learn how to control the occurrence of seizures.
- Understand the somatotopy of the thalamus and its relation with the efficiency of the deep brain stimulation therapy.
- A deeper understanding of the neural correlates of disorders of consciousness, with the goal of identifying objective markers of patients states of consciousness.

4.2 Brain Computer Interfaces (BCI)

BCI is a closely related domain to both the “Signal Processing” (Section 2.1.1) and “Network Modeling” (Section 2.1.2) aspects. It typically extracts from the signal a “brain state” that is a correlate of the “brain network”. While traditional MEG/EEG studies have been extensively exploited by the BCI community, the opposite nourishing of the former field by BCI has been much less explored. There is a continuing dispute in the BCI community on the advantages of going to source space or not (see e.g. [38]). By studying the invariants between source and sensor space, we hope not only to provide clues on the above dispute but also to open the opportunity of using BCI-like techniques to ease the more traditional brain signal processing. In some sense, such invariants are the information that BCI exploits in doing classification on sensor data. BCI also has the advantage of providing a more quantitative way (in term of classification quality) to evaluate methods. Controlling the amount of resources (computer power, number and quality of sensors, . . .) needed to achieve a given classification accuracy is also a strong BCI concern. This point of view is also complementary to that of more traditional brain signal modeling and can have a significant impact in terms of cost and ease of use in the clinical context.

5 Latest software developments, platforms, open data

5.1 Latest software developments

5.1.1 BCI-VIZAPP

Name: Real time EEG applications

Keyword: EEG

Functional Description: BCI-VIZAPP is a software suite for designing real-time EEG applications such as BCIs or neurofeedback applications. It has been developed to build a virtual keyboard for typing text and a photodiode monitoring application for checking timing issues, but can now be also used in other tasks such as EEG monitoring. Originally, it was designed to delegate signal acquisition and processing to OpenViBE but has recently been extended to get some of these capabilities. This allows for more integrated and robust applications but also opens up new algorithmic opportunities, such as real time parameter modification, more controlled interfaces, . . .

News of the Year: Bci-Vizapp has been enriched with numerous features, notably to read and save certain files created with OpenViBE or with MNE-python, thus allowing an easier communication with them. Bci-Vizapp is also the software base used (or which we aim to use it in the long term) for different current (Demagus and ConnectTC) or past (Techicopa) contracts and has integrated different elements to support them.

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5.1.2 Tractography.jl

Keywords: GPGPU, Diffusion MRI

Functional Description: Tractography.jl is a high-performance Julia package for brain tractography that leverages parallel computing and specialized hardware (e.g., GPUs) to reconstruct white matter fiber bundles from diffusion-weighted MRI data. This enables researchers to study the structural connectivity of the brain at unprecedented scales.

URL: <https://github.com/cronos-inria/Tractography.jl>

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5.1.3 tractography

Name: tractography

Keywords: Tractography, Diffusion MRI

Scientific Description: The tractography package provides a high-performance computational framework for reconstructing the complex 3D trajectories of white matter pathways from diffusion Magnetic Resonance Imaging (dMRI) data.

This software addresses the computational bottlenecks commonly associated with structural connectomics and neuroimaging research. Specifically, the package implements advanced tractography methods grounded in both stochastic differential equations and partial differential equations reformulations of the tractography problem, enabling a robust and precise mapping of neural topology. To handle the immense computational demands of large-scale, high-resolution dMRI datasets, the library is heavily optimized for parallel execution, seamlessly supporting both multi-core CPU and hardware-accelerated GPU architectures.

Functional Description: ‘tractography’ is a Python package designed for performing tractography, the process of reconstructing nerve fiber pathways from diffusion MRI (dMRI) data. Developed by the Inria CRONOS team, the package implements various tractography algorithms and is optimized for high performance, supporting execution on both CPUs and GPUs.

URL: <https://gitlab.inria.fr/cronos/software/tractography>

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5.1.4 BifurcationKit

Name: Automatic computation of numerical bifurcation diagrams

Keywords: Bifurcation, GPU

Functional Description: This Julia package aims at performing automatic bifurcation analysis of possibly large dimensional equations function of a real parameter by taking advantage of iterative methods, dense / sparse formulation and specific hardware (e.g. GPU).

It incorporates continuation algorithms (PALC, deflated continuation, ...) based on a Newton-Krylov method to correct the predictor step and a Matrix-Free/Dense/Sparse eigensolver is used to compute stability and bifurcation points.

The package can also seek for periodic orbits of Cauchy problems. It is by now one of the few software programs which provide shooting methods and methods based on finite differences or collocation to compute periodic orbits.

The current package focuses on large-scale, multi-hardware nonlinear problems and is able to use both Matrix and Matrix Free methods on GPU.

News of the Year: Development of a Proof of Concept (POC) on boundary value problems (BVP) (with Inria SAM SED). Improved calculation of normal shapes of periodic orbits. Correction of the calculation of normal shapes of equilibrium points.

URL: <https://github.com/rveltz/BifurcationKit.jl>

Publication: [hal-02902346](https://hal.archives-ouvertes.fr/hal-02902346)

Contact: Romain Veltz

Participant: an anonymous participant

5.1.5 SynapseElife

Keyword: Markov model

Functional Description: This is the main library, written in Julia language, for the simulation of a synapse model. The associated publication is 10.7554/eLife.80152. It implements a model of excitatory synapse in the rat hippocampus.

This code allows to replicate the results of the paper. It is also used by the Julia community to benchmark the methods for simulating piecewise deterministic Markov processes.

URL: <https://github.com/rveltz/SynapseElife.jl>

Publication: [hal-04275554](#)

Contact: Romain Veltz

Participant: Romain Veltz

5.1.6 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 $< 100\text{Hz}$ and medium diameter $< 1\text{m}$).

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.

Release Contributions: OpenMEEG has had small updates and bug corrections. Notably, bugs related to the python interface and to Blas/Lapack implementations have been handled.

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

Publications: [inria-00467061v2](#), [inria-00584205v1](#), [hal-01278377v1](#)

Contact: Théodore Papadopoulo

Participants: Eric Larson, Théodore Papadopoulo, 8 anonymous participants

6 New results

6.1 Sensor Level: Brain Signal Modeling (see Section 3.1)

6.1.1 Electrophysiology and BCI

Augmented Covariance Approaches for BCI

Participants: Igor Carrara, Théodore Papadopoulo.

EEG signals are complex and difficult to characterize, in particular because of their variability. They therefore require the use of specific and adapted signal processing methods. In a recent approach [1], sources were modeled as an autoregressive 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 autoregressive model directly at the measurement level. The objectives of this line of work is to explore the possibility of exploiting EEG/MEG autoregressive models to extract as much information as possible without requiring the complex head modeling needed for source reconstruction.

A first result in this line of research is the use of Augmented Covariance Matrices (ACMs) for BCI classification [3]. These ACMs appear naturally in the Yule-Walker equations that were derived to recover autoregressive models from data. ACMs being symmetric positive definite matrices, it is natural to apply Riemannian geometry based classification approaches on these objects as they represent the current state-of-the-art. Using these ACMs noticeably improves classification performance on several BCI benchmarks both in the within-session or in the cross-session evaluation protocols⁴. This is due to the fact that ACMs incorporate not only spatial (the classical covariance matrix) but also temporal information. As such, it contains information on the nonlinear components of the signal through the embedding procedure, which allows the leveraging of dynamical systems algorithms. This comes at the cost of introducing two hyper-parameters: the order of the autoregressive model and a delay that controls the time resolution at which the signal is considered, which have to be estimated.

The method also turned out to be useful in the context of learning with a limited amount of training data. This work on limited training data is described in the article [16].

Uncertainty Propagation: From EEG Measurements to BCI classification

Participants: Julie Feriau, Théodore Papadopoulo.

Affine invariant Log-Euclidean Riemannian metrics have proven over the years to be extremely effective for comparing symmetric positive definite matrices, in particular for classifying BCI data (see previous paragraph). We studied the problem of propagating uncertainty coming from measurements in the computation of these metrics, which has been largely overlooked so far.

Optimizing EEG based P300 classifiers

Participants: Martyna Nabialczyk, Evgenia Kartsaki, Théodore Papadopoulo.

The P300 speller is a virtual keyboard BCI system that allows paralyzed patients to communicate with the outside world. The development of this system was first carried out in the framework of the former ATHENA team in close collaboration with doctors at the University Hospital of Nice to ensure that the application would ultimately lead to products that are comfortable, easy to use, and truly beneficial to patients and is still used and developed within CRONOS. The system is based on the difference in EEG measurements depending on whether a letter on which a subject is focusing its attention is flashed or not. The obtained signal is quite challenging but exploitable. But this system is still based on a basic linear discriminant analysis classifier. The intent of this work is to study how more modern Riemannian based classifiers can improve the classification performance in various situations (within session, cross-session or cross-subject).

Exploring and exploiting the new capabilities of room temperature MEG sensors

Participants: Laura Gee, Théodore Papadopoulo, Christian Bénar (*Institut de neurosciences des systèmes, Marseille*).

⁴We refer to a within-session evaluation when the training data is acquired in the same session as the testing data. When this is not the case, we have a cross-session evaluation.

Traditionally, MEG sensor work with SQUIDs (superconducting quantum interference device) that require cryogenic temperatures. Recently, new magnetic sensors called OPMs (Optically Pumped Magnetometers) were developed and do not require such low temperatures. In particular, we are working with the company [Mag4Health](#) that develops a MEG machine with helium based OPMs that can work at room temperature. This allows to have sensors closer to the head and these new sensors are also able to measure the 3 components of the magnetic field (SQUIDs are measuring only one such components). But this sensors are also more noisy and the 3 measured components of the magnetic field are not suffering from the same level of noise. It is thus interesting to better study the sensitivity of these new MEG machines and to develop methods that can exploit efficiently the specificities of these sensors. This is the subject of the Ph.D thesis of L. Gee, co-supervised with C. Bénar who work in La Timone Hospital, which acquired recently a 96 (x3 channels) Mag4Health device.

Inverse Problems in Electromyography

Participants: Madeline Shaw, Emeline Manka, Samuel Deslauriers-Gauthier.

Although surface Electromyography (EMG) and Electroencephalography (EEG) share identical underlying physics governed by Maxwell’s equations—both aiming to recover physiological sources from non-invasive recordings—their methodological approaches have historically remained distinct. This project aims to bridge that gap by adapting advanced forward modeling and inverse problem techniques originally developed for EEG to the domain of EMG. Our primary objective is the estimation of motor unit spike trains using subject-specific volume conductors, necessitating the adaptation of established tools to handle anatomical extraction from MRI, tissue conductivity estimation, and complex volume deformations during movement. Concurrently, we are applying EEG-inspired algorithms, including Minimum Norm Estimates and Maximum Entropy on the Mean, to solve the inverse problem in EMG. The performance of these novel approaches is quantified using real forearm data validated against ground-truth intramuscular recordings, with ultimate applications in motor control analysis, neurorehabilitation, and muscle-computer interfaces.

6.1.2 Diffusion MRI

Mathematical Analysis of Tractography Algorithms

Participants: Samuel Deslauriers-Gauthier, Evgenia Kartsaki, Romain Veltz.

Current dMRI fiber tractography algorithms function as numerical approximations to an often ill-defined problem. Historically, the field has prioritized the empirical capacity to trace white matter trajectories over mathematical formulation or numerical precision. Data-driven approaches, for example jointly using diffusion and functional MRI data [20], have been prioritized to validate and advance tractography. In this work, we revisited these algorithms through a rigorous mathematical lens, reformulating them as classical stochastic differential equations and partial differential equations. This framework allowed us to derive new algorithms with well-characterized parameter behaviors [19, 30] and to investigate direct solutions to the associated Fokker-Planck equations [29]. Motivated by this theoretical foundation, we developed high-performance GPU-accelerated software (see 5.1.2, 5.1.3). These tools enabled the generation of connectivity matrices based on a record-breaking five hundred billion streamlines [18], providing exceptionally tight bounds on connectivity uncertainty. These results were presented at JuliaCon Paris 2025 and the inaugural International Society for Tractography Conference [18, 19]. A manuscript is being written for submission to a journal.

6.2 Source Level: Brain Dynamic Network Modeling (see Section 3.2)

6.2.1 Understanding Brain Functional Connectivity

Modeling Direct Electrostimulation for Functional Brain Mapping

Participants: Emeline Manka, Samuel Deslauriers-Gauthier, Théodore Papadopoulo, Evgenia Kartsaki, Petru Isan, Fabien Almairac (*CHU Nice, Université Côte d'Azur*).

Optimizing the balance between maximum lesion removal and the preservation of functional tissue remains the primary challenge in glioma surgery. While direct electrostimulation during awake surgery is the current gold standard for functional mapping, it is not viable for all patients. In this work, we addressed this limitation by developing a patient-specific conductivity model of the head to simulate electrophysiological signals.

We validated this physical approach using data recorded during awake surgeries on two patients at Nice University Hospital. Using anatomical MRI (pre- and post-operative) and electrocorticography recordings, we constructed tetrahedral meshes and simulated the propagation of stimulation artifacts using a Finite Element Method. Our results demonstrate a strong correlation between simulated and observed artifact amplitude distributions, effectively validating the physical conductivity model. Notably, we found that the presence of the resection cavity did not significantly alter the simulation fit. Furthermore, we proposed a one-source model for brain evoked potentials. While preliminary results are promising for certain cortical sites, the complexity of other observed patterns suggests that future iterations must incorporate heterogeneous conductivities (differentiating white and grey matter) and explicit propagation pathways via white matter tracts.

This work was presented at the annual conference of the Organization for Human Brain Mapping [31].

Log-Euclidean Frameworks for Smooth Brain Connectivity Trajectories

Participants: Olivier Bisson (*EPIONE, Inria*), Yanis Aeschlimann, Samuel Deslauriers-Gauthier, Xavier Pennec (*EPIONE, Inria*).

The brain is often studied from a network perspective, where functional activity is assessed using functional magnetic resonance imaging to estimate connectivity between predefined neuronal regions. Functional connectivity can be represented by correlation matrices computed over time, where each matrix captures the Pearson correlation between the mean fMRI signals of different regions within a sliding window. We introduce several Log-Euclidean Riemannian framework for constructing smooth approximations of functional brain connectivity trajectories. Representing dynamic functional connectivity as time series of full-rank correlation matrices, we leverage recent theoretical Log-Euclidean diffeomorphisms to map these trajectories in practice into Euclidean spaces where polynomial regression becomes feasible. Pulling back the regressed curve ensures that each estimated point remains a valid correlation matrix, enabling a smooth, interpretable, and geometrically consistent approximation of the original brain connectivity dynamics. Experiments on fMRI-derived connectivity trajectories demonstrate the geometric consistency and computational efficiency of our approach.

This work was published in [17].

Characterizing Dynamic Functional Connectivity Subnetwork Contributions in Narrative Classification with Shapley Values

Participants: Aurora Rossi (*COATI, Inria*), Yanis Aeschlimann, Emanuele Natale (*COATI, Inria*), Samuel Deslauriers-Gauthier, Peter Ford Dominey (*MR1093-CAPS, INSERM*).

Functional connectivity derived from functional magnetic resonance imaging data has been increasingly used to study brain activity. In this study, we model brain dynamic functional connectivity during narrative tasks as a temporal brain network and employ a machine learning model to classify in a supervised setting

the modality (audio, movie), the content (airport, restaurant situations) of narratives, and both combined. Leveraging Shapley values, we analyze subnetwork contributions within Yeo parcellations (7- and 17-subnetworks) to explore their involvement in narrative modality and comprehension. This work represents the first application of this approach to functional aspects of the brain, validated by existing literature, and provides novel insights at the whole-brain level. Our findings suggest that schematic representations in narratives may not depend solely on pre-existing knowledge of the top-down process to guide perception and understanding, but may also emerge from a bottom-up process driven by the temporal parietal subnetwork.

This work has been published in [15].

6.2.2 Dynamical models towards Whole Brain Models

Whole brains models are models of the whole brain modeled using a graph where each node is used to describe a cortical area and where the edges represent the connections between the cortical areas. Whole brains models are very attractive from a modeling point of view because we can use data such as structural connectivity from diffusion MRI in place of the graph edges. One needs to assign a dynamics to each node in order to study the structure-function mapping and thus study the link between fMRI and MRI. Traditionally, heuristically derived models of the dynamics of populations of neurons are used for the dynamics of the nodes. However, the model of neural populations can be rigorously derived from the dynamics of large networks of interconnected neurons making the link direct between microscopic elements and mesoscopic components.

The Impact of Homeostatic Inhibitory Plasticity in a Generative Biophysical Model

Participants: Iván Mindlin (*Sorbonne Université, Institut du Cerveau - Paris Brain Institute - ICM, Inserm, CNRS, 75013, Paris, France*), Carlos Coronel-Oliveros (*rinity College Dublin, The University of Dublin, Dublin, Ireland.*), Jacobo D. Sitt (*Sorbonne Université, Institut du Cerveau - Paris Brain Institute - ICM, Inserm, CNRS, 75013, Paris, France*), Rodrigo Cofre, Andrea Luppi (*Department of Psychiatry, University of Oxford, Oxford, UK*), Thomas Andrillon (*Sorbonne Université, Institut du Cerveau - Paris Brain Institute - ICM, Inserm, CNRS, 75013, Paris, France*), Yonatan Sanz-Perl (*Center for Brain and Cognition, Computational Neuroscience Group, Universitat Pompeu Fabra, Spain*), Rubén Herzog (*Instituto de Física Interdisciplinar y Sistemas Complejos (IFISC, UIB-CSIC), Campus UIB, Palma de Mallorca, Spain*).

A main characteristic of biological systems is their capacity to dynamically adapt to environmental changes. In the brain, synaptic plasticity enables the strengthening or weakening of connections between neurons, allowing neural circuits to adapt based on experience, learning, and environmental changes. Yet, it is homeostatically regulated such that it avoids excessive proliferation of synaptic contacts. These mechanisms can be studied with large-scale models of brain activity. Here, we embed a biologically grounded inhibitory-homeostatic plasticity rule into the Dynamic Mean Field (DMF) model, creating a Homeostatic Dynamic Mean Field (HDMF) model that dynamically tunes local excitation–inhibition balance. Convergence of excitatory firing rates is reached by mapping a large range of coupling strength to parameters of inhibitory synapses. The HDMF reproduces statistical observables of brain activity as well as the original DMF, and can sustain neuromodulatory perturbations without overhead computations. The HDMF can generate unprecedented sleep-like slow-wave activity, which can also coexist with wake-like asynchronous dynamics, permitting to model dissociated states of consciousness such as parasomnias. Together, these results show that a single homeostatic rule broadens the stability and expressiveness of the DMF, providing a unified platform for studying how local adaptive processes shape the diverse global dynamics of the human brain.

This work is available as a preprint [27].

Simulated 5-HT_{2A} Receptor Activation Accounts for the High Complexity of Brain Activity during Psychedelic States

Participants: Hugo M Martin (*CNRS, NeuroPsi Institute Paris, France*), Rodrigo Cofre, Alain Destexhe (*CNRS, NeuroPsi Institute Paris, France*).

Serotonergic psychedelics, such as lysergic acid diethylamide (LSD), psilocybin, and Dimethyltryptamine (DMT), have strong effects on human brain activity, yet their mechanisms of action at the whole-brain level are only partially understood. Here, we present a biophysically-based meanfield model that integrates cellular and network-level details to simulate the effects of these compounds at different spatial scales. By incorporating the brain-wide distribution of 5-HT 2A receptors, our model mechanistically links receptor activation to a reduction in leak membrane potassium conductance, consistent with electrophysiological data. Our simulations reveal that this microscopic perturbation leads to the emergence of a brain state characterized by asynchronous and irregular dynamics with increased firing rates, as well as significant alterations in spectral power. Specifically, we find a robust decrease in power within the delta, theta, and alpha frequency bands, a result consistent with empirical findings. This change in dynamics is accompanied by an increase in spontaneous complexity, as quantified by the Lempel-Ziv complexity index, as observed experimentally. Furthermore, our model accurately replicates experimental findings regarding the Perturbational Complexity Index, demonstrating that it does not increase significantly by psychedelic drug administration. This crucial dissociation, where spontaneous complexity and spectral power are increased while perturbational complexity is preserved, highlights the distinct neurophysiological substrates underlying different metrics in psychedelic states. Our multiscale model provides a robust, mechanistic framework for understanding how serotonergic psychedelics modulate global brain activity.

This work is available as a preprint [26].

Analysis of Large Size Networks of Hopfield Neurons

Participants: Olivier Faugeras, Etienne Tanré (*INRIA / LJAD, Nice, France*).

We revisit the problem of characterizing the thermodynamic limit of a fully connected network of Hopfield-like neurons. Our contributions are: a) a complete description of the mean-field equations as a set of stochastic differential equations depending on a mean and covariance functions, b) a provably convergent method for estimating these functions, and c) numerical results of this estimation as well as examples of the resulting dynamics. The mathematical tools are the theory of Large Deviations, Itô stochastic calculus, and the theory of Volterra equations.

This work has been published in [12].

Pros and Cons of Mean Field Representations of Large Size Networks of Spiking Neurons

Participants: Olivier Faugeras, Romain Veltz.

We have laid out a roadmap for classifying the behaviors of large ensembles of networks of spiking neurons through the analysis of the corresponding nonlinear Fokker-Planck equation. Rather than using this equation to simulate the network equations, we apply advanced methods for analyzing the bifurcations of its solutions. This analysis can then be used to predict the behaviors of the original network. We have used the example of a fully connected network of N Fitzhugh-Nagumo neurons with electrical and chemical synapses to convey the interest of our approach.

A manuscript is being written for submission to a journal.

Analysis of a Mean-field Limit of Interacting Two-dimensional Nonlinear Integrate-and-fire Neurons

Participants: Romain Veltz.

We study in this work [28] the solutions of a McKean-Vlasov stochastic differential equation (SDE) driven by a Poisson process. In neuroscience, this SDE models the mean field limit of a system of N interacting excitatory neurons, with N large. Each neuron spikes randomly with a rate depending on its membrane potential. At each spiking time, the neuron potential is reset to the value \bar{v} , its adaptation variable is incremented by \bar{w} and all other neurons receive an additional amount J/N of potential after some delay where J is the connection strength. Between jumps, the neurons drift according to some two-dimensional ordinary differential equation with explosive behavior. We prove the existence and uniqueness of solutions of a heuristically derived mean-field limit of the system when $N \rightarrow \infty$. We then study the existence of stationary distributions and provide several properties (regularity, tail decay, etc.) based on a Doeblin estimate using a Lyapunov function. Numerical simulations are provided to assess the hypotheses underlying the results.

These results set the basis for the rigorous study of mean-field models of stochastic networks of neurons, each described with an adaptive exponential integrate-and-fire model, whose use is widespread in whole brain models.

Mean-field Analysis of a Neural Network with Stochastic STDP

Participants: Pascal Helson (*Université de Bordeaux*), Etienne Tanré, Romain Veltz.

In this work [25], we study neural networks with stochastic synaptic plasticity.

Analyzing biological spiking neural network models with synaptic plasticity has proven to be challenging both theoretically and numerically. In a network with N all-to-all connected neurons, the number of synaptic connections is on the order of N^2 , making these models computationally demanding. Furthermore, the intricate coupling between neuron and synapse dynamics, along with the heterogeneity generated by plasticity, hinder the use of classic theoretical tools such as mean-field or slow-fast analyses to study the dynamics of the plastic network. To address these challenges, we study a stochastic spike-timing-dependent plasticity (STDP) model of connection in a probabilistic Wilson-Cowan spiking neural network model, which features binary neural activity. Taking the large N limit, we obtain a simplified yet accurate representation of the original spiking network. Our approach not only reduces computational complexity but also provides insights into the dynamics of this spiking neural network with plasticity. The model obtained is mathematically exact and capable of tracking transient changes. This analysis marks the first exploration of the dynamics, of McKean-Vlasov type, in a network of spiking neurons interacting with STDP.

6.2.3 Clinical applications

Optimization of Brain Models to Simulate the Effects of Anesthesia

Participants: Parker Rice, Evgenia Kartsaki, Samuel Deslauriers-Gauthier, Rodrigo Cofre.

Various whole-brain computational models have recently been developed to explore brain mechanisms. This project focuses on optimizing the parameters of a model designed to simulate the effects of anesthesia on brain networks. Building on an existing approach based on biophysical mean-field models that incorporate membrane conductances and synaptic receptors, the goal is to adjust the model parameters to best match experimental data.

Transcranial Direct Current Stimulation Modulates Primate Brain Dynamics Across States of Consciousness

Participants: Guylaine Hoffner (*Cognitive Neuroimaging Unit, CEA, INSERM, Université Paris-Saclay, NeuroSpin Center, Gif-sur-Yvette, France*), Pablo Castro (*Institute of Neuroscience (NeuroPSI), Paris-Saclay University, CNRS, Gif-sur-Yvette, France*), Lynn Uhrig (*Department of Anesthesiology and Critical Care, Necker Hospital, AP-HP, Université Paris Cité, Paris, France*), Camilo Miguel Signorelli (*Department of Computer Science, University of Oxford, Oxford, United Kingdom*), Morgan Dupont (*Cognitive Neuroimaging Unit, CEA, INSERM, Université Paris-Saclay, NeuroSpin Center, Gif-sur-Yvette, France*), Jordy Tasserie (*Center for Brain Circuit Therapeutics, Department of Neurology, Brigham & Women’s Hospital, Harvard Medical School, Boston, USA*), Alain Destexhe (*Institute of Neuroscience (NeuroPSI), Paris-Saclay University, CNRS, Gif-sur-Yvette, France*), Rodrigo Cofre, Jacobo Sitt (*Sorbonne Université, Institut du Cerveau – Paris Brain Institute (ICM), Inserm, CNRS, Paris, France*), Béchir Jarraya (*Cognitive Neuroimaging Unit, CEA, INSERM, Université Paris-Saclay, NeuroSpin Center, Gif-sur-Yvette, France*).

The resting primate brain is traversed by spontaneous functional connectivity patterns that show striking differences between conscious and unconscious states. Transcranial direct current stimulation (tDCS), a non-invasive neuromodulatory technique, can improve signs of consciousness in disorders of consciousness (DOCs); however, can it influence both conscious and unconscious dynamic functional connectivity? We investigated the modulatory effect of prefrontal cortex (PFC) tDCS on brain dynamics in awake and anesthetized non-human primates using functional MRI. In awake macaques receiving either anodal or cathodal tDCS, we found that cathodal stimulation robustly disrupted the repertoire of functional connectivity patterns, increased structure–function correlation (SFC), decreased Shannon entropy, and favored transitions toward anatomically based patterns. Under deep sedation, anodal tDCS significantly altered brain pattern distribution and reduced SFC. The prefrontal stimulation also modified dynamic connectivity arrangements typically associated with consciousness and unconsciousness. Our findings offer compelling evidence that PFC tDCS induces striking modifications in the fMRI-based dynamic organization of the brain across different states of consciousness. This study contributes to an enhanced understanding of tDCS neuromodulation mechanisms and has important clinical implications for DOCs.

This work has been published in [13].

A Mesoscale Framework for Psychedelic Drug Action in the Human Brain

Participants: Rui Dai (*Michigan Psychedelic Center, University of Michigan Medical School, Ann Arbor, MI, USA*), Rodrigo Cofre, Christopher Timmermann (*UCL Centre for Consciousness Research, Department of Experimental Psychology, University College London, London, United Kingdom*), Robin L Carhart-Harris (*Departments of Neurology and Psychiatry, University of California, San Francisco, San Francisco, CA, USA*), Anthony G Hudetz (*Department of Anesthesiology, University of Michigan Medical School, Ann Arbor, MI, USA*), Zirui Huang (*Center for Consciousness Science, University of Michigan Medical School, Ann Arbor, MI, USA*), George A Mashour (*Department of Anesthesiology, University of Michigan Medical School, Ann Arbor, MI, USA*).

The mechanism of psychedelic drug action is a dynamic area of neuroscience, with two major lines of investigation: (1) laboratory studies at the molecular and cellular level, and (2) human neuroimaging studies of functional brain networks. Despite considerable progress, there remains insufficient understanding of the link between molecular/cellular substrates of psychedelics and the whole-brain network effects that result. In this work, we report a study of psychedelic action that focuses on the intermediate spatial scale of local brain

regions ($<1 \text{ cm}^3$). We analyzed the effects of classical psychedelics (dimethyltryptamine [DMT], lysergic acid diethylamide [LSD], psilocybin) and non-classical psychedelics (nitrous oxide, ketamine) in humans using functional magnetic resonance imaging. We found that all five drugs reduced regional homogeneity, that is, they disrupted local synchrony, in small-scale brain regions; this disruption occurred extensively in cortical regions and sparsely in subcortical regions. Dynamic analysis of both regional homogeneity and global functional connectivity showed an inverse pattern, with large-scale functional connectivity being enhanced as local synchrony declined. We then conducted dominance analysis to assess the contribution of various neurotransmitter receptors to changes in regional homogeneity. DMT, LSD, and psilocybin showed the 5-HT receptors as the most dominant association; by contrast, regional homogeneity changes attributable to both nitrous oxide and ketamine were most strongly associated with the NMDA receptor. Both neuronal (including interneurons) and non-neuronal cell types were linked to psychedelic-induced changes in synchrony at the level of local brain regions. These data, across five drugs from two drug classes, provide evidence that a diverse set of molecular and cellular events lead to a common outcome of disrupted synchrony in local brain regions, which in turn mediate drug-specific changes in global functional connectivity effects.

This work is available as a preprint [24].

6.3 Group Level (see Section 3.3)

Alignment of Brain Networks

Participants: Yanis Aeschlimann, Samuel Deslauriers-Gauthier, Théodore Papadopoulo, Anna Calissano (*University College of London*).

Every brain is unique, having its structural and functional organization 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 project questions such an assumption: can the structural and functional properties of a specific region of an atlas be assumed to be the same across subjects? In this work, 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. Structural connectivity is one view of brain networks provided by dMRI, but these networks can also be observed from a functional point of view via fMRI. We thus propose to simultaneously exploit structural and functional information in the alignment process. This allows us to explore multiple perspective of brain networks. Our results show that the permutations induced by one type of connectivity (structural, functional) are not always supported by the other connectivity network, but when considering a combined alignment, it is possible to find permutations of regions which are supported by both connectome modalities, leading to an increased similarity of functional and structural connectivity across subjects.

This work has been published in [9, 22] and in the thesis of Yanis Aeschlimann [21].

6.4 Other Results

We report here results either obtained in the framework of the team that preceded Cronos and that are only published now, or works that do not fit well with the main team objectives.

Investigating the Cognitive Drivers of Auditory Attention Detection

Participants: Joan Belo, Maureen Clerc, Daniele Schön (*Institut de Neurosciences des Systèmes*).

While M/EEG-based Auditory Attention Detection (AAD) can identify which audio stream a user is focusing on, performance varies significantly between individuals. This work investigated the hypothesis that executive functions—specifically sustained attention, working memory, and attentional inhibition—underlie

this variability. We designed a challenging paradigm using dichotic polyphonic piano excerpts presented to 41 participants with varying musical expertise.

Our results demonstrate that attentional inhibition is a significant predictor of AAD performance, explaining 6% of reconstruction accuracy and 8% of classification accuracy. Surprisingly, neither musical expertise nor other executive functions showed a significant impact. These findings indicate that cognitive control mechanisms directly affect the robustness of neural auditory representations, providing crucial insights for the development of next-generation, neuro-steered hearing aids.

This work was published in [10].

Improving Generative Fairness in VAEs on Imbalanced Data

Participants: Aymene Mohammed Bouayed (*Be-Ys Research*), Samuel Deslauriers-Gauthier, Adrian Iaccovelli (*Be-Ys Research*), David Naccache (*DIENS, ENS, CNRS, PSL University*).

Variational Autoencoders (VAE) utilizing global priors typically mirror the class frequencies of the training set within the latent space. This characteristic leads to the underrepresentation of tail classes and reduced generative fairness when applied to imbalanced datasets. While existing methods improve robustness via heavy-tailed Student's t-distribution priors, they continue to allocate latent volume proportionally to class frequency.

In this work, we address this limitation by explicitly enforcing equitable latent space allocation. We propose Conditional-VAE, a method that defines a per-class Student's t joint prior over latent and output variables to prevent dominance by majority classes. The model is optimized using a closed-form objective derived from the β -power divergence. Furthermore, to ensure class-balanced generation, we derive an equal-weight latent mixture of Student's t-distributions. Experimental results on standard databases (SVHN-LT, CIFAR100-LT, and CelebA) demonstrate that Conditional-VAE consistently achieves lower Fréchet inception distance scores than both VAE and Gaussian-based VAE baselines, particularly under severe class imbalance. In per-class F1 evaluations, the proposed approach substantially improves generative fairness and diversity compared to conditional Gaussian VAEs in highly imbalanced regimes.

This work is available as a preprint [23].

CNN Explainability with Multivector Tucker Saliency Maps for Self-Supervised Models

Participants: Aymene Mohammed Bouayed (*Be-Ys Research*), Samuel Deslauriers-Gauthier, Adrian Iaccovelli (*Be-Ys Research, France*), David Naccache (*DIENS, ENS, CNRS, PSL University*).

Interpreting the decisions of Convolutional Neural Networks (CNN) is essential for understanding their behavior, yet it remains a significant challenge, particularly for self-supervised models. Most existing methods for generating saliency maps rely on reference labels, restricting their use to supervised tasks. The EigenCAM approach is the only notable label-independent alternative, leveraging singular value decomposition to generate saliency maps applicable across CNN models, but it does not fully exploit the tensorial structure of feature maps. In this work, we introduce the Tucker Saliency Map (TSM) method, which applies Tucker tensor decomposition to better capture the inherent structure of feature maps, producing more accurate singular vectors and values. These are used to generate high-fidelity saliency maps, effectively highlighting objects of interest in the input. We further extend EigenCAM and TSM into multivector variants—Multivec-EigenCAM and Multivector Tucker Saliency Maps (MTSM)—which utilize all singular vectors and values, further improving saliency map quality. Quantitative evaluations on supervised classification models demonstrate that TSM, Multivec-EigenCAM, and MTSM achieve competitive performance with label-dependent methods. Moreover, TSM enhances interpretability by approximately 50% over EigenCAM for both supervised and self-supervised models. Multivec-EigenCAM and MTSM further advance state-of-the-art interpretability performance on self-supervised models, with MTSM achieving the best results.

This work has been published in [11].

7 Bilateral contracts and grants with industry

7.1 Bilateral contracts with industry

FinalSpark: collaborative research agreement - 2024-2028

Participants: Patricia Reynaud-Bouret (*DR CNRS, LJAD*), Paula Pousinha (*MCF, IPMC*), Ingrid Bethus (*PR, IPMC*), Evgenia Kartsaki, Gilles Scarella (*IG, CNRS, LJAD*), Gregorio Rebecchi (*PhD student, LJAD*), Romain Veltz.

This is a collaborative research agreement on the study of the “deformation of the neuronal network by synaptic plasticity”. G. Rebecchi is a Ph.D. student, since October 1st, 2024 under the supervision of P. Reynaud-Bouret and I. Bethus on the topic described above. This PhD is funded by CNRS and by FinalSpark.

1. **Description of the transfer.** *Knowledge transfer.* This is a **collaborative research agreement** between **FinalSpark**, Université Côte d’Azur, Inria and CNRS. The Parties wishes to collaborate in order to understand more precisely the synaptic connectivity of the neurospheres and how it can be manipulated.
2. **Transfer modalities.** It is based on a contract. The study is on-going.
3. **Contribution.** R. Veltz is one of the parties on the contract as an expert in dynamical systems and synapses models.

7.2 Bilateral Grants with Industry

Demagus: BPI Grant April 2022–September 2025

Participants: Laura Gee, Éléonore Haupaix-Birgy, Noémie Gonnier, Côme Le Breton, Théodore Papadopoulos, Julien Wintz.

This grant has been obtained with the startup Mag4Health, CNRS and INSERM (see Section 3.1.3). This company develops a new MEG machine working with optically pumped magnetometers (magnetic sensors), which potentially means lower costs and better measurements. CRONOS is in charge of developing a real time interface for signal visualization, source reconstruction and epileptic spikes detection. The initial funding was for 2 years, but three extensions of 6 months have been obtained. This work is related to the research goals described in Section 3.1.3.

8 Partnerships and cooperations

8.1 International initiatives

SynPlasTool

Participants: Romain Veltz, Hélène Marie (*IPMC*).

Title: Development of the Synapse Plasticity Tool for prediction of synapse plasticity outcome in silico.

Coordinator Name : Hélène Marie

Partner Institution: IPMC

Date/Duration: 2024-2026

SynPlasTool is funded by FC3R, obtained in collaboration with H. Marie (IPMC), 37500 euros. The main goal is to make easily accessible (web platform, ...) to experimentalists the model that we developed [10.7554/eLife.80152](#). It is mainly a programming project that relies on the software described in [5.1.5](#).

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

MUSCULAR (Inria London Programme)

Participants: Samuel Deslauriers-Gauthier.

Coordinator Name : Samuel Deslauriers-Gauthier

Partner Institution: Imperial College London

Date/Duration: 2023-2025

Web site

During its third year, the associated team MUSCULAR (Inria London Programme) continued its effort on developing novel algorithms to estimate motor unit spike trains from surface electromyography (EMG). Two different approaches are pursued in parallel: electrode location optimization and physics-informed inverse problems.

Electrode optimization: The first approach is based on the idea that the electrode configuration is not optimized and leads to variations in sensitivity across populations. For example, the number of identified motor neurons is typically larger in males than females. We also observe variations in sensitivity across target muscle groups within a single individual. Using the forward models developed during the first year, we generated highly realistic EMG signals, using our previously developed myoelectric digital twin [8], representing a large population of individuals with varying anatomical features. The large amount of data generated allowed us to globally optimize electrode design for specific populations (females/males) or for specific muscle architectures (e.g. pennate v.s. fusiform). The strength of this approach is to leverage highly realistic simulations to optimize over a large population whose EMG signals would be unfeasible to acquire in vivo (potentially thousands of individuals).

Physics informed inverse problems: The second approach leverages volume conductor knowledge to enhance the estimation of motor unit spike trains. Using anatomical MRI data of the forearm — acquired in various positions during the first year with optimized sequences — the team has constructed physically realistic forward models for EMG in two subjects. We are now investigating the theoretical aspects of the problem, building on our expertise in electroencephalography (EEG). One of the challenges we have investigated is the inclusion of the known temporal components of EMG, which are typically unknown in EEG.

The members of MUSCULAR also submitted an EIC Pathfinder proposal which was rated excellent (4.75 / 5.00), but unfortunately not funded. Given this excellent feedback, we have started improving the proposal for resubmission in early 2026.

While this is the last year of the associated team, we have secured funding for a student exchange which ensure the teams will continue collaborating into 2026.

8.2 International research visitors

8.2.1 Visits of international scientists

- In September, L. Florack and L. Smolders from Eindhoven Technological University visited the team to discuss their work on geodesic tractography and brain structure–function mapping.
- P. Ford-Dominey visited the team on several occasions to discuss input-driven functional connectivity. These discussion led to an ANR proposal currently in review.

8.3 National initiatives

ANR ChaMaNe, Mathematical Challenges in Neurosciences

Participants: Romain Veltz.

Coordinator Name : Delphine Salort (Sorbonne Université)

Partner Institutions:

- Partner 1: Biologie Computationnelle et Quantitative (CQB), France
- Partner 2: LJAD, Université Nice, France

Date/Duration: 2020-2025

Web site

This project aimed at a mathematical study, on the one hand, of the intrinsic dynamics of a neuron and their consequences, and on the other hand, of the qualitative dynamics of large neural networks with respect to the intrinsic behavior of the individual neurons, the interactions between them, memory effects, spatial structure, etc.

FHU InnovPain 2

Participants: Petru Isan, Théodore Papadopoulo, Romain Veltz.

Coordinator Name : Denys Fontaine (Pasteur Hospital)

Date/Duration: 2023–2027

Web site

The FHU INOVRAIN is a Hospital-University Federation focused on chronic refractory pain and innovative therapeutic solutions. It involves 6 hospital facilities, 13 academic research teams and 12 platforms and core facilities.

Inria-Inserm fellowship

Participants: Laura Gee, Théodore Papadopoulo, Christian Bénar.

Date/Duration: 2024–2027

The Ph.D. of L. Gee is funded by an Inria-Inserm fellowship (see section 6 for a description of the work).

ANR NeuroMotor

Participants: Samuel Deslauriers-Gauthier.

Coordinator Name : François Hug (LAMHESS, Université Côte d'Azur)

Date/Duration: 2024–2027

There are many physical disabilities with a neurological origin, such as stroke and spinal cord injuries, that significantly impact a person's mobility, physical capacity, stamina, or dexterity. In the era of personalized medicine, optimizing the treatment of these physical disabilities requires: i) accessing direct information on the neural commands that are sent to the muscles, and ii) integrating this knowledge into the development and assessment of rehabilitation and neurotechnology aimed at restoring movement. The breakthrough of our approach lies in changing the level at which we observe the control of movement, i.e., shifting focus from the level of whole muscles to the spinal (alpha) motor neurons. To achieve this, we will combine the use of dense grids of surface EMG electrodes with algorithms that decode the firing activity of spinal motor neurons. By unraveling the "neural code" for movement generation, we will address critical gaps in our understanding of the control of movement in health and disease. In this project, we will decode the activity of large populations of motor neurons from different muscles. We will identify motor neuron synergies, defined as functional groups of motor neurons that share inputs from various supraspinal, spinal and sensory sources. In this translational project, we will examine the structure and plasticity of these synergies in both healthy controls and patients with neurological impairments (stroke, spinal cord injury). We will also enhance the electrode design to facilitate the transfer of these methods into clinical settings.

ANR spinPAIN-PATH

Participants: Romain Veltz.

Coordinator Name : Emmanuel Deval (IPMC, Université Côte d'Azur)

Date/Duration: 2025–2029

The main objective of this project is to better understand spinal pain processes, which still remain to be fully deciphered. It will focus on the role of particular ion channels, Acid-Sensing Ion Channels (ASICs), highly expressed in the spinal pain neuronal network but where their functions have yet to be fully elucidated. Indeed, if their role in pain has been largely documented in peripheral sensory neurons, far less is known in the central nervous system (CNS), particularly at the spinal cord level. This project is based on preliminary data, demonstrating (i) a large expression of particular ASIC subunits in spinal neurons both in mouse and human, and (ii) a potent analgesic effect of specific ASIC blockers injected intrathecally in mice. Importantly, the *in vivo* analgesic effect observed in mice with the ASIC1a inhibitor, mambalgin-1, can be as strong as that of morphine and partially independent of the endogenous opioid system, opening new potential therapeutic perspectives in a context of world opioid crisis. In line with the preliminary data, the specific aims are 1) to localize the different ASIC subunits in the different neuronal populations and characterize their association in the spinal dorsal horn (SDH) of both mice and humans, 2) to assess their overall contribution to the SDH network activity by combining *in vitro* primary culture model with computational modeling and, 3) to explore the *in vivo* and *ex vivo* contribution of spinal ASICs to long-term sensitization processes, with a particular focus on inhibitory interneurons, in neuropathic pain condition, which needs new therapeutic perspectives and where spinal ASICs have been already involved.

8.4 Regional initiatives

NeuroMod

Participants: Rodrigo Cofre Torres, Samuel Deslauriers-Gauthier, Olivier Faugeras, Evgenia Kartsaki, Théodore Papadopoulo, Romain Veltz.

Direction: T. Papadopoulo and I. Bethus.

Web site.

The NeuroMod Institute for Modeling in Neuroscience and Cognition aims at promoting modeling as an approach for integrating brain mechanisms and cognitive functions. To meet this central challenge of integration in cognitive science, the institute relies on the interdisciplinary resources available within the Université Côte d'Azur: more than 250 researchers and 16 laboratories.

Université Côte d'Azur encourages interaction between human sciences (psychology, behavioral economics, language sciences), modeling (computer science, mathematics, physics, etc.) and neuroscience (biology, neurophysiology, cognitive neuroscience, medicine, etc.). NeuroMod is unique because of the variety of approaches used to integrate different models at multiple levels, from neurons and their molecular mechanisms, to cognitive processes and behaviors, through neural network dynamics.

NeuroMod also provides interdisciplinary training for Master students, PhD students and future faculty members. We opened an international elite degree in Modeling for Neuronal and Cognitive Systems (Master of Science Mod4NeuCog) and a national Master's degree in Cognitive Science.

CRONOS is deeply involved in this regional initiative through its researchers, but also through its engineer E. Kartsaki, who devotes part of its time to software projects of the institute.

PSI ion channels

Participants: Théodore Papadopoulo, Romain Veltz.

Coordinator Name : M. Mantegazza, E. Lingueglia (IPMC, Université Côte d'Azur)

Date/Duration: 2025–2031

The Programme Stratégique IdEx (PSI) Ion Channels capitalizes on Université Côte d'Azur's teams already present in former LABEX ICST 1.0 and 2.0 projects (F. Lesage, M. Mantegazza, E. Lingueglia & E. Deval, and E. Honoré from IPMC, G. Sandoz from iBV and L. Counillon from LP2M) to include new teams (from IPMC (H. Marie/J. Barik, M. Chami/A. DaCosta, P. Blancou/T. Simon) and iBV (O. Soriani), strengthening basic and translational research in biology, but also from Inria (T. Papadopoulo) and the J. A. Dieudonné laboratory (P. Reynaud-Bouret) for mathematical modeling, and UR2CA (D. Fontaine/M. Lanteri-Minet) for clinics) in order to fully exploit the University's strengths and extend its scope to build a multidisciplinary approach targeting the pathophysiology of ion channels and excitability⁵.

The PSI has several objectives:

- Train PhD students offering competitive PhD fellowships.
- Boost Université Côte d'Azur's International development and visibility.
- Develop technological innovations.
- Strengthen interaction with industry and the University Hospital.
- Help the evolution of Université Côte d'Azur's teams.

The landscape of the PSI Ion Channels will cover from basic science to translation and innovation through cutting edge techniques (ex vivo & in vivo electrophysiology, neurostimulation, optopharmacology, transcriptomics, high-speed imaging), integrative science (neuroinflammation, mouse and zebrafish models, computational modeling and AI), pathophysiology (pain, migraine, cancer, heart disease, autism, intellectual disabilities, Alzheimer's disease, mental disorders, epilepsy) and therapy (neurostimulation, pharmacology, precision medicine).

9 Dissemination

Participants: Rodrigo Cofre, Rachid Deriche, Samuel Deslauriers-Gauthier, Olivier Faugeras, Théodore Papadopoulo, Romain Veltz.

⁵IPMC: Institut de Pharmacologie Moléculaire et Cellulaire, iBV: Institut de Biologie Valrose, LP2M: Laboratoire de Physiomédecine Moléculaire, UR2CA: Unité de Recherche Clinique Côte d'Azur.

9.1 Promoting scientific activities

9.1.1 Scientific events: organisation

Chair of conference program committees

- Théodore Papadopoulos was in the scientific committee of NeuroMod days 2025.

Reviewer

- Théodore Papadopoulos served for the conferences ICIP, ISBI and CORTICO and for the NeurIPS workshop entitled “Foundation Models for the Brain and Body”⁶.
- Samuel Deslauriers-Gauthier served for the International Conference on Geometric Science of Information (GSI), for the MICCAI workshop CDMRI, and for ISBI.

9.1.2 Journal

Member of the editorial boards

- Olivier Faugeras is the Editor-in-Chief of “Mathematical Neuroscience and Applications” (MNA), published by Episciences.
- Théodore Papadopoulos serves as Associate Editor in “Frontiers: Brain Imaging Methods” and as Review Editor for “Frontiers: Artificial Intelligence in Radiology”.
- Romain Veltz is an Editor for “Mathematical Neuroscience and Applications” (MNA).

Reviewer - reviewing activities

- Théodore Papadopoulos served several international journals (IEEE Transactions on Biomedical Engineering, IEEE Transactions on Neural Systems and Rehabilitation Engineering, Computers in Biology and Medicine, IEEE Transactions on Medical Imaging, IEEE Transactions on Automation Science and Engineering).
- Samuel Deslauriers-Gauthier reviewed for Medical Imaging Analysis (MedIA).
- Rodrigo Cofre reviewed for Cell Reports and Nature Communications.
- Romain Veltz reviewed for the journals SIAM, Stochastic Processes and Applications, PLOS Computational Biology, Journal of Mathematical Imaging and Vision, Mathematical Neurosciences and Applications.

9.1.3 Invited talks

- Romain Veltz, “Theoretical / numerical study of modulated traveling pulses in inhibition stabilized networks”, ANR ChaMaNe, February 2025
- Théodore Papadopoulos “Brain Computer Interfaces. . . a field with many challenges and opportunities”, MOMI workshop, Sophia Antipolis, May 26th, 2025.
- Romain Veltz, “Pros / cons of mean field representations of large size networks of spiking neurons”, CAMDAM workshop, Montreal, Canada, June 4th, 2025.
- Théodore Papadopoulos “Estimating and Exploiting Brain Dynamics”, BMW workshop, Frejus, June 17th, 2025.

⁶ ICIP: International Conference on Image Processing, ISBI: International Symposium on Biomedical Imaging, CORTICO: Collectif pour la Recherche Transdisciplinaire sur les Interfaces Cerveau-Ordinateur, CVPR: Conference on Computer Vision and Pattern Recognition, NeurIPS: Neural Information Processing Systems.

- Romain Veltz, “SYNPLASTOOL : development of a GUI tool for the prediction of synapse plasticity outcome in silico”, Replacement in Neuroscience, November 2025 (online, 700 persons).
- Rodrigo Cofre, “Computational and Neurobiological Modeling of Structure-Function Coupling in Different Consciousness States”, presented at the NeuroMod Meeting 2025, Antibes, July 8th, 2025.
- Samuel Deslauriers-Gauthier presented at the Neuromod Institute Open Day.

9.1.4 Leadership within the scientific community

- Olivier Faugeras is a member of the French Academy of Sciences.
- Rachid Deriche is a member of Academia Europaea.

9.1.5 Scientific expertise

- Théodore Papadopoulo was member of a panel in the ANR-NSF CNS grant selection.
- Théodore Papadopoulo was selected to be a member of a EIC Pathfinder grant selection panel. Due to a conflict of interest, he had to resign.
- Théodore Papadopoulo reviewed project proposals for Université de Toulouse and Université Côte d’Azur.
- Théodore Papadopoulo is the scientific referent of Yuxiu Shao, recently hired at Université Côte d’Azur on a NeuroMod-LJAD CPJ (Chaire de Professeur Junior) position.
- Samuel Deslauriers-Gauthier reviewed project proposals for the Institut des Neurosciences cliniques de Rennes.

9.1.6 Research administration

- Théodore Papadopoulo is the director of the [NeuroMod Institute](#).
- Théodore Papadopoulo is a member of the Neuromod scientific council and represents Neuromod in the EUR Healthy (EUR: University Research School) and in the Maison de la Simulation of Université Côte d’Azur.
- Théodore Papadopoulo is a member of the steering committee of the [IHU RespiERA](#).
- Théodore Papadopoulo is the alternate Inria representative at the CRBSP (Comité de la recherche en matière biomédicale et de santé publique) of the University Hospital of Nice.

9.2 Teaching - Supervision - Juries - Educational and pedagogical outreach

9.2.1 Teaching

- Master: Théodore Papadopoulo *Inverse problems for brain functional imaging*, 3h ETD, M2, Mathématiques, Vision et Apprentissage, ENS Cachan, France.
- Master: Théodore Papadopoulo and Samuel Deslauriers-Gauthier, *Functional Brain Imaging*, each 15h ETD, M1,M2 in the MSc Mod4NeuCog of Université Côte d’Azur.
- Master: Théodore Papadopoulo and Samuel Deslauriers-Gauthier, *Application of machine learning to MRI, electrophysiology & brain computer interfaces*, each 10h ETD, M1, M2 in the MSc Data Science and Artificial Intelligence of Université Côte d’Azur.
- Master: Samuel Deslauriers-Gauthier and Romain Veltz, *Introduction to Python programming and simulation*, each 15h ETD, M1, MSc Mod4NeuCog of Université Côte d’Azur.

- Master: Romain Veltz, *Mathematical methods for neuroscience*, 24h ETD, M2, Mathématiques, Vision et Apprentissage, ENS Cachan, France.
- Master: Rodrigo Cofre, *Scientific Communication*, 24h ETD, M2, MSc Mod4NeuCog of Université Côte d'Azur, France.
- Master: Rodrigo Cofre, *Introduction to modeling in neuroscience and cognition*, 8h ETD, M1, MSc Mod4NeuCog of Université Côte d'Azur, France.
- Master: Rodrigo Cofre, *Digital expertise I*, 8h ETD, M1, MSc SmartEdTech of Université Côte d'Azur, France.
- Master: Rodrigo Cofre, *Digital expertise II*, 8h ETD, M2, MSc SmartEdTech of Université Côte d'Azur, France.

9.2.2 Supervision

- PhD defended in December: Yanis Aeschlimann, "Brain networks from simultaneous modelling of functional MRI and diffusion MRI", started in Oct. 2022. Supervisors: Samuel Deslauriers-Gauthier, Théodore Papadopoulo [21].
- PhD in progress: Petru Isan, "Cerebral electrophysiological exploitation of in vivo evoked potentials to guide the resection of adult brain tumors", started in Oct. 2023. Supervisor: F. Almairac. Co-Supervisors: Théodore Papadopoulo, Samuel Deslauriers-Gauthier.
- PhD in progress: Émeline Manka, "Modeling of evoked potentials by direct current stimulation and their links to electromyography", started in Oct. 2024. Supervisors: Samuel Deslauriers-Gauthier, Théodore Papadopoulo.
- PhD in progress: Laura Gee, "Exploring and exploiting the new capabilities of room temperature MEG sensors", started in Dec. 2024. Supervisors: Théodore Papadopoulo, C.Bénar (INSERM, Marseille).
- PhD in progress: A. Bouayed, "Fast, interpretable and fair image generation on imbalanced data", to be defended in March 2026. Supervisors: D. Naccache, A. Iaccovelli, Samuel Deslauriers-Gauthier.
- PhD in progress: P. Castro, "New approaches in modeling and fMRI data analysis of the brain in different states of consciousness", to be defended in September 2027. Supervisors: B. Jarraya (NeuroSpin, Paris), A. Destexhe (NeuroPsi, Paris), Rodrigo Cofre.
- Romain Veltz supervised the M2 student A. Ackay on "Bifurcation Theory in Whole-Brain Models: Exploring Cortical Dynamics for Wake and Sleep State Transitions", November 2024 to February 2025.
- Samuel Deslauriers-Gauthier and Romain Veltz supervised the M2 internship (InterMaths Network) of H. Harshit on "A Finite Volume Framework for Probabilistic Tractography", April 2025 to August 2025.
- Samuel Deslauriers-Gauthier and Rodrigo Cofre supervised the M2 internship (MSc Mod4NeuCog of Université Côte d'Azur) of P. Rice on "Optimization of whole brain models to simulate the effect of anesthesia".
- Samuel Deslauriers-Gauthier supervised the M2 internship (MSc Mod4NeuCog of Université Côte d'Azur) of T. Stei on "Predicting task-related functional connectivity from structural connectivity".
- Théodore Papadopoulo supervised the M2 student J. Feriau on "Uncertainty propagation: From electroencephalogram measurements to BCI classification".
- Rodrigo Cofre supervised the M1 student D. Zuniga on "Dynamical Structure-Function Correlations of fMRI Human Brain Signals under LSD".
- Samuel Deslauriers-Gauthier supervised the M1 internship (MSc Mod4NeuCog of Université Côte d'Azur) of M. Shaw on "Inverse problems in electromyography (EMG)".

9.2.3 Juries

- Olivier Faugeras was a member of several committees awarding prizes from the French Academy of Sciences.
- Théodore Papadopoulo participated as a reviewer in the PhD jury of I. Siviero at Université of Verona on June 19th, 2025.
- Théodore Papadopoulo participated as a reviewer in the PhD jury of S. Reynaud at IMT Atlantique in Brest on September 29th, 2025.
- Théodore Papadopoulo participated as a reviewer in the PhD jury of H. Agouram at University of Aix-Marseille on December 9th, 2025.
- Théodore Papadopoulo and Samuel Deslauriers-Gauthier participated in the PhD jury of Y. Aeschlimann at Université Côte d'Azur on December 15th, 2025.
- Romain Veltz participated in the PhD jury of A. Rossi at Université Côte d'Azur on September 25th, 2025.
- Samuel Deslauriers-Gauthier participated in the PhD jury of L. Smolders at Eindhoven University of Technology on January 12th, 2025.
- Samuel Deslauriers-Gauthier was part of the M2 jury for the MSc Mod4NeuCog of Université Côte d'Azur.
- Rodrigo Cofre participated in the Comité de suivi de thèse (CST) of I. Mindlin: PhD student at the Sorbonne University (ED3C Cerveau - Cognition - Comportement), PhD under the direction of J. Sitt, ICM Paris.
- Rodrigo Cofre participated in the CST of C. Picard: PhD student at the Paris-Saclay University (École doctorale Biosigne), under the direction of V. Ego-Stern, NeusoPsi Saclay.
- Rodrigo Cofre participated in the CST of L. Martineau: PhD student at IRMA Strasbourg University (École doctorale Mathématiques, Sciences de l'information et de l'ingénieur), under the direction of S. Geffray et C. Pouzat.
- Rodrigo Cofre participated in the CST of T. Hardy: PhD student at Université Paris-Cité (INCC UMR 8002, CNRS, 75006 Paris), under the direction of C. Sergent.
- Théodore Papadopoulo participated in the CST of L. Abdalah: PhD student at Université Côte d'Azur, under the direction of V. Zarzoso and W. Da Cruz Freitas.
- Romain Veltz participated in the CST of A. Bavoil: PhD student at Université Côte d'Azur, under the direction of J.B. Caillay and A. Nême.
- Romain Veltz participated in the CST of P. Izan: PhD student at Université Côte d'Azur, under the direction of F. Almairac and Samuel Deslauriers-Gauthier.
- Romain Veltz participated in the CST of G. Rebecchi: PhD student at Université Côte d'Azur, under the direction of P. Reynaud-Bouret and I. Bethus.

9.3 Popularization

9.3.1 Specific official responsibilities in science outreach structures

- Romain Veltz is Science Outreach Officer at the Inria Centre at Université Côte d'Azur since 2025. He was responsible for the **Chiche program**, organized the Café'In, coordinated Intro, and ran the one-week MATHC2+ internship for 10th-grade students.

9.3.2 Participation in Live events

- Romain Veltz has given a one hour conference to the Fête de la Science at Juan-les-Pins in front of a general audience on October 11th, 2025.
- Rodrigo Cofre has given a one hour talk at Café'In INRIA "Explorer la conscience avec des drogues : De l'anesthésie générale aux psychédéliques en thérapie? " on April 24th, 2025.
- Rodrigo Cofre has given a one hour conference to the Fête de la Science at Juan-les-Pins in front of a general audience on October 10th, 2025.
- Romain Veltz gave 8 chiches (one hour each) to 10th-grade students.
- Théodore Papadopoulo and I. Bethus gave an [interview at BFM TV Côte d'Azur](#) in the contexts Brain's week and NeuroMod.

10 Scientific production

10.1 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](https://doi.org/10.1088/1741-2552/ab8b2b). URL: <https://inria.hal.science/hal-02945585> (cit. on p. 15).
- [2] C. Bénar, T. Papadopoulo, B. Torrèsani and M. Clerc. 'Consensus Matching Pursuit for multi-trial EEG signals'. In: *Journal of Neuroscience Methods* 180.1 (May 2009), pp. 161–170. DOI: [10.1016/j.jneumeth.2009.03.005](https://doi.org/10.1016/j.jneumeth.2009.03.005). URL: <https://inria.hal.science/hal-04391937> (cit. on p. 9).
- [3] I. Carrara and T. Papadopoulo. 'Classification of BCI-EEG based on augmented covariance matrix'. In: *IEEE Transactions on Biomedical Engineering* 71.9 (9th Sept. 2024), pp. 2651–2662. DOI: [10.1109/TBME.2024.3386219](https://doi.org/10.1109/TBME.2024.3386219). URL: <https://hal.science/hal-03977680>. In press (cit. on p. 15).
- [4] 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* (15th July 2019). DOI: [10.1016/j.neuroimage.2019.116017](https://doi.org/10.1016/j.neuroimage.2019.116017). URL: <https://inria.hal.science/hal-02187859> (cit. on pp. 9, 10).
- [5] S. Deslauriers-Gauthier, M. Zucchelli, M. Frigo and R. Deriche. 'A Unified Framework for Multimodal Structure-function Mapping Based on Eigenmodes'. In: *Medical Image Analysis* (20th Aug. 2020), p. 22. DOI: [10.1016/j.media.2020.101799](https://doi.org/10.1016/j.media.2020.101799). URL: <https://inria.hal.science/hal-02925913> (cit. on p. 9).
- [6] S. Hitziger, M. Clerc, S. SAILLET, C. Bénar and T. Papadopoulo. 'Adaptive Waveform Learning: A Framework for Modeling Variability in Neurophysiological Signals'. In: *IEEE Transactions on Signal Processing* 65 (15th Aug. 2017), pp. 4324–4338. DOI: [10.1109/TSP.2017.2698415](https://doi.org/10.1109/TSP.2017.2698415). URL: <https://inria.hal.science/hal-01548428> (cit. on p. 9).
- [7] J. Kybic, M. Clerc, T. Abboud, O. Faugeras, R. Keriven and T. Papadopoulo. 'A common formalism for the Integral formulations of the forward EEG problem'. In: *IEEE Transactions on Medical Imaging* 24.1 (Jan. 2005), pp. 12–28. DOI: [10.1109/tmi.2004.837363](https://doi.org/10.1109/tmi.2004.837363). URL: <https://inria.hal.science/hal-04389249> (cit. on p. 9).
- [8] K. Maksymenko, A. K. Clarke, I. Mendez Guerra, S. Deslauriers-Gauthier and D. Farina. 'A Myoelectric Digital Twin for Fast and Realistic Modelling in Deep Learning'. In: *Nature Communications* 14.1 (23rd Mar. 2023), p. 1600. DOI: [10.1038/s41467-023-37238-w](https://doi.org/10.1038/s41467-023-37238-w). URL: <https://inria.hal.science/hal-04390364> (cit. on p. 25).

10.2 Publications of the year

International journals

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