# Master 2
# Computational Neuroscience and Neuroengineering
# (M2 CNN)

**Facts & Figures**

Degree: Master of Life Sciences and Health (MSc)

Duration: 1 year (60 EC), full time

Start month(s): september 2020

Language of instruction: English

Enrolled students: 30 students start the Master's programme per year

Classes hours: 15-20 hours per week

Master's legal tuition fee 2020-2021: In 2019-2020, the total Tuition fees were 334 € per academic year for Master's studies for all students. Fees for academic year 2020-21 will be published early in 2020.

Apply here: *https://inception.universite-paris-saclay.fr/en/*

## Master in Computational Neuroscience and Neuroengineering

One of the greatest challenges of modern science is to understand how the brain processes information in order to imitate its computing and learning capabilities (Artificial Intelligence, neuromorphic electronic circuits, machine learning,...) and to compensate the brain failures with computational and technological tools (Closed-Loop Neurosciences, Brain Computing Interface,...).
Thus, the Computational Neurosciences and Neuroengineering Master aims to train students to face problems raised by brain perception, processing and transmission of information. The training program is based on experimental, computational and theoretical approaches, combining neurosciences, physics, applied mathematics and computer sciences at different scales (cell, network, behaviour) and different organizational levels (micro, meso- and macroscopic scales).
Thanks to the reputation of the laboratories and research teams involved, the Master degree offers a very high level courses programme with a high international visibility.

## Goals

The target of this Master program is to present the concepts, technological achievements, methodological approaches and research challenges in computational neurosciences and neuroengineering. It also aims to raise students' awareness of the theoretical, experimental, applicative, entrepreneurial and ethical themes of Neurosciences using the concepts of Physics and Engineering Sciences.
Students have access to an unique interdisciplinary training, enhancing their skills in research, analysis and scientific presentation and developing their ability to work as part of a multidisciplinary team.

## Job opportunities

The CNN Master's degree trains future engineers, researchers and lecturers specialized in Computational Neuroscience and Neuroengineering with an interdisciplinary culture and approaches ranging from theory to experimentation by combining computational methodologies. Engineer jobs and Phd projects in academic, industrial laboratories, integration in R&D departments in France or abroad, represent the main opportunities.

## Courses description

The CNN Master courses programme targets students with a range of backgrounds, including Life Sciences, Computing Science, Mathematics, Physics and Engineering. One part of the courses is focused on the theoretical approaches and the remainder is focused on a research project. Student will achieve the CNN Master with his own skills and interests.

During the first semester, lectures such as the physiological bases of neuroscience, the neural bases of perception, the techniques for measuring and stimulating neural activity, the processing and analysis of neural signals, the dynamical systems and computational neuroscience, will provide the necessary tools to understand the complex phenomena involved in processing and transmitting information in the brain. A supervised scientific project will complete the students' training during the semester one.

Semester two begins with a Master thesis of three to six months. This Master thesis project gives students real research experiences in computational neurosciences and neuroengineering. They will have the opportunity to work closely with a leading research team in the academic laboratories and opportunities will be created to work on industry lead projects. They will benefit from the supervision of experienced researchers. The project can be carried out with a research group at University Paris-Saclay, with an industrial partner or with a research institute in France or worldwide.

**S1 - Semester 1**

| Courses | EC* | Hours |
|---|---|---|
| Physiological bases of neuroscience | 3 | 25 |
| Neural bases of perception | 3 | 25 |
| Dynamical systems and computational neuroscience | 3 | 25 |
| Closed-loop neuroscience | 3 | 25 |
| Methods for measuring and stimulating neuronal activity, principles and applications | 3 | 25 |
| Machine learning | 3 | 25 |
| Supervised project | 12 | 50 |

**S2 - Semester 2**

| | EC | CM | TD | TP |
|---|---|---|---|---|
| Master thesis project | 30 | - | - | - |

*EC: European Credits

## Research environment

The Research institute involved in the Computational Neurosciences and Neuroengineering Master is the Paris-Saclay Institute of Neurosciences (NeuroPSI), a fundamental research institute in Neurosciences focused on the multi-scale approaches of the nervous system, from molecule to cognition and from embryo to adult. It is a Joint Research Unit of the CNRS and the University of Paris-Sud (UMR 9197). Together with NeuroSpin, which is entirely focused on the brain imaging and the study of cognitive processes, it forms the NeuroSaclay organization, which is the Neuroscience component of the Université Paris-Saclay. Students benefit from the emulation, intellectual stimulation, and various experimental and technological platforms of the NeuroPSI Institute and NeuroSpin.

Two departments in particular of NeuroPSI will be involved in the training of students:

- The Cognitive Neurosciences Department, whose purpose is to understand the neural bases of cognitive functions such as perception, communication, decision-making, learning and memory, but also to identify the mechanisms involved in pathologies or alterations in these functions.
- The Department of Integrative & Computational Neurosciences (ICN), whose purpose is to study the brain at multiple scales to identify the computational principles and thalamocortico-cortical neurophysiological mechanisms that govern the emergence of higher brain functions, such as perception and learning. The ICN is also in charge of two international antennas, the French node of the International Coordination Facilities in Neuroinformatics (INCF) and the European Institute for Theoretical Neuroscience (EITN). The ICN is an active participant in the Human Brain Project. It is a major European scientific project that aims to better understand the brain and its pathologies by about 2024, using information science technics (computational neuroscience, neuroinformatics, neuromorphic computation, neuro-robotics, etc.).

CentraleSupélec, one of France's most prestigious engineering schools, as well as its research laboratories, in particular the Signals and Systems Laboratory (UMR8506), which brings together researchers of excellence in signal processing, statistics, machine learning and dynamical systems, is actively involved in the Master. The influence of the lecturers involved in the Master benefits the national and international visibility. The network of foreign collaborators also provides unique opportunities for M2 students in terms of international exchanges and internships abroad.

## Admission requirements

Firstly, the application to the M2 CNN will be made through the submission of an application form on the website of the University of Paris-Saclay.

The applicant is requested to attach to the application form all mandatory supporting documents. He may also complete his application with additional documents that he wishes to bring to the attention of the M2 CNN admission committee.

In a second step, an interview will be proposed to the candidates according to the decision of the admission committee.

The admission to the M2 program concerns candidates with a very good academic record and a strong motivation for the Master CNN program.

Student with level equivalent to Master 1 or Master 2
Student with level equivalent to engineer degree
English level equivalent to B2 certification

## Deadline for application

Applicants must submit a complete application form between 1st February and 15th July.

*Click here for details on the  application process*

## Mandatory supporting documents

- A Curriculum Vitae.
- A letter of application to the M2 CNN training.
- All transcripts of validated years/semesters until the date of application.
- Reference letters.

## Scholarship application :

Master student can apply to the scholarship provided by the Université Paris-Saclay.
https://www.universite-paris-saclay.fr/en/programme-de-bourses-internationales-de-master

## Potential laboratories for the Master thesis :

Institut de Neurosciences Paris-Saclay (NeuroPSI), Université Paris-Saclay
Centre de recherches NeuroSpin du CEA
Laboratoire des Signaux et Systèmes de CentraleSupélec, Université Paris-Saclay
INRIA Sophia-Antipolis
Centre de Recherche Cerveau & Cognition, Université de Toulouse 3
Laboratoire Plasticité du Cerveau, ESPCI
Institut des Sciences Cognitives Marc Jeannerod, Université de Lyon 1
Institut de Neurobiologie de la Méditerranée, Université d'Aix-Marseille
Institut des Neurosciences de la Timone, Université d'Aix-Marseille
Laboratoire de Neurosciences Cognitives Computationnelles, ENS
Institut de la Vision, Université Pierre et Marie Curie
Laboratoire de Physique Statistique, ENS
Laboratoire des Systèmes Perceptifs, ENS
Institut du Cerveau et de la Moelle épinière, Université Pierre et Marie Curie
Centre Interdisciplinaire de Recherche en Biologie, Collège de France
…

## Contact

Do you have any questions about the Master CNN?

Please contact the Master's coordinator :
Professor Sabir Jacquir
Email : sabir.jacquir@u-psud.fr

## Master 2
## CNN : Computational Neuroscience and Neuro-Engineering

## Description of teaching units

### UE 1: Physiological bases of neuroscience (CM: 25h)

Coordinator: Sabir Jacquir

1) Goals
This course will focus on the study of the brain, its functions and its adaptability (brain plasticity) to the environment. The latest knowledge on the molecular and physiological basis of synapse and neuron function will be presented. At a more macroscopic level, the anatomy and structure of the brain will be addressed. The neural processes responsible for processing sensory information and perception, as well as their short- and long-term regulation through interaction with the environment, will be described.

2) Course program

- Chapter 1: Issues and questions in neuroscience

In this chapter, the current challenges and issues in neuroscience will be presented.

- Chapter 2: Development of the nervous system

This chapter will present the development of the nervous system from fertilization to brain formation, neurogenesis, axonal guidance, synaptogenesis and maturation of neural networks. It is about understanding the generation of large regions of the brain and the different brain functions associated with them.

- Chapter 3: Nervous system organization: from neuron to network, transmission of the nervous signal

This chapter will present the general organization and cellular components of the nervous system. Excitation and inhibition circuits as well as the structure of neural networks are introduced and studied. It describes the elementary principles involved in the generation of an action potential and communication between neurons (soma, axon, dendrite, synapse, ion channels, rest potential).

- Chapter 4: Synaptic transmission

This chapter presents the bases of synaptic transmission and homeostatic regulatory mechanisms. It describes the physical and biological principles underlying these behaviors.

- Chapter 5: Synaptic plasticity, functional plasticity

This chapter will be devoted to the plasticity and the learning of the perceptual-motor function.

3) Skills acquired
At the end of this course, the student will be able to:
- Understand neural communication processes at the physiological level.
- Have a global vision of the complexity of the nervous system and the interactions between the different components of the brain.
- Be able to identify the neural processes responsible for processing sensory and motor information.

4) Teaching team
- Christophe Bernard (INSERM, Institut de Neurosciences des Systèmes)
- Daniel E. Shulz (CNRS, NeuroPSI)

**UE 2 : Neural bases of perception (CM : 25h)**

Coordinator: Jean-Marc Edeline

1) Goals
This course will present the neural bases of perception in the auditory, vision, somatosensory and olfactory modality. It will give a focus on the neural plasticity that constantly operates and biases our perception.
2) Course program
- Chapter 1: Anatomy and Physiology of the auditory system
- Chapter 2: Functional properties of visual cortex neurons assessed by electrophysiology and in vivo imaging
- Chapter 3: Visual system modeling
- Chapter 4: Functional organization in the somatosensory system
- Chapter 5: Olfactory system
- Chapter 6: Neuronal coding of communication sounds in song birds
- Chapter 7: Multisensory Interactions

3) Skills acquired
At the end of this course, the student will be able to:
- Understanding the anatomy and physiology of the main sensory systems.
- Understanding the neural bases of the sensory code.
- Understanding the main techniques and methodologies to study the sensory systems.

4) Teaching team
- Brice Bathellier (CNRS, Institut de l'audition)
- Cathérine Del Negro (Univ ParisX, NeuroPSI)
- Jean-Marc Edeline (CNRS, NeuroPSI)
- Frédéric Chavane (CNRS, INT Marseille)
- Luc Esténabez (CNRS, NeuroPSI)
- *Nicolas Giret (CNRS*, NeuroPSI)
- Marc Pananceau (Univ Paris-Saclay, NeuroPSI)

**UE 3: Dynamical systems and computational neuroscience (CM: 17h, TD-TP: 8h)**

Coordinator: Antoine Chaillet

1) Goals
This course constitutes an introduction to tools for the analysis of dynamical processes involved in brain functioning. Despite their huge complexity, brain functions are indeed based on elementary dynamics, some of which can be apprehended by a mathematical approach. Mastering these techniques is fundamental to progress in our understanding of brain functioning, to optimize instrumentation for brain activity measurements (brain imaging, electrophysiological recordings…), to improve brain machine interfaces, to build up neuro-inspired computational units, and to understand the mechanisms involved in some brain diseases and thus improve their treatment.
2) Course program
- Chapter 1: Mathematical models of neurons

This chapter presents well-known neuron models. It introduces conductance-based models through the famous Hodgkin-Huxley model and underlines its electronic analogy. It then presents simplified models, such as integrate & fire or FitzHugh-Nagumo models, as well as simple models of synapses and neuronal plasticity. Numerical simulation of these models is
also introduced.
- Chapter 2: Analysis of neuron models

This chapter present mathematical tools to study neuronal behavior. It introduces the notion of phase diagram and bifurcation. These notions are first given for one-dimensional systems, and then for planar systems. The chapter establishes a link between these bifurcations and the qualitative behavior of the neuron. It also shows how to simplify a neuron model based on singular perturbation theory. It finally introduces the notion of "phase response curve", which helps simplifying complex oscillatory behaviors to the mere time evolution of its phase, and shows how to use this technique in practice for the prediction of neuronal synchronization.
- Chapter 3: Biophysical neuron model

This chapter presents a realistic neuron model based on dendritic modeling.

- Chapter 4: Neuronal populations “Mean field model”

This chapter addresses the dynamics of a whole population of neurons or a cerebral structure. It presents simplified models of the activity of a population based on a mean field theory.

- Chapter 5: Neuronal populations “Neural field model”

This chapter addresses the dynamics of a whole population of neurons or a cerebral structure. It presents simplified models of the activity of a population, such as the Wilson-Cowan model or neural fields. It shows how to predict the behavior of such models by stability or bifurcation analysis. It also provides tools to identify such models based on experimental data.

- Chapter 6: Synapse modeling and plasticity

This chapter focuses on synaptic modeling and the exploration of synaptic plasticity.

- Chapter 7: Neuromorphic computing

This chapter focuses on computing units and processors inspired by the processing of information by the brain.

3) Skills acquired

By the end of this course, students will be able to:

- Understand neuroscience fundamentals, for possible interaction with professionals of the field (neurosurgeons, computational neuroscientists, experimenters).
- Model the activity of a neuron or a whole neuronal population.
- Predict their behavior both analytically and numerically.

4) Teaching team

- Antoine Chaillet (CentraleSupelec, Laboratoire Signaux Systèmes)
- Andrew Davison (CNRS, NeuroPSI)
- Alain Destexhe (CNRS, NeuroPSI)
- Sabir Jacquir (Univ Paris-Saclay, NeuroPSI)

## UE 4: Closed-loop neuroscience (CM: 25h)

Coordinator: Valérie Ego-Stengel

1) Goals

This course addresses the specific problems of the closed loop in neuroscience. Such loops arise from the bidirectional interaction between a biological system and a technological device. In the case of brain-machine interfaces, for example, it exists an interaction between a brain structure and a computer or robot. This course presents various techniques for influencing neural activity in real time, such as electrical, magnetic or optogenetic stimulation. It then focuses on brain-machine interface techniques by interpreting user intentions from EEG signals, as well as more recent techniques exploiting brain plasticity. Finally, neuro-robotics techniques are described, focusing in particular on neuro-inspired robotics (in which the robot is programmed based on knowledge of brain function) and on robotic prostheses or orthoses.

2) Course program

- Chapter 1: Closed-loop Neuroscience and Brain Machine Interfaces

Description of the different types of brain-machine interfaces, the different components (recording, stimulation, algorithms...).
Sensory neuroprostheses (and sensory substitution), EEG-based interfaces, invasive interfaces, Neurofeedback.
Brain plasticity underlying learning.

- Chapter 2: Closed-loop neuroscience

Dynamic clamp, application to the manipulation of oscillatory rhythms of sleep and epilepsy.

- Chapter 3: Retinal neuroprosthesis for vision restoration
- Chapter 4: BCI Handling of attention in non-human primates by ICM

Decoding the focal point of attention in monkeys in the prefrontal cortex.

- Chapter 5: Learning and memory in the rodent space navigation system
- Chapter 6: Brain-Computer Interfaces

EEG-based interfaces in humans. Medical applications.

- Chapter 7: Real and neuro-inspired learning

Courses on different types of learning (with reinforcement, supervised, unsupervised...) in animals and in neural networks (deep learning...)+ demo of the learning robot.

- Chapter 8: Neurorobotic

Closed-loop retinal stimulation to understand neuronal coding.

3) Skills acquired
- To know the techniques for artificially influencing neural activity for therapeutic or experimental purposes.
- To know the components of a brain-machine interface device.
- To know the techniques of neuro-inspired robotics.

4) Teaching team

- Valerie Ego-Stengel (CNRS, NeuroPSI)
- Thierry Bal/Alain Destexhe (CNRS, NeuroPSI)
- Olivier Marre (Institut de la Vision)
- Suliann Ben Hamed (CNRS, Institut Jeannerod, Lyon)
- Karim Benchenane (ESPCI, CNRS)
- Fabrizio de Vico Fallani (ICM)
- Thomas Deneux (CNRS, NeuroPSI)
- Mehdi Khamassi (ISIR, UPMC)

**UE 5: Methods for measuring and stimulating neuronal activity, principles and applications (CM : 25h)**

Coordinator: Isabelle Férézou

1) Goals
The aim of this UE is to present methods for recording and stimulating neuronal activity as a means to access the organization and functioning of the brain. It will present methods to record or stimulate neural activity at different spatial and temporal scales. The principles and main applications of cellular (unit or multiple activity) and network (EEG, ECoG, LFP) electrophysiological approaches as well as invasive (calcium or voltage-sensitive imaging in conventional or multi-photonic microscopy) and non-invasive (fMRI) brain imaging approaches will be described. Data analysis methods specific to each modality will be detailed, in particular through practical sessions where actual data sets will be analyzed. We will see how these methods, applied to either human subjects or animal models make it possible to establish causal links between patterns of neural activity and cognitive functions.

2) Course program
Chapter 1: Introduction to the different scales of neural activity recording and stimulation, what are the main issues and challenges to be addressed? (Isabelle Ferezou CM, 1h30).
This introductory chapter provides an overview of the challenges faced in the recording or stimulation of neural activity. Nowadays, the diversity of experimental approaches available in Neuroscience allows us to study neural dynamics at different spatial and temporal scales. Before going deeper into the principles of the different methodologies, this course aims to highlight the complementarity of these approaches, their respective interests, and the challenges that remain to be overcome to better understand the neural bases of behavior.

Chapter 2: Good practices for data acquisition and analysis, statistical tools for the analysis of large data sets (Andrew Davison CM 1h, Arthur Tenenhaus TD-TP 2h).
This chapter presents a number of good practices, standards, and software for conducting data acquisition and analysis in a manner that promotes collaboration, data exchange, and reproducibility of analysis. It also includes a practical work illustrating the most common statistical tools deployed to analyze large data sets from neuronal recordings.

Chapter 3: Biophysical models of brain signals (Alain Destexhe, CM 2h).
There are a multitude of methods used to "read" neuronal activity, but to correctly interpret the signals collected with these methods and extract relevant neurophysiological findings, it is essential to understand the biophysical origin of these signals. This chapter will overview the modeling of the different brain signals, at multiple scales. At the single-cell level, we will consider intracellular recordings and the extracellular (unit) recordings. At the mesoscopic level, we will consider signals such as the local field potential, calcium imaging signals and voltage-sensitive dye signals. Finally, at the macroscopic level, we will overview the modeling of electrocorticogram, electroencephalogram, magneto-encephalogram and fMRI signals.
In each case, we will summarize the biophysical basis of each signal, how to model them, and which tools are available for this modeling.

Chapter 4: Targeted neural stimulation methods (Isabelle Férézou CM, 1h30)
In this chapter, we will present the tools available nowadays to Neuroscientists (electrical microstimulation, transcranial magnetic stimulation, optogenetics) to stimulate neuronal activity and thus establish correlates between activation of specific neuronal populations at different scales and behavior.

Chapter 5: Non-invasive neural recording methods used in humans. (Bertrand Thirion CM 2h, Alexandre Gramfort CM 2h, TP 3h,).
In this chapter, we will present the principles and applications of the main methods commonly used in humans (EEG, MEG, MRI, fMRI, dMRI, PET) to study the neural correlates of cognitive activity. The presentation of analysis methods will focus on the most used modalities: function MRI on the one hand, EEG and MEG on the other hand, from preprocessing to the computation of activation maps.

Chapter 6: Electrophysiology (Marc Pananceau CM, 2h, Gilles Ouanounou CM 2h, Pierre Yger CM 3h).
This chapter presents the main electrophysiological recording methods applied to in vitro and in vivo preparations reading of neuronal activity at the synaptic, cellular and network scales, which can range from single-cell membrane potential (intracellular recording, blind or targeted patch-clamp), or action potentials recording (juxta, extra, tetrodes, Utah arrays, NeuroPixels) to more global recording methods (field potential, ECoG). The course will be complemented by tutorials on both spectral analysis and the reconstruction of discharge times of a population of neurons from multi-electrode electrophysiological recordings.

Chapter 7: Optical recording of neuronal network dynamics (Isabelle Ferezou CM, 2h, Laurent Bourdieu CM, 2h, Thomas Deneux TP 2h)
This chapter will cover optical methods allowing the visualization of neuronal activity in anesthetized or behaving animals either at the mesoscopic scale of the cortical column, or at the microscopic scale of individual neurons. It will present the optical acquisition methods: wide-field imaging and confocal microscopy, bi- and tri-photonic microscopy. And the contrast agents, that can be intrinsic to the brain (light absorption), but more usually extrinsic fluorescent molecules and genetically engineered proteins sensitive to voltage or to calcium concentration. The practical session will focus on the most commonly used method: biphotonic calcium imaging.

3) Skills acquired
At the end of this course, students will be able to:
- Have a comprehensive overview of the technological arsenal available nowadays to neuroscientists.
- Assess the relevance of using one method over another based on the scientific questions addressed.
- Identify the limitations of the different methods for a well-versed interpretation of the experimental results described in the literature of the field.

4) Teaching team
Laurent Boudieu, CNRS, IBENS
Andrew Davison,CNRS, NeuroPSI
Thomas Deneux, CNRS, NeuroPSI
Alain Destexhe, CNRS, NeuroPSI
Isabelle Ferezou, CNRS, NeuroPSI
Gilles Ouanounou, CNRS, NeuroPSI
Marc Pananceau, Univ. Paris-Saclay, NeuroPSI
Bertrand Thirion, INRIA, NeuroSPIN
Alexandre Gramfort, INRIA, NeuroSPIN
Pierre Yger, Institut de la Vision

**UE 6: Machine learning (CM : 17h, TD-TP : 8h)**

Coordinator : Arthur Tenenhaus

1) Goals

Neuroscience is a field where very large data are generated ("Big Data", several tens of GB per session in fMRI, EEG, high temporal and spatial resolution optical recordings, or multi-electrode electrophysiology). The analysis of these data requires very specific analytical methods, which are themselves the subject of advanced research. This course presents an overview of machine learning methods as well as examples of the application of the different approaches developed.

2) Course program

Chapter 1: Regression and classification (Ridge Regression, Generalized Linear Model -including logistic regression, Support Vector Machines). Extensions to core methods.
Chapter 2: Generalized Linear Model and Selection of Variables (Sparsity Constraints).
Chapter 3: Aggregation methods (Boosting, Random Forrest)
Chapter 4: Statistical tools for the analysis of large data.
Chapter 5: Model of mixtures
Chapter 6: Dimension reduction (Analysis in Principal Components).
Chapter 7: K-means / Hierarchical clustering.

3) Skills acquired

At the end of this course, students will be able to define, understand and choose a machine learning method and to implement it in line with the specific problem.

4) Teaching team

Arthur Tenenhaus (CentraleSupelec)

## UE 7 : Supervised scientific project

Coordinator: Sabir Jacquir

Goal

A supervised scientific project will complete the students' training during the semester one. This project is focused on a scientific issue including a bibliographic and/or experimental and/or simulation works.

## UE 8: Master thesis

Coordinator: Sabir Jacquir

Goal

Semester two begins with a research Master thesis of three to six months. This Master thesis project gives students real research experiences in computational neuroscience and neuroengineering. They will have the opportunity to work closely with a leading research team in the academic laboratories and opportunities will be created to work on industry lead projects. They will benefit from the supervision of experienced researchers. The project can be carried out with a research group at University Paris-Saclay, with an industrial partner or with a research institute in France or worldwide.