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Project-Team Odyssée

Computer and biological vision

Sophia Antipolis - Méditerranée, Paris - Rocquencourt

THEME BIO

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2. Overall Objectives

2.1. Presentation

ODYSSÉE focuses on computational neuroscience and some of its applications. We try to unveil the principles that govern the functioning of neurons and assemblies thereof, to understand the relations between the anatomy of the human brain and its functions and to use our results to bridge the gap between biological and computational vision. Our work is very mathematical but we make heavy use of computers for numerical experiments and simulations. We have close ties with several top groups in biological neuroscience. We are pursuing the idea that the "unreasonable effectiveness of mathematics" can also be brought to bear on neuroscience.

We conduct research in the following five main areas.

1. Modeling and simulating single neurons.
2. Modeling and simulating assemblies of neurons.
3. Measuring and modeling the human brain anatomical connectivity using diffusion magnetic resonance.
4. Measuring and modeling the functioning of the human brain through its electrical activity using magneto- and electroencephalography.
5. Computational and biological vision.

2.2. Highlights

The project of installing a magnetoencephalography machine (MEG) in La Timone, Marseille, has been successfully completed after some six years of efforts between the "Laboratoire de Neurophysiologie et de Neuropsychologie", INSERM U751, directed by Professor Patrick Chauvel, and the Odyssée project team. This will reinforce the collaboration between INRIA, INSERM and CNRS and contribute greatly to the creation of a pole of excellence in theoretical and clinical neuroscience in the PACA region. The equipment has been paid for by a combination of sponsors including CNRS, INRIA, INSERM, the local collectivities Conseil Général 13, Conseil Général 06, Conseil Régional PACA, Marseille Provence Métropole, the Ministry of enseignement supérieur et de la recherche and the AP-HM. The machine was inaugurated in November 2008.

3. Scientific Foundations

3.1. Computational Neurosciences

Keywords: *dynamical systems*, *neuron models*, *neuronal networks*, *stochastic calculus*.

optical imaging A usually invasive technique that allows to display a visual correlate of the activity of the cortex. One distinguishes intrinsic and extrinsic optical imaging.

Understanding the principles of information processing in the brain is challenging, theoretically and experimentally. Computational neuroscience attempts to build models of neurons at a variety of levels, microscopic, i.e. the minicolumn containing of the order of one hundred or so neurons, mesoscopic, i.e. the macrocolumn containing of the order of $10^4 - 10^5$ neurons, and macroscopic, i.e. a cortical area such as the primary visual area V1.

Modeling such assemblies of neurons and simulating their behaviour involves putting together a mixture of the most recent results in neurophysiology with such advanced mathematics as dynamical systems theory, bifurcation theory, probability theory, stochastic calculus, and statistics, as well as the use of simulation tools [64]

In order to test the validity of the models we rely heavily on experimental data. These data come from single or multi electrode recordings and optical imaging and are provided by our collaborations with neurophysiology laboratories such as the UNIC http://www.unic.cnrs-gif.fr/ or the INCM http://www.incm.cnrs-mrs.fr/. Other sources of measurements such as functional MRI, MEG and EEG, see 3.3 below, are either obtained within Odyssée as it is the case for EEG, or from other collaborative efforts such as the one with La Timone, see 2.2 above, or Neurospin.

The Odyssée team works at the three levels. We have proposed two realistic models of single neurons [2], [9] by making use of physiological data and the theory of dynamical systems and bifurcations. At this level of analysis we have also proposed a variety of theoretical tools from the theory of stochastic calculus [32] and solved an open problem of determining the probability law of the spike intervals for a simple but realistic neuron model, the leaky integrate and fire with exponentially decaying synaptic currents. We have also provided a mathematical analysis, through bifurcation theory, of the behaviour of a particular mesoscopic model [5], the one due to Jansen and Rit [75].

We have also started some efforts at the macroscopic level, in particular for modeling visual areas, see 3.4 below. For this particular level, information about the anatomical connectivity such as the one provided by diffusion imaging techniques is of fundamental importance, see 3.2 below.

3.2. Diffusion Imaging

Keywords: *DT-MRI*, *Diffusion MRI*, *HARDI*, *ODF*, *QBI*, *Tractography*.

DT-MRI Diffusion Tensor Magnetic Resonance Imaging is an MRI technique that allows to measure in-vivo and in a non-invasise way the restricted diffusion of water molecule in a biological tissue. A tensor describes the 3D shape of diffusion.

HARDI High Angular Resolution Diffusion Imaging allows apparent diffusion coefficients to be measured along a large number of directions, poses no assumptions on the underlying diffusion process and is capable of detecting the presence of multiple diffusion directions within an individual voxel.

QBI Q-Ball Imaging is a HARDI method that measures apparent diffusion coefficients along many directions distributed almost isotropically on the surface of a sphere.

ODF The Orientation Distribution Function describes the probability distribution for a water molecule to displace in a given direction.

Because the relationship between brain structure and brain function is fundamental to neuroscience, developing techniques that allow to recover the anatomical connectivity in the in vivo brain is of utmost importance and a major goal to achieve if one wants to understand how the brain works and acquire a better understanding of its mechanisms.

Diffusion Magnetic Resonance Imaging (DMRI) not only gives scientists access to data relating to local white matter architecture but is also the unique non invasive method currently available to explore the microstructure of biological tissues like those of the white matter in the human brain. This is why our research deals with the development of new processing tools for DMRI. Because of the complexity of the data, this imaging modality raises a large amount of mathematical and computational challenges. We have therefore started by developing new algorithms relying on Riemannian geometry, differential geometry, partial differential equations and front propagation techniques to correctly and efficiently estimate, regularize, segment and process Diffusion Tensor MRI (DT-MRI) (see [7], [77]).

However, due to the limited current resolution of diffusion-weighted (DW) MRI, one third to two thirds of imaging voxels in the human brain white matter contain fiber crossing bundles. Therefore, it's also of utmost importance to tackle the problem of recovering fiber crossing and develop techniques that go beyond the limitations of diffusion tensor imaging (DTI). We are contributing towards these objectives and or recent work deals with the development of local reconstruction methods, segmentation and tractography algorithms able to infer multiple fiber crossing from diffusion data. To do so, high angular resolution diffusion imaging (HARDI) is used to measure diffusion images along several directions. Q-ball imaging (QBI) is a recent such HARDI technique that reconstructs the diffusion orientation distribution function (ODF), a spherical function that has its maxima aligned with the underlying fiber directions at every voxel. QBI and the diffusion ODF play a central role in our work focused on the development of a robust and linear spherical harmonic estimation of the HARDI signal and our development of a regularized, fast and robust analytical QBI solution that outperform the state-of-the-art ODF numerical technique available. Those contributions are fundamentals and have already started to impact on the Diffusion MRI, HARDI and Q-Ball Imaging community. These contributions are the basis of our probabilistic and deterministic tractography algorithms exploiting the full distribution of the fiber ODF (see [4], [70]).

Overall, we are now able to show local reconstruction, segmentation and tracking results on complex fiber regions with known fiber crossing on simulated HARDI data, on a biological phantom and on multiple human brain datasets. Most current DTI based methods neglect these complex fibers, which might lead to wrong interpretations of the brain anatomy and functioning.

In order to acquire a better understanding of the brain mechanisms and to improve the diagnosis of neurological disorders, we are also interested in the application of our tools to important neuroscience problems: the analysis of the connections between the cerebral cortex and the basal ganglia, involved in motor tasks, the study of the anatomo-functional network of the human visual cortex and the reconstruction of the transcallosal fibers intersecting with the corona radiata and superior longitudinal fasciculus, regions usually neglected by most

DTI-based methods and recovered thanks to the ODF-based probabilistic. Our work is done in collaboration with the Center for Magnetic Resonance Research of the University of Minnesota (Minneapolis), the centre IRMf of the hospital la Timone (Marseille), the Centre for Neuro Imaging Research (CENIR - Pitié-Salpêtrière - Paris), the Max Planck Institute for Human Cognitive and Brain Sciences (Leipzig,Germany) and the Montreal Neurological Institute (McGill - Montréal).

3.3. Electrical and Magnetic Functional Brain Imaging

Electroencephalography (EEG) and Magnetoencephalography (MEG) are two non-invasive techniques for measuring (part of) the electrical activity of the brain. While EEG is an old technique (Hans Berger, a german neuropsychiatrist, measured the first human EEG in 1929), MEG is a rather new one: the first measures of the magnetic field generated by the electrophysiological activity of the brain have been done in 1968 at MIT by D. Cohen. Nowadays, EEG is relatively inexpensive and used commonly to detect and qualify neural activities (epilepsy detection and characterisation, neural disorder qualification, BCI, ...). MEG is, comparatively, much more expensive as SQUIDS work in very challenging conditions (at liquid helium temperature) and as a specially shielded room must be used to separate the signal of interest from the ambient noise. However, as it reveals a complementary vision to that of EEG and as it is less sensitive to the head structure, it also bears great hopes and more and more MEG machines are installed throughout the world. INRIA and Odyssée have participated to the acquisition of one such machine that has just been installed in the hospital "La Timone" in Marseille, see 2.2 above.

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

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

- First, as acquisition is continuous and at upto 1kHz rate, the amount of data for each experiment is huge. Data selection and reduction (finding the interesting time instants or interesting frequencies) and pre-processing (removing artifacts, enhancing the signal to noise ratio, ...) is currently largely done manually. Making a better and more systematic use of the measurements is an important step to optimally exploit the M/EEG data [3].
- With a proper model of the head and of the sources of brain electromagnetic activity, it is possible to simulate the electrical propagation and reconstruct sources that can explain the measured signal. Proposing better models [6], [79] and means to calibrate them [81] so as to have better reconstructions are other important aims of our work.
- Finally, it is our goal to exploit the temporal resolution of M/EEG and apply the various methods we developed to better understand some aspects of the brain functioning, and/or to extract more subtle information out of the measurements. This is interesting not only as a cognitive goal, but also serves the purpose of the validation of our algorithms and can lead to the use of such methods in the field

of Brain Computer Interfaces. To be able to conduct such kind of experiments, an EEG lab is being set up at Odyssée.

3.4. Biological and Computer Vision

Another scientific focus of the team is the combined study of computer and biological vision. We think that a more detailed knowledge of the visual perception in humans and primates can have a potential impact on algorithm design and performance. Thus, we develop so-called bio-inspired approaches to model visual tasks. This work is multidisciplinary: It involves knowledge from neuroscience and physiology, it tries to reproduce what psychophysical experiments reveal and, as a final goal, we want to compete with recent computer vision approaches.

The models that we develop are bio-inspired with regards to several aspects, depending on the scale chosen for the modelization.

- At the microscopic level, one interesting aspect it to study the neural code: The nervous system use spikes as a way to emit and code the information, which is certainly one explanation of the extraordinary performance of the visual system. So we need to define a mathematical framework to be able to analyze this spiking langage and, based on those results, one can imagine some computer vision applications where spikes are used to code signals.
- At the macroscopic level, we imitate the functional hierarchy of the visual cortex and propose the variational framework and integro-differential equations as a way to model cortical layers activity.
- We also develop phenomenological models, in order to reproduce a percept. For example, we are developing bio-inspired models for motion estimation, focusing on V1-MT and V2 layers and interactions.

Validation of these models is crucial. Since we claim that our models are bio-inspired, our goal is also to validate them through biology. For example, the spiking retina simulator (Virtual Retina) reproduces closely cell measurements done on cat ganglion cells, for various kinds of experiments. At the perceptual level, our models should also be able to reproduce a percept, which may be not trivial to reproduce with standard computer vision approaches. Computer vision is another way to prove the efficiency of our approaches, and it is one goal to show compare the performances of our approaches with respect to state-of-the-art computer vision approaches. This is currently done for example for action recognition, based on classical image databases.

This modeling activity brings new insight and tools for computer vision. But it also raises fundamental issues that will be the focus of future research. Understanding the neural code is certainly the most challenging one. Since we believe that spikes are one possible explanation of the visual system performance, and represent a new paradigm for computer vision, more fundamental work has to be done to understand how to better exploit the richness of this code.

4. Software

4.1. Software for Diffusion MRI

Keywords: *Diffusion tensor MRI*, *HARDI*, *Q-Ball Imaging*.

Participants: Maxime Descoteaux [correspondent], Christophe Lenglet [Odyssée and Siemens SCR - Princeton from Oct 1st 2006 to July 2008. CMRR/Univ. Minnesota since August 2008], Demian Wassermann, Aurobrata Ghosh, Rachid Deriche.

The algorithms developed within the Odyssée Project team and related to the Diffusion Tensor and Q-Ball imaging are all available upon request from the INRIA source forge (https://gforge.inria.fr) as an extension to the Brainvisa (http://brainvisa.info) software platform for visualization and analysis of multi-modality brain data. One can use all the estimation and visualization tools developed at Odyssee, from DTI estimation, regularization, segmentation to Q-ball estimation, to fiber ODF estimation and tractography algorithms.

We now have users from IRISA, VISAGES, Rennes (Barillot et al), from INSERM, Paris and Université de Montreal (H. Benali, J.C. Cohen-Adad et al), from Salpêtrière Hospital, Paris (S.Lehericy, C.Delmaire, et al), from Toulouse (Landreau et al), from Eindhoven Technical University, CalTech in USA and other national and international sites.

The current library comprising geometric and variational methods developed to estimate, regularize, segment and perform tractography in DT (Diffusion Tensor) and HARDI (High Angular Resolution) MRI images was improved in two fundamental ways. In the first place, the building system was changed from Automake to CMake technologies. This improvement lead to adding support to use the library in Linux, Windows and OS X, systematize testing procedure. In the second place, the library was embedded into two open-source high level languages languages, TCL and Python.

Within the new library, new visualization schemes for Q-Ball images represented by spherical harmonic decomposition were developed. These visualization schemes based on open-source software tools, the Visualization Toolkit (VTK) and the CImg library, greatly improve the speed and Application Programming Interface (API) usability of the visualization library.

This work allowed integration with the interactive medical imaging platforms MedINRIA MedINRIA and 3D Slicer QBallSlicer.

This work was partially supported by the ARC Diffusion MRI. To learn more, please visit the web page http://www-sop.inria.fr/odyssee/arc2007/

4.2. Virtual Retina

Keywords: *retina*, *simulator*, *spikes*.

Participants: Adrien Wohrer [correspondent], Pierre Kornprobst [projet Odyssée].

Virtual Retina is under CeCILL C licence: APP logiciel Virtual Retina: IDDN.FR.OO1.210034.000.S.P.2007.000.31235

We finalized our work concerning the retina simulation software, called Virtual Retina, which transforms a video into spike trains [15], [35]. To learn more, see Section 5.5.7, and please visit the web page http://www-sop.inria.fr/odyssee/software/virtualretina/

4.3. Navisio

Keywords: *age related macular disease*, *reading-aid systems*, *scotomatas*.

Participants: Émilien Tlapale, Éric Castet [Institut de Neurosciences Cognitives de la Méditerranée, UMR 6193, CNRS, Marseille, France], Jean-Baptiste Bernard [Institut de Neurosciences Cognitives de la Méditerranée, UMR 6193, CNRS, Marseille, France], Pierre Kornprobst.

Navisio software as a new integrated system to help low vision patients read complex electronic documents (here, PDF files) with more comfort. Navisio aims at taking into account main psychophysical results on reading performance of visually impaired patients. To do this, we analyze what are the main factors influencing reading performance, and review some existing reading aid systems, dealing with printed and electronic documents. Then, we show how Navisio allows to extend the capabilities of existing reading systems, focusing on the facilitation to navigate in complex documents, and on the highly customizable display. Navisio performance was evaluated against a standard CCTV magnifier tool, with 26 low vision patients. Two kinds of texts were proposed (simple and complex documents) elaborated from a standardised text database. Results show a clear advantage of Navisio in terms of reading speed and comfort. Navisio is intended to evolve: extensions to any scanned document, thanks to recent computer vision approaches in document layout analysis, are being considered.

This work is described in [37].

4.4. MEG and EEG processing with OpenMEEG

Keywords: *Boundary Element Methods*, *EEG*, *MEG*, *forward problem*, *inverse problem*.

Participants: Maureen Clerc [correspondent], Alexandre Gramfort, Perrine Landreau, Théo Papadopoulo.

In 2008, the 1.0 version of OpenMEEG has been released. OpenMEEG provides state-of-the art tools for processing EEG and MEG data. It incorporates a newly proposed, symmetric BEM for the forward problem, and a distributed source inverse problem, with three different types of regularizations, two of which are original, based on norms of the surface gradient of the source distribution. OpenMEEG is a free, open software written in C++, and can be accessed either through a command line interface or through a user-friendly interface. http://www-sop.inria.fr/odyssee/software/OpenMEEG/

5. New Results

5.1. Single neuron models

5.1.1. High-resolution intracellular recordings using a real-time computational model of the electrode

Participant: Romain Brette.

This work was done in collaboration with the UNIC lab (CNRS Gif-sur-Yvette).

Intracellular recordings of neuronal membrane potential are a central tool in neurophysiology. In many situations, especially in vivo, the traditional limitation of such recordings is the high electrode resistance and capacitance, which may cause significant measurement errors during current injection. We introduce a computer-aided technique, Active Electrode Compensation (AEC), based on a digital model of the electrode interfaced in real time with the electrophysiological setup. The characteristics of this model are first estimated using white noise current injection. The electrode and membrane contribution are digitally separated, and the recording is then made by online subtraction of the electrode contribution. Tests performed in vitro and in vivo demonstrate that AEC enables high-frequency recordings in demanding conditions, such as injection of conductance noise in dynamic-clamp mode, not feasible with a single high-resistance electrode until now. AEC should be particularly useful to characterize fast neuronal phenomena intracellularly in vivo. This work has appeared in [18].

5.1.2. Dynamic I-V curves are reliable predictors of naturalistic pyramidal-neuron voltage traces

Participant: Romain Brette.

Neuronal response properties are typically probed by intracellular measurements of current-voltage (I-V) relationships during application of current or voltage steps. Here we demonstrate the measurement of a novel I-V curve measured while the neuron exhibits a fluctuating voltage and emits spikes. This dynamic I-V curve requires only a few tens of seconds of experimental time and so lends itself readily to the rapid classification of cell type, quantification of heterogeneities in cell populations, and generation of reduced analytical models. We apply this technique to layer-5 pyramidal cells and show that their dynamic I-V curve comprises linear and exponential components, providing experimental evidence for a recently proposed theoretical model. The approach also allows us to determine the change of neuronal response properties after a spike, millisecond by millisecond, so that postspike refractoriness of pyramidal cells can be quantified. Observations of I-V curves during and in absence of refractoriness are cast into a model that is used to predict both the subthreshold response and spiking activity of the neuron to novel stimuli. The predictions of the resulting model are in excellent agreement with experimental data and close to the intrinsic neuronal reproducibility to repeated stimuli. This work has appeared in [16].

5.1.3. Characterizing synaptic conductance fluctuations in cortical neurons and their influence on spike generation

Participant: Romain Brette.

This work was done in collaboration with the UNIC lab (CNRS Gif-sur-Yvette).

Cortical neurons are subject to sustained and irregular synaptic activity which causes important fluctuations of the membrane potential (V(m)). We review here different methods to characterize this activity and its impact on spike generation. The simplified, fluctuating point-conductance model of synaptic activity provides the starting point of a variety of methods for the analysis of intracellular V(m) recordings. In this model, the synaptic excitatory and inhibitory conductances are described by Gaussian-distributed stochastic variables, or "colored conductance noise". The matching of experimentally recorded V(m) distributions to an invertible theoretical expression derived from the model allows the extraction of parameters characterizing the synaptic conductance distributions. This analysis can be complemented by the matching of experimental V(m) power spectral densities (PSDs) to a theoretical template, even though the unexpected scaling properties of experimental PSDs limit the precision of this latter approach. Building on this stochastic characterization of synaptic activity, we also propose methods to qualitatively and quantitatively evaluate spike-triggered averages of synaptic time-courses preceding spikes. This analysis points to an essential role for synaptic conductance variance in determining spike times. The presented methods are evaluated using controlled conductance injection in cortical neurons in vitro with the dynamic-clamp technique. We review their applications to the analysis of in vivo intracellular recordings in cat association cortex, which suggest a predominant role for inhibition in determining both sub- and supra-threshold dynamics of cortical neurons embedded in active networks. This work has appeared in [28].

5.1.4. Dynamics and bifurcations of the adaptive exponential integrate-and-fire model

Participants: Romain Brette, Jonathan Touboul.

This work was partially supported by the EC IP project FP6-015879, FACETS and the Fondation d'Entreprise EADS.

Recently, several two-dimensional spiking neuron models have been introduced, with the aim of reproducing the diversity of electrophysiological features displayed by real neurons while keeping a simple model, for simulation and analysis purposes. Among these models, the adaptive integrate-and-fire model is physiologically relevant in that its parameters can be easily related to physiological quantities. The interaction of the differential equations with the reset results in a rich and complex dynamical structure. We relate the subthreshold features of the model to the dynamical properties of the differential system and the spike patterns to the properties of a Poincaré map defined by the sequence of spikes. We find a complex bifurcation structure which has a direct interpretation in terms of spike trains. For some parameter values, spike patterns are chaotic. This work has appeared in [31].

5.1.5. A characterization of the first hitting time of Double Integral Processes to curved boundaries

Participants: Olivier Faugeras, Jonathan Touboul.

This work was partially supported by the EC IP project FP6-015879, FACETS and the Fondation d'Entreprise EADS.

We continued the study of the statistics of spike trains and found a new formula for computing first hitting times of integrate-and-fire neurons with exponentially decaying synaptic conductances. This formula is valid for approximating any first hitting times for what we call Double Integral processes, which are non-Markov. The problem of finding the probability distribution of the first hitting time of a Double Integral Process (DIP) such as the Integrated Wiener Proces (IWP) has been an important and difficult endeavor in stochastic calculus. It has applications in many fields of physics (first exit time of a particle in a noisy force field) or in biology and neuroscience (spike time distribution of an integrate-and-fire neuron with exponentially decaying synaptic current). The only results available are an approximation of the stationary mean crossing time and the distribution of the first hitting time of the IWP to a constant boundary. We generalize these results and find an analytical formula for the first hitting time of the IWP to a continuous piecewise cubic boundary. We use this formula to approximate the law of the first hitting time of a general DIP to a smooth curved boundary, and we provide an estimation of the convergence of this method. The accuracy of the approximation is computed in

the general case for the IWP and the effective calculation of the crossing probability can be carried out through a Monte-Carlo method. This work will appear in [32].

5.1.6. Spiking dynamics of bidimensional integrate-and-fire neurons

Participants: Romain Brette, Jonathan Touboul.

This work was partially supported by the EC IP project FP6-015879, FACETS and the Fondation d'Entreprise EADS.

Spiking neuron models are hybrid dynamical systems combining differential equations and discrete resets, which generate complex dynamics. Several two-dimensional spiking models have been recently introduced, modelling the membrane potential and an additional variable, and where spikes are defined by the divergence to infinity of the membrane potential variable. These simple models reproduce a large number of electrophysiological features displayed by real neurons, such as spike frequency adaptation and bursting. The patterns of spikes, which are the discontinuity points of the hybrid dynamical system, have been mainly studied numerically. Here we show that the spike patterns are related to orbits under a discrete map, the adaptation map, and we study its dynamics and bifurcations. Regular spiking corresponds to fixed points of the adaptation map while bursting corresponds to periodic orbits. We find that the models undergo a transition to chaos via a cascade of period adding bifurcations. Finally, we discuss the physiological relevance of our results with regard to electrophysiological classes. This work is submitted to SIAM Dynamical Systems.

5.1.7. Sensitivity To The Cutoff Value In The Quadratic Adaptive Integrate-And-Fire Model

Participant: Jonathan Touboul.

This work was partially supported by the EC IP project FP6-015879, FACETS and the Fondation d'Entreprise EADS.

The quadratic adaptive integrate-and-fire model is recognized as very interesting for its computational efficiency and its ability to reproduce many behaviors observed in cortical neurons. For this reason it is currently widely used, in particular for large scale simulations of neural networks. This model emulates the dynamics of the membrane potential of a neuron together with an adaptation variable. The subthreshold dynamics is governed by a two-parameter differential equation, and a spike is emitted when the membrane potential variable reaches a given cutoff value. Subsequently the membrane potential is reset, and the adaptation variable is added a fixed value called the spike-triggered adaptation parameter. We show in this note that when the system does not converge to an equilibrium point, both variables of the subthreshold dynamical system blow up in finite time whatever the parameters of the dynamics. The cutoff is therefore essential for the model to be well defined and simulated. The divergence of the adaptation variable makes the system very sensitive to the cutoff. Changing this parameter dramatically changes the spike patterns produced. Furthermore from a computational viewpoint, the fact that the adaptation variable blows up and the very sharp slope it has when the spike is emitted implies that the time step of the numerical simulation needs to be very small (or adaptive) in order to catch an accurate value of the adaptation at the time of the spike. It is not the case for the similar quartic and exponential models whose adaptation variable does not blow up in finite time, and which are therefore very robust to changes in the cutoff value. This work is submitted to Neural Computation.

5.1.8. Bifurcations of cycles, rhythms and epilepsy in neural mass models

Participants: Olivier Faugeras, Jonathan Touboul.

This work was partially supported by the EC IP project FP6-015879, FACETS and the Fondation d'Entreprise EADS.

Temporal lobe epilepsy is one of the most common chronic neurological disorder characterized by the occurrence of spontaneous recurrent seizures which can be observed at the level of populations through electroencephalogram (EEG) recordings. The aim of this work is to understand from a theoretical viewpoint the occurrence of this type of seizures and the origin of the oscillatory activity in some classical cortical column models. We relate these rhythmic activities to the structure of the set of periodic orbits in the models, and therefore to their bifurcations. We will be mainly interested Jansen and Rit model, and study the codimension

one, two and a codimension three bifurcations of equilibria and cycles of this model. We can therefore understand the effect of the different biological parameters of the system of the apparition of epileptiform activity and observe the emergence of alpha, delta and theta sleep waves in a certain range of parameter.

5.1.9. The Cauchy problem for one-dimensional spiking neuron models

Keywords: *Spiking neurons*, *integrate-and-fire model*.

Participant: Romain Brette.

This work was partially supported by the EC IP project FP6-015879, FACETS and the Fondation d'Entreprise EADS.

We consider spiking neuron models defined by a one-dimensional differential equation and a reset — i.e., neuron models of the integrate-and-fire type. We address the question of the existence and uniqueness of a solution on R for a given initial condition. It turns out that the reset introduces a countable and ordered set of backward solutions for a given initial condition, which has important implications in terms of neural coding and spike timing precision. This work has been accepted for publication in Cognitive Neurodynamics. This work has appeared in [17], see also [63].

5.1.10. Statistical analysis of spike trains

Participant: Bruno Cessac.

This work was partially supported by the EC IP project FP6-015879, FACETS and the Fondation d'Entreprise EADS.

Spike train analysis, in vivo ou in vitro, uses ad hoc statistical models. Our goal is to propose a generic method to construct optimal statistical models for the spike train analysis and to produce new algorithms for experimental data treatment.

We first have done the mathematical analysis of the generic dynamics in Integrate-and-Fire with conductance based synapses. We have also rigorously established the one-to-one correspondence between spike trains and membrane potential trajectories in the asympotics (symbolic coding) [19], [20]. On this basis we have proposed a new simulation algorithm of such networks [66] and a new interpretation of spike trains in terms of metrics [47]. In [67], [38] we have shown that Gibbs distribution, coming from statistical physics and ergodic theory, produce optimal (statistical entropy maximisation under constraints) statistical models in neural networks with slow synaptic adaptation. The dynamics of synaptic efficacies imposes the Gibbs potential and provides therefore a canonical method for constructing statistical models. This result is complementary to the analysis of Hebbian plasticity effects on neurons dynamics, performed in [30], using also methods from dynamical system theory and non equilibrium statistical physics. Using standard results in ergodic theory, we have in parallel developed numerical codes for experimental spike trains analysis [65]. Part of these codes are already available in the gForge-ENAS library. The goal is now to apply these methods to experimental data coming on one hand from INCM (A. Rhiele experiments) and on the other hand from Chile (A. Palacios team).

5.2. Assemblies of neuron models and simulation

5.2.1. A constructive mean-field analysis of multi population neural networks with random synaptic weights and stochastic inputs

Participants: Bruno Cessac, Olivier Faugeras, Jonathan Touboul.

This work was partially supported by the EC IP project FP6-015879, FACETS and the Fondation d'Entreprise EADS.

We deal with the problem of bridging the gap between two scales in neuronal modeling. At the first (microscopic) scale, neurons are considered individually and their behavior described by stochastic differential equations that govern the time variations of their membrane potentials. They are coupled by synaptic connections acting on their resulting activity, a nonlinear function of their membrane potential. At the second (mesoscopic) scale, interacting populations of neurons are described individually by similar equations. The equations describing the dynamical and the stationary mean-field behaviors are considered as functional equations on a set of stochastic processes. Using this new point of view allows us to prove that these equations are well-posed on any finite time interval and to provide, by a fixed point method, a constructive method for effectively computing their unique solution. This method is proved to converge to the unique solution and we characterize its complexity and convergence rate. We also provide partial results for the stationary problem on infinite time intervals. These results shed some new light on such neural mass models as the one of Jansen and Rit [75]: their dynamics appears as a coarse approximation of the much richer dynamics that emerges from our analysis. Our numerical experiments confirm that the framework we propose and the numerical methods we derive from it provide a new and powerful tool for the exploration of neural behaviors at different scales. This work has been submitted to Frontiers in Neuroscience [72].

5.2.2. Neural Fields: homogeneous states

Keywords: *Integro-differential equations*, *Neural fields*, *Neural masses*, *synchronization*.

Participants: Olivier Faugeras, François Grimbert, Jean-Jacques Slotine [MIT].

This work was partially supported by the EC IP project FP6-015879, FACETS and the Fondation d'Entreprise EADS.

Neural fields are an interesting option for modelling macroscopic parts of the cortex involving several populations of neurons, like cortical areas. Two classes of neural field equations are considered: voltage and activity based. The spatio-temporal behaviour of these fields is described by nonlinear integro-differential equations. The integral term, computed over a compact subset of R^q, $q = 1, 2, 3$, involves space and time varying, possibly non-symmetric, intra-cortical connectivity kernels. Contributions from white matter afferents are represented as external input. Sigmoidal nonlinearities arise from the relation between average membrane potentials and instantaneous firing rates. Using methods of functional analysis, we characterize the existence and uniqueness of a solution of these equations for general, homogeneous (i.e. independent of the spatial variable), and locally homogeneous inputs. In all cases we give sufficient conditions on the connectivity functions for the solutions to be absolutely stable, that is to say independent of the initial state of the field. These conditions bear on some compact operators defined from the connectivity kernels, the sigmoids, and the time constants used in describing the temporal shape of the post-synaptic potentials. Numerical experiments are presented to illustrate the theory. An important contribution of our work is the application of the theory of compact operators in a Hilbert space to the problem of neural fields with the effect of providing very simple mathematical answers to the questions asked by neuroscience modelers.

This work has appeared in [25].

5.2.3. Neural Fields: stationary states

Keywords: *Integro-differential equations*, *Neural fields*, *Neural masses*, *bumps*, *persistent states*, *stationary solutions*.

Participants: Olivier Faugeras, François Grimbert, Romain Veltz.

This work was partially supported by the EC IP project FP6-015879, FACETS and the Fondation d'Entreprise EADS.

Neural continuum networks are an important aspect of the modeling of macroscopic parts of the cortex. Two classes of such networks are considered: voltage- and activity-based. In both cases our networks contain an arbitrary number, n, of interacting neuron populations. Spatial non-symmetric connectivity functions represent cortico-cortical, local, connections, external inputs represent non-local connections. Sigmoidal nonlinearities model the relationship between (average) membrane potential and activity. Departing from most of the previous work in this area we do not assume the nonlinearity to be singular, i.e., represented by the discontinuous Heaviside function. Another important difference with previous work is our relaxing of the assumption that the domain of definition where we study these networks is infinite, i.e. equal to R or R^2. We explicitly consider the biologically more relevant case of a bounded subset Ω of R^q, $q = 1, 2, 3$, a better model of a piece of cortex. The time behaviour of these networks is described by systems of integro-differential equations. Using methods of functional analysis, we study the existence and uniqueness of a stationary, i.e., time-independent, solution of these equations in the case of a stationary input. These solutions can be seen as "persistent", they are also sometimes called "bumps". We show that under very mild assumptions on the connectivity functions and because we do not use the Heaviside function for the nonlinearities, such solutions always exist. We also give sufficient conditions on the connectivity functions for the solution to be absolutely stable, that is to say independent of the initial state of the network. We then study the sensitivity of the solution(s) to variations of such parameters as the connectivity functions, the sigmoids, the external inputs, and, last but not least, the shape of the domain of existence Ω of the neural continuum networks. These theoretical results are illustrated and corroborated by a large number of numerical experiments in most of the cases $2 \leq n \leq 3$, $2 \leq q \leq 3$.

This work has been accepted for publication in Neural Computation [73].

5.3. Brain anatomical imaging using Diffusion MRI

5.3.1. Deterministic and Probabilistic Tractography Based on Complex Fiber Orientation Distributions

Keywords: *Diffusion tensor imaging (DTI)*, *High angular resolution diffusion imaging (HARDI) crossings*, *Probabilistic fiber tractography*, *Q-Ball imaging (QBI)*, *callosal Fibers*.

Participants: Rachid Deriche, Maxime Descoteaux, Alfred Anwander [Max Planck Institute for Human Cognitive and Brain Sciences, Leipzig, Germany], Thomas Knoesche [Max Planck Institute for Human Cognitive and Brain Sciences, Leipzig, Germany].

This work was partially supported by the CRSNG Canada graduate scholarship and PAI Procope (2006-2007).

In this work, we propose an integral concept for tractography to describe crossing and splitting fibre bundles based on the fibre orientation distribution function (ODF) estimated from high angular resolution diffusion imaging (HARDI). We show that in order to perform accurate probabilistic tractography, one needs to use a fibre ODF estimation and not the diffusion ODF. We use a new fibre ODF estimation obtained from a sharpening deconvolution transform (SDT) of the diffusion ODF reconstructed from q-ball imaging (QBI). This SDT provides new insight into the relationship between the HARDI signal, the diffusion ODF, and the fibre ODF. We demonstrate that the SDT agrees with classical spherical deconvolution and improves the angular resolution of QBI. Another important contribution of this paper is the development of new deterministic and new probabilistic tractography algorithms using the full multidirectional information obtained through use of the fibre ODF. An extensive comparison study is performed on human brain datasets comparing our new deterministic and probabilistic tracking algorithms in complex fibre crossing regions. Finally, as an application of our new probabilistic tracking, we quantify the reconstruction of transcallosal fibres intersecting with the corona radiata and the superior longitudinal fasciculus in a group of 8 subjects. Most current DTI-based methods neglect these fibres, which might lead to incorrect interpretations of brain functions.

This work has been published in [24].

5.3.2. High Angular Resolution Diffusion MRI Segmentation Using Region-Based Statistical Surface Evolution

Keywords: *Diffusion tensor imaging (DTI)*, *Orientation distribution function (ODF)*, *Q-Ball imaging (QBI)*, *Segmentation*, *Spherical harmonic (SH)*.

Participants: Rachid Deriche, Maxime Descoteaux.

This work was partially supported by the CRSNG Canada graduate scholarship, FQRNT-INRIA and PAI Procope (2006-2007).

In this article we develop a new method to segment high angular resolution diffusion imaging (HARDI) data. We first estimate the orientation distribution function (ODF) using a fast and robust spherical harmonic (SH) method. Then, we use a region-based statistical surface evolution on this image of ODFs to efficiently find coherent white matter fiber bundles. We show that our method is appropriate to propagate through regions of fiber crossings and we show that our results outperform state-of-the-art diffusion tensor (DT) imaging segmentation methods, inherently limited by the DT model. Results obtained on synthetic data, on a biological phantom, on real datasets and on all 13 subjects of a public NMR database show that our method is reproducible, automatic and brings a strong added value to diffusion MRI segmentation.

This work has been published in [23].

5.3.3. Labeling of ambiguous sub-voxel fibre bundle configurations in high angular resolution diffusion MRI

Keywords: *3D Curve inference*, *Branching*, *Crossing*, *Fanning*, *High angular resolution diffusion imaging (HARDI)*, *Q-ball imaging (QBI)*, *orientation distribution function (ODF)*, *tractography*.

Participants: Rachid Deriche, Maxime Descoteaux, Peter Savadjiev [School of Computer Science, McGill University, Montreal Canada], Jennifer S. W. Campbell [School of Computer Science/McConnell Brain Imaging Center, McGill University, Montreal Canada], G. Bruce Pike [McConnell Brain Imaging Center, McGill University, Montreal Canada], Kaleem Siddiqi [School of Computer Science, McGill University, Montreal Canada].

This work was partially supported by the CRSNG Canada graduate scholarship and FQRNT-INRIA.

Whereas high angular resolution reconstruction methods for diffusion MRI can estimate multiple dominant fibre orientations within a single imaging voxel, they are fundamentally limited in certain cases of complex subvoxel fibre structures, resulting in ambiguous local orientation distribution functions. In this article we address the important problem of disambiguating such complex subvoxel fibre tract configurations, with the purpose of improving the performance of fibre tractography. We do so by extending a curve inference method to distinguish between the cases of curving and fanning fibre bundles using differential geometric estimates in a local neighbourhood. The key benefit of this method is the inference of curves, instead of only fibre orientations, to model the underlying fibre bundles. This in turn allows distinct fibre geometries that contain nearly identical sets of fibre orientations at a voxel, to be distinguished from one another. Experimental results demonstrate the ability of the method to successfully label voxels into one of the above categories and improve the performance of a fibre-tracking algorithm.

This work has been presented and published in [29].

5.3.4. Mapping neuronal fiber crossings in the human brain

Keywords: *Diffusion tensor imaging (DTI)*, *Orientation distribution function (ODF)*, *Q-Ball imaging (QBI)*, *Segmentation*, *Spherical harmonic (SH)*.

Participants: Rachid Deriche, Maxime Descoteaux.

This work was partially supported by the CRSNG Canada graduate scholarship, FQRNT-INRIA and PAI Procope (2006-2007).

Obtaining information about the anatomical connectivity of the human brain, noninvasively, is a difficult challenge facing neuroscientists. The adult human brain contains tens of billions of neuronal cells, each with multiple cell contacts that form a complex web. Moreover, higher-order structures, termed neural tracts or fiber bundles, form a complicated 3D network connecting different brain regions. The distinct connectivity pattern of a given brain region determines how it processes information and how it functions. Being able to map these complex neural patterns in vivo is essential for understanding the fundamental basis of many developmental disorders as well as defining how the brain's structure relates to its function. This article, published in [41], gives a nice overview of our recent work toward achieving these objectives.

5.3.5. Detection of multiple pathways in the spinal cord using Q-ball imaging

Keywords: *Diffusion tensor imaging*, *High angular resolution diffusion imaging*, *Q-ball*, *Spinal cord*, *White matter*.

Participants: Rachid Deriche, Maxime Descoteaux, Julien Cohen-Adad [University of Montreal/UPMC Paris 6], Serge Rossignol [CRSN, University of Montreal], Rick D. Hoge [Biomedical Engineering Institute, University of Montreal], Habib Benali [U678 INSERM, CHU Pitié-Salpêtrière].

This work was partially supported by ARC Diffusion MRI.

Magnetic resonance diffusion tensor imaging (DTI) has been extensively applied to the spinal cord for depicting its architecture and for assessing its integrity following spinal lesions. However, DTI is limited in representing complex white matter architecture, notably in the presence of crossing fibres. Recently, q-ball imaging (QBI) has been proposed as a new method for recovering complex white matter architecture. In this work, we applied this technique to both ex-vivo and in-vivo spinal cords of cats using a 3T scanner. For the purpose of comparison, gradients have been applied in 55 and 100 encoding directions and b-values varied from 800 to 3000 s/mm^2. As a result, QBI was able to retrieve crossing fibre information, where the DTI approach was constrained in a unique diffusion direction. To our knowledge, this is the first study demonstrating the benefits of QBI for detecting the presence of longitudinal, commissural and dorso-ventral fibres in the spinal cord. It is a first step towards in vivo characterization of the healthy and injured human spinal cord using high angular resolution diffusion imaging and QBI.

This work has been published in [21], [39].

5.3.6. Diffusion Abnormalities in the Primary Sensorimotor Pathways in Writer's Cramp

Keywords: *Diffusion tensor imaging (DTI)*, *Dystonia*, *High angular resolution diffusion imaging (HARDI) crossings*, *Probabilistic fiber tractography*, *Q-Ball imaging (QBI)*, *Writer's cramp*, *callosal Fibers*.

Participants: Rachid Deriche, Maxime Descoteaux, Demian Wassermann, Christophe Lenglet, Christine Delmaire [CENIR,CHUPS, Paris], Marie Vidailhet [UPMC,Paris 6, INSERM U679], Stéphane Lehéricy [CENIR,CHUPS,Paris].

This work was partially supported by the ARC Diffusion MRI.

Writer's cramp is a task-specific form of primary dystonia that occurs in patients having a long history of repetitive, stereotyped, overlearned writing movements before the onset of dystonia. Structural imaging studies have shown the involvement of the sensorimotor circuit in dystonia. Early morphological imaging studies in stroke patients reported that dystonia was observed after damage in several subcortical areas including the basal ganglia, the thalamus, and less often the cerebellum, suggesting a role of the basal ganglia in dystonia. A common hypothesis to explain to pathophysiology of dystonia is that defects in the basal ganglia and particularly the indirect pathway result in impaired suppression of unwanted excessive muscle activity that is observed in dystonia. Subsequently, progress in image analysis methods, such as voxel-based statistical comparisons in grey matter density, allowed the detection of structural changes in primary dystonia. Changes in grey matter density were reported in writer's cramp in the basal ganglia, as well as the sensorimotor cortex, the thalamus, and the cerebellum. Using similar imaging approaches, grey matter changes were detected in other forms of primary dystonia. These observations suggest that writer's cramp may be associated not only with the dysfunction of the basal ganglia but also of several brain structures interconnected within the

sensorimotor network. More recently, diffusion tensor magnetic resonance imaging (DTI) has shown its ability to assess white matter integrity. In white matter, water diffusion is directionally dependent, predominantly along the direction of axons. This property can be quantified using various objective measures, the most popular being fractional anisotropy (FA). FA which can be computed using region-of- interest measurements or tractography or voxel-wise measurements, and quantifies diffusion anisotropy within a voxel. From DTI images, axonal orientation within each voxel can be estimated based on its alignment with the direction of fast diffusion. Then, by subsequently relating the predominant diffusion orientation among neighboring voxels, three dimensional pathways macroscopically representing axonal bundles can be obtained by the technique called tractograpy. Using DTI, changes in FA were reported in the subcortical white matter of the sensorimotor cortex in DYT1 carriers. Therefore, diffusion abnormalities may involve fibers connecting the sensorimotor cortex with subcortical structures. In this work, we combined voxel-wise cross-subject statistics and tractography to test this hypothesis and evaluate white matter pathology in patients with writer's cramp.

This work has been published in [69],[40].

5.3.7. *Impact of Rician Adapted Non-Local Means Filtering on HARDI*

Keywords: *High angular resolution diffusion imaging (HARDI)*, *Rician Noise*.

Participants: Rachid Deriche, Maxime Descoteaux, Nicolas Wiest-Daesslé [Visages, INRIA Rennes - Bretagne Atlantique], Sylvain Prima [Visages, INRIA Rennes - Bretagne Atlantique], Christian Barillot [Visages, INRIA Rennes - Bretagne Atlantique].

This work was partially supported by ARC Diffusion MRI.

In this work [42] we study the impact of denoising the raw high angular resolution diffusion imaging (HARDI) data with the Non-Local Means filter adapted to Rician noise (NLMr). We first show that NLMr filtering improves robustness of apparent diffusion coefficient (ADC) and orientation distribution function (ODF) reconstructions from synthetic HARDI datasets. Our results suggest that the NLMr filtering improve the quality of anisotropy maps computed from ADC and ODF and improve the coherence of q-ball ODFs with the underlying anatomy while not degrading angular resolution. These results are shown on a biological phantom with known ground truth directions and on a real human brain dataset. Most importantly, we show that acquiring multiple diffusion-weighted (DW) images and averaging these images along each direction can be avoided because NLMr filtering of the individual DW images produces better quality generalized fractional anisotropy maps and more accurate ODF fields than when computed from the averaged DW datasets.

This work has been published in [42].

5.3.8. *Diffusion Maps Clustering for Magnetic Resonance Q-Ball Imaging Segmentation*

Keywords: *Clustering*, *Laplacian Eigenmaps*, *N-Cuts Segmentation*, *Orientation distribution function (ODF)*, *Q-Ball Imaging*, *Spectral Embedding*.

Participants: Rachid Deriche, Maxime Descoteaux, Demian Wassermann.

This work was partially supported by the ARC Diffusion MRI and the INRIA CORDIS frameworks.

White matter fiber clustering aims to get insight into anatomical structures in order to generate atlases, perform clear visualizations, and compute statistics across subjects, all important and current neuroimaging problems. In this work [34], we present a diffusion maps clustering method applied to diffusion MRI in order to segment complex white matter fiber bundles. It is well known that diffusion tensor imaging (DTI) is restricted in complex fiber regions with crossings and this is why recent high-angular resolution diffusion imaging (HARDI) such as Q-Ball imaging (QBI) has been introduced to overcome these limitations. QBI reconstructs the diffusion orientation distribution function (ODF), a spherical function that has its maxima aligned with the underlying fiber populations. In this paper, we use a spherical harmonic ODF representation as input to the diffusion maps clustering method. We first show the advantage of using diffusion maps clustering over classical methods such as N-Cuts and Laplacian eigenmaps. In particular, our ODF diffusion maps require a smaller number of hypotheses from the input data, reduces the number of artifacts in the segmentation, and automatically exhibits the number of clusters segmenting the Q-Ball image by using an adaptive scale-space

parameter. We also show that our ODF diffusion maps clustering can reproduce published results using the diffusion tensor (DT) clustering with N-Cuts on simple synthetic images without crossings. On more complex data with crossings, we show that our ODF-based method succeeds to separate fiber bundles and crossing regions whereas the DT-based methods generate artifacts and exhibit wrong number of clusters. Finally, we show results on a real-brain dataset where we segment well-known fiber bundles.

This work has been published in [34].

5.3.9. Simultaneous Manifold Learning and Clustering: Grouping White Matter Fiber Tracts Using a Volumetric White Matter Atlas

Keywords: *Clustering*, *Laplacian Eigenmaps*, *N-Cuts Segmentation*, *Orientation distribution function (ODF)*, *Q-Ball Imaging*, *Spectral Embedding*.

Participants: Rachid Deriche, Demian Wassermann.

This work was partially supported by the ARC Diffusion MRI and the INRIA CORDIS frameworks.

We propose a new clustering algorithm. This algorithm performs clustering and manifold learning simultaneously by using a graph-theoretical approach to manifold learning. We apply this algorithm in order to cluster white matter fiber tracts obtained from Diffusion Tensor MRI (DT-MRI) through streamline tractography. Our algorithm is able to cluster these fiber tracts by incorporating information about the shape of the fiber and a priori knowledge as the probability of the fiber belonging to known anatomical structures. This anatomical knowledge is incorporated as a volumetric white matter atlas, in this case LONI's ICBM DTI-81.

This work has been published in [46].

5.3.10. A polynomial based approach to extract the maxima of an antipodally symmetric spherical function and its application to extract fiber directions from the Orientation Distribution Function in Diffusion MRI

Keywords: *Fiber bundles*, *Homogeneous Polynomial basis*, *Lagrange Multiplier*, *Orientation distribution function (ODF) maxima*, *Spherical Harmonic basis*, *Stationary points*, *Symmetric Tensor Basis*.

Participants: Rachid Deriche, Aurobrata Ghosh, Elias Tsigaridas [Galaad Project Team, INRIA Sophia Antipolis, Méditerranée], Bernard Mourrain [Galaad Project Team, INRIA Sophia Antipolis, Méditerranée], Pierre Comon.

This work was partially supported by the ARC Diffusion MRI and the ANR-06-BLAN-0074 "Decotes" contracts.

In this work we extract the geometric characteristics from an antipodally symmetric spherical function (ASSF), which can be described equivalently in the spherical harmonic (SH) basis, in the symmetric tensor (ST) basis constrained to the sphere, and in the homogeneous polynomial (HP) basis constrained to the sphere. All three bases span the same vector space and are bijective when the rank of the SH series equals the order of the ST and equals the degree of the HP. We show, therefore, how it is possible to extract the maxima and minima of an ASSF by computing the stationary points of a constrained HP. In Diffusion MRI, the Orientation Distribution Function (ODF), represents a state of the art reconstruction method whose maxima are aligned with the dominant fiber bundles. It is, therefore, important to be able to correctly estimate these maxima to detect the fiber directions. The ODF is an ASSF. To illustrate the potential of our method, we take up the example of the ODF, and extract its maxima to detect the fiber directions. Thanks to our method we are able to extract the maxima without limiting our search to a discrete set of values on the sphere, but by searching the maxima of a continuous function. Our method is also general, not dependent on the ODF, and the framework we present can be applied to any ASSF described in one of the three bases.

This work has been published in [74].

5.3.11. Riemannian Framework for estimating Symmetric Positive Definite 4th Order Diffusion Tensors

Keywords: *4th order DTI (HARDI)*, *High Order Diffusion tensor imaging (HO-DTI).*

Participants: Rachid Deriche, Aurobrata Ghosh, Maxime Descoteaux.

This work was partially supported by ARC Diffusion MRI.

DTI is an important tool to investigate the brain in vivo and non-invasively in spite of its shortcomings in regions of fiber-crossings. HARDI models such as QBI and Higher Order Tensors (HOT) were invented to overcome this shortcoming. HOTs, however, have not been explored extensively even though sophisticated estimation schemes were developed for DTI that guarantee positive diffusivity, such as the Riemannian framework. Positive diffusivity is an important constraint in diffusion MRI since it represents the physical phenomenon of molecular diffusion. It seems apt, to leverage the work done on DTI, to apply the positivity constraint to the HOT model. We, therefore, propose to extend the Riemannian framework from DTI to the space of 4th order diffusion tensors. We also review the existing methods for estimating 4th order diffusion tensors and compare all methods on synthetic, phantom and real datasets extensively to test for robustness and speed. Our contributions for extending the Riemannian framework from DTI to estimating 4th order diffusion tensors guarantees positive diffusivity, is robust, is fast, and can be used to discern multiple fiber directions.

This work has been published in [44].

5.3.12. Mathematical Methods for Diffusion MRI Processing

Keywords: *Diffusion MRI*, *Diffusion Tensor Imaging (DTI)*, *Funk-Radon Transform (FRT)*, *High Angular Resolution Diffusion Imaging (HARDI)*, *Manifold learning*, *N-cuts*, *Non-uniform complexity*, *Orientation Distribution Function (ODF)*, *Q-Ball Imaging (QBI)*, *Segmentation*, *Spherical Harmonics (SH)*, *Stratification*, *Sub-voxel Fiber configurations*, *Tractography*.

Participants: Rachid Deriche, Christophe Lenglet, Maxime Descoteaux, Demian Wassermann, Peter Savadjiev [School of Computer Science, McGill University, Montreal Canada], Jennifer S. W. Campbell [School of Computer Science/McConnell Brain Imaging Center, McGill University, Montreal Canada], G. Bruce Pike [McConnell Brain Imaging Center, McGill University, Montreal Canada], Kaleem Siddiqi [School of Computer Science, McGill University, Montreal Canada], Alfred Anwander [Max Planck Institute for Human Cognitive and Brain Sciences, Leipzig, Germany], Gloria Haro [Universitat Politecnica de Catalunya, Barcelona, Spain], Guillermo Sapiro [Department of Electrical and Computer Engineering, University of Minnesota, Minneapolis MN USA], Paul Thompson [LONI, University of California, Los Angeles CA, USA].

This work was partially supported by the ARC Diffusion MRI and the NSF/INRIA and the INRIA/FQRNT frameworks.

[27] reviews recent mathematical models and computational methods for the processing of diffusion Magnetic Resonance Images, including state-of-the-art reconstruction of diffusion models, cerebral white matter connectivity analysis, and segmentation techniques. We focus on Diffusion Tensor Images (DTI) and Q-Ball Images (QBI).

5.4. Brain functional imaging using MEG/EEG

The work depicted in this sub-theme concerns various aspects related to the problem of estimating the sources in the brain corresponding to some given activity. Besides the forward and inverse EEG/MEG problems (see sections 5.4.1 and 5.4.3) which are directly connected to this problem, there are a number of additional problems such as finding the events of interest in the recorded signal (section 5.4.2). Some of the tools described in this sub-theme are distributed in the opensource library OpenMEEG (see section 4.4).

5.4.1. Inverse problems of MEG and EEG

Keywords: *EEG*, *Inverse problem*, *MEG*, *Source localization*.

Participants: Maureen Clerc, Alexandre Gramfort, Kaushik Majumdar, Theo Papadopoulo, Fehmi Ben Hassen [LAMSIN-ENIT], Juliette Leblond [APICS project-team], Meriem Zghal [APICS project-team].

This work was partially supported by the Fondation d'Entreprise EADS.

Investigating on brain activity with EEG or MEG measurements requires the solution of ill-posed inverse problems, whose solution implies regularization. Source models for EEG and MEG can be either distributed dipoles or isolated dipoles. In distributed models, the relationship between sources and measurements is linear, but the problem is undercontrained because thousands of putative positions for the cortical activity must be handled at the same time. In isolated dipole models, on the contrary, there are less unknowns than measurements, but the relationship between sources and measurements is more complex.

Their work on rational approximation has allowed researchers from the APICS project-team to propose an original method for source localization, when the sources are modeled as isolated dipoles. The force of the method is to provide a good and stable estimation of the number of sources and of their positions and moments. It requires the knowledge of the potential on the inner skull surface, provided by a Cortical Mapping method developed at Odyssée [68]. Cortical Mapping and rational approximation techniques are now being combined, leading to a dipolar source localization directly from scalp electrode measurements [36].

We are engaged in an ANR grant on Multimodal Neuroimaging of Rapid Brain Processes in the Human Visual System (ViMAGINE). An initial step in the exploration of the Human Visual System has been to perform retinotopy, i.e. determine the subject-dependent mapping linking positions in the visual field to the positions of the associated activity in the low-level visual cortex [52]. Since brain activity is not static, but varies in time, the regularization of the inverse problem should take time into account. A new approach has been proposed to track cortical activity with spatio-temporal constraints, and its implementation uses graph-cuts for computational efficiency [53]. This spatio-temporal regularization is a post-processing which is applied to a minimum-norm inverse problem. Another kind of minimum-norm processing takes into account a statistical measure of phase-synchronization between sources [78].

5.4.2. Single trial analysis of brain signals

Keywords: *Brain Computer Interface*, *EEG*, *MEG*, *Matching Pursuit*, *Signal analysis*.

Participants: Maureen Clerc, Theo Papadopoulo, Jean Le Pavec, Joan Fruitet, Alexandre Gramfort, Christian Bénar [INSERM U751], Bruno Torrésani [LATP, CMI, Université de Provence].

This work was partially supported by the Fondation d'Entreprise EADS.

The signal-to-noise ratio of EEG and MEG measurements is very low, and advanced signal processing tools must be used to extract information from the signals. The time series we have to handle are multivariate (several sensors) and generally multi-trial, because experiments are repeated to enhance signal-to-noise ratio.

In the signal processing literature, there is a growing interest in sparse representations, using the matching pursuit algorithm, which iteratively subtracts from the signal its projection on atoms selected from a dictionary. So far, most approaches have assumed a stable pattern across channels or trials, even though cross-trial variability is often observed in brain signals. We have adapted Matching Pursuit for brain signals with cross-trial variability in all their characteristics (time, frequency, number of oscillations). The originality of our approach is to select each atom using a voting technique that is robust to variability, and to subtract it by adapting the parameters to each trial. Because it is designed to handle inter-trial variability using a voting technique, the method is called Consensus Matching Pursuit (CMP) [56].

We are starting to explore the use of EEG for Brain Computer Interfaces, more specifically, the classification of signals corresponding to different mental states, voluntarily produced by a subject. For this, we use Support Vector Machines, and we observe that the classification performance strongly depends on the type of mental tasks performed by the subject [49].

5.4.3. Forward models for MEG and EEG

Keywords: *EEG*, *Head model*, *MEG*, *conductivity*, *segmentation*.

Participants: Maureen Clerc, Emmanuel Olivi, Theo Papadopoulo, Jérôme Piovano, Sylvain Vallaghé, Jean-Michel Badier [INSERM U751].

This work was partially supported by the Fondation d'Entreprise EADS.

Most methods for the inverse source problem in electroencephalography (EEG) and magnetoencephalography (MEG) use a lead field as an input. The lead field is the function which relates any source in the brain to its measurements at the sensors. Its computation requires to solve a forward problem. In his PhD thesis, Sylvain Vallaghé has obtained several new results concerning the computation and calibration of the forward problem [14].

The inverse source localization problem of EEG and MEG strongly depends on the quality of the forward solution. The information required to specify the forward problem are the geometrical and physiological description of the head, in terms of its electrical conductivity. We have proposed a global sensitivity analysis of conductivity, which provides new information about EEG forward models. It identifies the main input parameters which need model refinement, and gives directions on how to calibrate these models [54], [82].

For complex geometries, there is no analytical formula of the lead field. The common approach is to numerically compute the value of the lead field for a finite number of point sources (dipoles). There are several drawbacks. The model of the source space is fixed (a set of dipoles) and the computation can be expensive for as much as 10000 dipoles. The common idea to bypass these problems is to compute the lead field from a sensor point of view. We use the adjoint method to derive general EEG and MEG sensor-based lead field equations. Within a simple framework, we provide a complete review of the explicit lead field equations, and we are able to extend these equations to non-pointlike sensors [83].

Another problem with EEG and MEG forward modeling is the obtention of the complex geometry of the head. This is particularly true for the skull which is barely visible in standard T1 images. The local statistics based approach of segmentation [80],[45] has been adapted to segment the head using simultaneously T1- and T2-images. T1-images are best used to obtain the skin, grey matter and white matter interfaces, whereas T2-images enhance the contrast of CSF so that the inner interface of the skull (as well as blood vessels which are often segmented as grey/white matter material) are visible. This approach leads to interfaces described by levelsets that can directly be used for the M/EEG forward method described [79].

5.4.4. Forward models for nerve models

Keywords: *Functional Electrical Stimulation*, *nerve model*.

Participants: Kyle Beauchamp, Maureen Clerc, Romain Veltz, Jean-Louis Divoux [MXM], Sabir Jacquir [Université Bourgogne], David Guiraud [DEMAR].

This work was partially supported by an NSF-INRIA grant (Vanderbilt University).

We are studying the 3D potential induced by functional electrical stimulation, with the aim to propose a numerical model of nerve-cuff electrode. This model will be used to study and predict interactions between nerve fibres and electrode during stimulation. Our recent contributions to this topic concern both the numerical resolution of the problem and the experimental validation, with a robotized probe and an electrode designed specifically for the experiment. The computation of current densities and voltage within the nerve can eventually be used to determine whether an axon is fired or not depending on its position [51].

5.5. Biological and Computational Vision

5.5.1. Texture and color segmentation based on the combined use of the structure tensor and the image components

Keywords: *Image segmentation*, *Kullback–Leibler distance*, *Level set theory*, *Local structure tensor*, *Nonlinear diffusion*, *Texture segmentation*.

Participants: Rachid Deriche, Rodrigo De Luis Garcia [Laboratorio de Procesado de Imagen (LPI) - Universidad de Valladolid, Spain], Carlos Alberola-López [ETSI Telecomunicación and Universidad de Valladolid, Spain].

In this paper, we propose a novel segmentation scheme for textured gray-level and color images based on the combined use of the local structure tensor and the original image components. The structure tensor is a well-established tool for image segmentation and has been successfully employed for unsupervised segmentation of textured gray-level and color images. The original image components can also provide very useful information. Therefore, a combined segmentation approach has been designed that combines both elements within a common energy minimization framework. Besides, an original method is proposed to dynamically adapt the relative weight of these two pieces of information. Quantitative experimental results on a large number of gray-level and color images show the improved performance of the proposed approach, in comparison to several related approaches in recent studies. Experiments have also been carried out on real world images in order to validate the proposed method.

This work has been published in [22].

5.5.2. *Can the nonlocal characterization of Sobolev spaces by Bourgain et al. be useful to solve variational problems?*

Keywords: *Sobolev spaces*, *image restauration*, *infinite Laplacian*, *numerical approximation*, *optimization*, *space of bounded variations*, *variational problems*.

Participants: Gilles Aubert [Laboratoire J.A. Dieudonné, Université de Nice-Sophia Antipolis], Pierre Kornprobst.

We question whether the recent characterization of Sobolev spaces by Bourgain, Brezis and Mironescu (2001) could be useful to solve variational problems on $W^{1,p}(\Omega)$. To answer this, we introduced in [61] a sequence of functionals so that the semi-norm is approximated by an integral operator involving a differential quotient and a radial mollifier. Then, for the approximated formulation, we proved existence, uniqueness and convergence of the solution to the unique solution of the initial formulation. We showed that these results can also be extended in the BV–case. Interestingly, this approximation leads to a unified implementation, for Sobolev spaces (including with high p–values) and for the BV space. Finally, we showed how this theoretical study can indeed lead to a numerically tractable implementation, and we give some image diffusion results as an illustration.

5.5.3. *Efficient Segmentation of Piecewise Smooth Images*

Participants: Jérôme Piovano, Théo Papadopoulo.

Segmentation models based on local information combine local statistics of the regions along the contour (inside and outside) to obtain its evolution [80]. Although these models are more robust to region inhomogeneities and to local coherence than models based on global statistics, they have their own drawbacks. First, as the statistics are computed locally, the global coherence of the segmentation may not be guaranteed. Second, there is no evolution in areas where the local statistics inside and outside the contour are the same. [45] proposes solutions to both problems using some heuristics to impose coherence and standard scale space theory. Statistical information at various scales are combined for each point of the contour to obtain an evolution speed.

5.5.4. *Towards bridging the Gap between Biological and Computational Image Segmentation*

Keywords: *Biological Vision*, *Boltzmann Machines Learning* , *Boundary Contour System*, *Computer Vision*, *Edge Grouping*, *Feature Contour System*, *Line Process*, *Mean Field Theory*, *Neural Networks*, *Perceptual Grouping*, *Surface Process*, *Variational Techniques for Computer Vision*.

Participants: Rachid Deriche, Olivier Faugeras, Iasonas Kokkinos [Odyssée/National Technical University of Athens, Computer Vision, Speech Communication and Signal Processing Group], Petros Maragos [National Technical University of Athens, Computer Vision, Speech Communication and Signal Processing Group].

This work was partially supported by the EC IP project FP6-015879, FACETS and the Fondation d'Entreprise EADS.

Computational Vision The branch of computer science and applied mathematics that studies way of emulating visual performances with computers.

This work [26] presents a joint study of biological and computational vision. First we briefly review the most common models of neurons and neural networks and the function of cells in the V1/V2 areas of the visual cortex. Subsequently, we present the biologically plausible models for image segmentation that have been proposed by Stephen Grossberg and his collaborators during the previous two decades in a series of papers. We have implemented the B.C.S. (Boundary Contour System) and F.C.S. (Feature Contour System) models that form the basic building blocks of this model of biological vision, known as FACADE (Form And Colour and DEpth) theory. During their implementation, we faced several problems, like a large number of parameters and instability with respect to these; this was not traded off with a higher performance when compared to classical computer vision algorithms. This has led us to propose a simplified version of the B.C.S./F.C.S. system, and to explore the merits of using nonlinear recurrent dynamics. The biologically plausible model we propose is paralleled with classical computational vision techniques, while a link with the variational approach to computer vision is established. By interpreting the network function in a probabilistic manner we derive an algorithm for learning the network weights using manually determined segmentations excerpted from the Berkeley database. This facilitates learning the terms involved in the variational criterion that quantifies edge map quality from ground truth data. Using the learned weights our network outperforms classical edge detection algorithms, when evaluated on the Berkeley segmentation benchmark.

5.5.5. Action recognition using a bio-inspired feedforward model

Keywords: *Action recognition*, *Biological motion recognition*, *MT*, *Motion analysis*, *Spiking networks*, *V1*.

Participants: Maria-Jose Escobar, Pierre Kornprobst, Guillaume Masson [Centre de Recherche en Neurosciences Cognitives, CNRS, FRE2098, 13402 Marseille, France], Thierry Viéville.

This work was partially supported by the EC IP project FP6-015879, FACETS and the Fondation d'Entreprise EADS.

biological motion motion of a living character

In this work, we consider a bio-inspired model of V1 and MT layers related to motion estimation and integration. The V1 layer is formed as an array of direction-selective V1 complex cells tuned for different speeds and directions of motion. Each V1 complex cell is modeled with a motion energy detector following [60]. The MT layer performs some integration of the V1 output. Our goal is to investigate to which extent the motion pattern activities at the MT level could be sufficient to recognize a human action in a video.

In [43], we show that reproducing the functional properties of MT cells with various center–surround interactions enriches motion representation and improves the action recognition performance. To do so, we reproduce some of the richness of center-surround interactions of MT cells. Interestingly, as observed in neurophysiology, our MT cells not only behave like simple velocity detectors, but also respond to several kinds of motion contrasts. Results show that this diversity of motion representation at the MT level is a major advantage for an action recognition task. Defining motion maps as our feature vectors, we used a standard classification method on the Weizmann database: We obtained an average recognition rate of 98.9%, which is superior to the recent results by Jhuang et al. [76]. These promising results encourage us to further develop bio–inspired models incorporating other brain mechanisms and cortical layers in order to deal with more complex videos.

In [57], we question whether analysing a spiking output from a spiking version of our V1-MT model could be be used to perform action recognition. To answer this, we adapted the model from [43] to deal with spiking simulations, and in order to analyze spike trains, we consider two characteristics of the neural code: mean firing rate of each neuron and synchrony between neurons. Interestingly, we show that they both carry some relevant information for the action recognition application. We compare our results to Jhuang et al. [76] on the

Weizmann database and we obtain satisfying results. This contribution opens promising perspectives that we plan to follow.

5.5.6. A Simple Mechanism to Reproduce the Neural Solution of the Aperture Problem in Monkey Area MT

Keywords: *Aperture problem*, *MT*, *Motion analysis*, *V1*.

Participants: Maria-Jose Escobar, Pierre Kornprobst, Guillaume Masson [Centre de Recherche en Neurosciences Cognitives, CNRS, FRE2098, 13402 Marseille, France].

This work was partially supported by the EC IP project FP6-015879, FACETS and the Fondation d'Entreprise EADS.

aperture problem The aperture problem is defined by the fact that the motion direction of a contour is ambiguous, because the motion component parallel to the line cannot be inferred based on the visual input. This means that a variety of contours of different orientations moving at different speeds can cause identical motion percept.

In [48], we propose a simple mechanism to reproduce the neural solution of the aperture problem in monkey area MT. More precisely, our goal is to propose a model able to reproduce the dynamical change of the preferred direction (PD) of a MT cell depending on the motion information contained in the input stimulus. The PD of a MT cell measured through drifting gratings differs of the one measured using a barberpole, which is highly related with its aspect ratio. For a barberpole, the PD evolves from the perpendicular direction of the drifting grating to a PD shifted according to the aspect ratio of the barberpole. The mechanisms underlying this dynamic are unknown (lateral connections, surround suppression, feed-backs from higher layers). Here, we show that a simple mechanism such as surround-inhibition in V1 neurons can produce a significant shift in the PD of MT neurons as observed with barberpoles of different aspect ratios.

5.5.7. Virtual Retina: Large-scale retina simulator

Keywords: *retina*, *simulator*, *spikes*.

Participants: Adrien Wohrer [correspondant], Pierre Kornprobst [projet Odyssée].

We finalized our work concerning the retina simulation software, called Virtual Retina, which transforms a video into spike trains [15], [35]. Our goal was twofold: Allow large scale simulations (up to 100,000 neurons) in reasonable processing times and keep a strong biological plausibility (see [58] for a review), taking into account implementation constraints. The underlying model includes a linear model of filtering in the Outer Plexiform Layer, a well-posed shunting feedback at the level of bipolar cells accounting for rapid contrast gain control [84], and a spike generation process modeling ganglion cells. We proved the pertinence of our software by reproducing several experimental measurements from single ganglion cells such as cat X and Y cells. This software will be an evolutionary tool for neuroscientists that need realistic large-scale input spike trains in subsequent treatments, and for educational purposes. We also developed a web service, so that one may test directly the main software on his own data, without any installation.

This work was partially supported by the EC IP project FP6-015879, FACETS and the Fondation d'Entreprise EADS. To learn more, please visit the web page http://www-sop.inria.fr/odyssee/software/virtualretina/

5.5.8. Biological motion integration based on form cues

Keywords: *MT*, *Motion analysis*, *V1*.

Participants: Emilien Tlapale, Guillaume Masson [Institut de Neurosciences Cognitives de la Méditerranée, UMR 6193, CNRS, Marseille, France], Thierry Viéville [Cortex project-team], Pierre Kornprobst.

This work was partially supported by the EC IP project FP6-015879 (FACETS), the EC ICT project No. 215866 (SEARISE) and the Région Provence-Alpes-Côte d'Azur.

In [50], we propose a model of motion integration modulated by form information, which is able to explain a large class of classical motion stimuli percepts. This model is related to other multi-layer architectures incorporating both feedforward, feedback and inhibitive lateral connections such as Bayerl and Neumann [62]. There are two main contributions. The first contribution is that we propose a new anisotropic integration model as an alternative to model several additional layers or specific feature detectors. The second is that we show that this model is able to reproduce a large set of motion percept and that it is also competitive on real videos, given an efficient implementation using GPGPU.

6. Contracts and Grants with Industry

6.1. Fondation d'Entreprise EADS: A multi-scale investigation of the operating brain with an eye on visual perception.

Participants: Maureen Clerc, Rachid Deriche, Olivier Faugeras, Pierre Kornprobst, Théo Papadopoulo.

This project deals with the problem of better measuring, modeling and simulating the set of representations that are used and the flow of processing that is performed in the human brain to achieve efficient visual perception. This is indeed a challenge because despite all the knowledge that has been accumulated on the functioning of the brain over the last years, many very basic questions still remain open, e.g.: What is the "information" conveyed by neuronal electrical and chemical activity? How is the information encoded in this activity? How is the information distributed among brain areas? In particular, what are the respective roles of feedforward and feedback connections between brain areas? Can we infer any "computational" paradigms from the observation of the functioning of the brain and the computer simulation of parts of this functioning? Most of these questions arise from the fact that it has proven to be extremely difficult to connect 1) the small scale knowledge of the functioning of one neuron or a small population of neurons (chemical/electrical models) to 2) the large scale (in space and/or in time) knowledge (spatial organisation, main connections, spatial and temporal activations,...) provided by brain imagery observations (functional Magnetic Resonance Images (fMRI), MagnetoEncephalography (MEG), ElectroEncephalography (EEG), Diffusion Magnetic Resonance Images (DMRI), optical imaging). Similarly, the large scale knowledge of the brain activations has turned out to be difficult to relate to 3) the mathematical and computational principles underlying their (somewhat) equivalent computer implementations (when they exist). As an example, what we know about the processing of visual motion in humans has hardly ever been compared with the field of motion analysis in computer vision. But certainly the abilities of the best computer programs in terms of the analysis of 2D and 3D motions of objects in video sequences of images are way behind the state of the art of most mammalian brains. The intent of this project is double. First we want to build some connections between these three levels of description, particularly for the low-level vision areas of the brain and the feedback loops between these areas. Second we want to show that this increase of knowledge can be put to good use from the technological standpoint and opens the door to new ways of interacting with the machines our societies build. The project covers some of the parts of the current research program of the Odyssée laboratory which are not covered by other grants. The potential impacts of our research are multifold:

1. By combining single-neuron models (microscopic scale) which can reproduce large numbers of observed spiking behaviours (see point 6 below) into medium size networks (containing of the order of 105 individuals and their connections), we will be able to reach the so-called mesoscopic scale of what seems to be the elementary processing unit in the human cortex, the cortical column. The computer simulation of a few of these units can be achieved using existing simulators such as mvaspike. The results can be confronted with optical imaging measurements which can also be used to estimate the parameters. Bridging the gap between the microscopic and mesoscopic levels of description is an important challenge in neuroscience.
2. By combining these neural-mass models with a description of the cortex geometry such as the one obtained from anatomical MRI and anatomical connectivity such as the one obtained from DMRI

we will be able to reach the macroscopic level of description of a significant part of a brain area. The computer simulation of these parts can then be confronted with fMRI, MEG and EEG measurements since they operate at comparable spatio-temporal scales. Bridging the gap between the mesoscopic and macroscopic levels of description can have an important impact for the understanding of such aspects of brain disfunctioning as epilepsy. Related to this remark this will also provide better electrical source models which are much needed in MEG and EEG.

3. Still at the macroscopic level, the role of feedback connections between brain areas is much less well known and understood than that of feedforward ones. They seem to be central for some fundamental visual processes such as figure-ground segregation and attention where they are likely to carry learned or innate priors. Furthermore, they are a generic organizational feature of the cortex, therefore the knowledge acquired in the context of the processing of visual information can potentially be transferred to other areas than vision; this may contribute to define new computational paradigms for information processing, e.g., in computer vision where the use of priors is becoming essential.
4. Pushing the level of sophistication of brain descriptions (electrical source models, geometry, physical properties of tissues) used into the imaging methods can lead to better tools or at the very least to a better understanding of the limitations of the existing ones and thus ways to improve them. This may contribute to enhance currently available medical imaging techniques, in a broad sense, and therefore have a strong impact on Health programs.
5. Low-level vision areas in the brain correspond to functions that have fairly well-denned counterparts in the computer vision field. It would therefore be very interesting to compare the performances of biologically inspired and computer vision based algorithms in particular to investigate whether the latter have intrinsic limitations with respect to the former or/and to assess the level of details absolutely necessary to reproduce interesting aspects of brain behaviour.
6. Models of "computation" should also be compared. Traditional neural networks process continuous quantities in a way that resembles how an analog or digital computer using oating point arithmetic would solve a minimization problem or compute the solution of a partial differential equation. Real neurons deal with action potentials which are discrete events (their duration is of the order of 1ms), spikes, that are produced every few milliseconds in the 1011 neurons of a human brain, propagate along the 1015 connections between them and create or inhibit electrical activity here and there. The way such huge asynchronous networks can embody the kind of computation that seems to be necessary to achieve, e.g., visual perception, is very different from that of traditional neural network technology (which failed in this program) and essentially unknown. Unveiling some of these mysteries can potentially have a strong impact on computation paradigms for many real time applications and for such emerging areas as Brain Computer Interface.

In this project we focus on the points 2-5 above, points 1 and 6 being partly supported by another grant (European project FACETS). Bullier has shown that the time scale at which the feedback connections referred to above occur in the visual system is of the order of a few tens of milliseconds. This is way beyond what can currently be achieved using fMRI with humans. Moreover, fMRI reflects neuronal activity only very indirectly via such physiological parameters as blood oxygenation and it is still unclear how accurately these reflect neuronal activity and to what detail. On the other hand such modalities as Electroencephalography (EEG) and Magnetoencephalography (MEG) do offer the kind of time resolution that is needed to observe cortical feedbacks. However, to get the feedback information, the MEG and EEG techniques must be enhanced to incorporate connectivity and better spatio-temporal source models. This observation is central to our project.

7. Other Grants and Activities

7.1. Actions nationales

7.1.1. ARC Diffusion MRI

Keywords: *Brain Anatomical Imaging*, *Diffusion Tensor Imaging*, *HARDI*, *Q-Ball Imaging*, *Tractography*.

Participants: Rachid Deriche, Maxime Descoteaux, Demian Wassermann, Aurobratha Ghosh.

Duration: January 2007 to December 2008

Our partners in this project are the INSERM Imparabl team of the Laboratoire d'Imagerie Fonctionnelle LIF/U678 Faculté de Médecine Pierre et Marie Curie - Hopital Pitié-Salpêtrière and the CENIR : Center for NeuroImaging Research of the Hopital Pitié-Salpêtrière. In this ARC project, our broad goal is to develop and validate algorithms that will help us to have a better knowledge and better understand the structural organization of the white matter fiber bundles in the human brain and help to identify the neural connectivity patterns with the help of Diffusion Magnetic Resonance Imaging (MRI). Our algorithms will be based on formulations using tensor calculus, partial differential equations, variational methods and differential geometry and will ultimately be useful for clinicians as well as researchers (web site: http://www-sop.inria.fr/odyssee/arc2007/)

7.1.2. ARC MACACC Modélisation de l'Activité Corticale et Analyse du Code neural Cérébral.

Keywords: *mesoscopic models of cortical columns*, *spike train statistics*.

Participants: Bruno Cessac, Maureen Clerc, Olivier Faugeras, Pierre Kornprobst, Theodore Papadopoulo, Horacio Rostro, Jonathan Touboul, Juan-Carlos Vasquez.

Duration: January 2008 to December 2009

This project involves the following partners : The INRIA project teams ODYSSEE, ALCHEMY, CORTEX the Institut de Neurosciences Cognitives de la Méditerranée (INCM-Dyva), and the Laboratoire de Mathématiques Jean-Alexandre Dieudonné (Nice University). It is jointly founded by an ARC INRIA and the Doeblin fundation. Neuronal information processing is related to the brain bio-electrical activity. Current neuro imaging techniques allow the measurement of this bio-electric activity at different time and space scales, from neurons to the brain as a whole (e.g. LFP, ECoG, EEG, MEG). But the analysis of data coming from these measures requires the parallel development of suitable models. Namely, these models have to be, on one hand, close enough to phenomenology, taking into account the various type of bio-electrical activity and their scales relations, in order to propose a coherent representation of information processing in the brain (from neurons to neuronal populations, cortical columns, brain area, etc). On the other hand, these models must be well posed and analytically tractable. This requires a constant interaction between neurobiology, modelling and mathematics. In this spirit, this project aims to tackle the following questions, combining results from neuroscience, dynamical systems theory and statistical physics.

1. Statistical models of spikes trains. The analysis of experimental data, in vivo or in vitro, of spike trains, requires suitable statistical models. The models typically used (e.g. Poisson) are ad hoc and may not be adapted to all situations. Our goal is to propose a generic method to construct the probability distribution of spikes trains, using an approach combining mathematical modelling and analysis and in vivo experiments, together with numerical simulations.
2. Mesoscopic models of cortical columns. Brain imaging techniques, like optical imaging, require a modelling of cortical brain activity at a space scale of order 0.1-1 mm2. The goal is, on the theoretical side, to propose a mesoscopic model of the biological signal measured in optical imaging, at the space scale of a cortical column, and to analyse this model, using analytical methods and numerical simulations. This model will be then compared to the cortical activity of the visual system (area V1-V2), measured by optical imaging.

7.1.3. ANR HR-CORTEX

Participants: Romain Brette, Olivier Faugeras, Easwar Subramanian.

Duration: 1st December 2006 to 30th November 2009

This project combines different expertises, such as mathematics, computer science, computational neuroscience and electrophysiology (in vitro and in vivo), to yield accurate and reliable methods to properly characterize high-conductance states in neurons. The partners in this project are Odyssée and UNIC (CNRS - Gif-sur-Yvette, France). We plan to address several of the caveats of present recording techniques, namely (1) the impossibility to perform reliable high-resolution dynamic-clamp with sharp electrodes, which is the intracellular technique mostly used in vivo; (2) the unreliability and low time resolution of single-electrode voltage-clamp recordings in vivo; (3) the impossibility of extracting single-trial conductances from Vm activity in vivo. We propose to address these caveats with the following goals:

1. Obtain high-resolution recordings applicable to any type of electrode (sharp and patch), any type of protocol (current-clamp, voltage-clamp, dynamic-clamp) and different preparations (in vivo, in vitro, dendritic patch recordings).
2. Obtain methods to reliably extract single-trial conductances from Vm activity, as well as to "probe" the intrinsic conductances in cortical neurons. These methods will be applied to intracellular recordings during visual responses in cat V1 area in vivo.
3. Obtain methods to extract correlations from Vm activity and apply these methods to intracellular recordings in vivo to measure changes in correlation in afferent activity.
4. Obtain methods to estimate spike-triggered averages from Vm activity and obtain estimates of the optimal patterns of conductances that trigger spikes in vivo. These results will be integrated into computational models to test mechanisms for selectivity.

In all of these methods, we take advantage of the real-time feedback between a computer and the recorded neuron. This real-time feedback will be used to (a) design a new type of recording paradigm, which we call Active Electrode Compensation (AEC), and which consists in a real-time computer-controlled compensation of the electrode artefacts and bias which currently limit recording precision; (b) to use the AEC method to improve current-clamp, voltage-clamp and dynamic-clamp recordings of cortical neurons; (c) use this method as an essential tool to design methods for estimating conductances and statistical characteristics of network activity from intracellular recordings.

Thus, we expect this project to provide three main contributions: (1) It will provide technical advances in the precision and resolution of several currently-used recording techniques, such as dynamic-clamp and voltage-clamp, which are currently limited. We aim at obtaining high-resolution (>= 20 KHz) reliable measurement or conductance injection. This advance should be of benefit for in vivo and in vitro electrophysiologists. (2) It will enable us to perform high-resolution conductance measurements in high-conductance states in vivo and in vitro and better understand this type of network activity. (3) It will enable us to better understand the spike selectivity of cortical neurons, by directly measuring single-trial conductances underlying visual responses, as well as the conductance time courses linked to the genesis of spikes. Those measurements will be directly integrated into computational models. The mechanisms of spike selectivity in cortical neurons is still a subject of intense debate, and we expect to provide here crucial measurements, which we hope will help us better understand input selectivity in visual cortex (web site: http://www.di.ens.fr/~brette/HRCORTEX/).

7.1.4. ANR ViMAGINE

Participants: Maureen Clerc, Rachid Deriche, Olivier Faugeras, Alexandre Gramfort, Emmanuel Olivi, Théo Papadopoulo.

The partners of this project are Odyssée, the LENA (CHU Pitié-Salpétrière), and the Pariétal project-team at INRIA Futurs and Neurospin-Saclay. It has been accepted in summer 2008 and is funded for four years.

This project takes a new challenge on the non invasive exploration of the Human visual system in vivo. Beyond the basic mechanisms of visual perception – which have already been investigated at multiple scales and through a large variety of modalities – we are primarily interested in proposing and exploring innovative solutions to the investigation of dynamic neural activations and interactions at the systems level. Bridging the elements involved in this endeavour requires that we are capable of observing, modelling and predicting the interplay between the anatomical/functional architecture of the brain systems and some identified timing

properties of neural processes. The overall framework in which this project will be conducted is a federation of partners who will be bringing complementary expertise to this multidisciplinary research. The collaborators include experts in (1) electromagnetic and magnetic resonance brain imaging methods, (2) computational models of neural systems and (3) the neuroscience of vision. A central asset of our group is the easy access to state-of-the-art imaging platforms (e.g. high-density MEG and EEG arrays; 3T and 7T MR scanners) that will ensure the acquisition of quality experimental data.

7.2. Europe

7.2.1. SEARISE: Smart Eyes, Attending and Recognizing Instances of Salient Events

Participants: Neil Bruce, Olivier Faugeras, Pierre Kornprobst, Emilien Tlapale.

SEARISE is a three-year project started in March 2008. It involves the following academic partners: Fraunhofer-Gesellschaft (Germany), University of Genoa (Italy), Ulm University (Germany) University of Bangor (Wales). Two industrial partners are also involved: TrackMen Ltd. and LTU Arena.

The SEARISE project develops a trinocular active cognitive vision system, the Smart-Eyes, for detection, tracking and categorization of salient events and behaviours. Unlike other approaches in video surveillance, the system will have human-like capability to learn continuously from the visual input, self-adjust to ever changing visual environment, fixate salient events and follow their motion, categorize salient events dependent on the context. Inspired by the human visual system, a cyclopean camera will perform wide range monitoring of the visual field while active binocular stereo cameras will fixate and track salient objects, mimicking a focus of attention that switches between different interesting locations.

The core of this artificial cognitive visual system will be a dynamic hierarchical neural architecture – a computational model of visual processing in the brain. Information processing in Smart-Eyes will be highly efficient due to a multi-scale design: Controlled by the cortically plausible neural model, the active cameras will provide a multi-scale video record of salient events. The processing will self-organize to adapt to scale variations and to assign the majority of computational resources to the informative parts of the scene.

The Smart-Eyes system will be tested in real-life scenarios featuring the activity of people in different scales. In a long-range distance scenario, the system will be monitoring crowd behaviour of sport fans in a football arena. In a short range scenario, the system will be monitoring the behaviour of small groups of people and single individuals. The system's capability for self-adaptation will be specifically demonstrated and quantified compared to systems with 'classical' architecture that are trained once and then used on a set of test scenes.

To learn more: http://www.searise.eu/web/doku.php

7.2.2. FACETS : Fast Analog Computing with Emergent Transient States

Participants: Romain Brette, Maria-Jose Escobar, Olivier Faugeras, Mathieu Galtier, François Grimbert, Horacio Rostro-Gonzalez, Pierre Kornprobst, Théo Papadopoulo, Émilien Tlapale, Jonathan Touboul, Romain Veltz.

FACETS is an integrated project within the biologically inspired information systems branch of IST-FET. The FACETS project aims to address, with a concerted action of neuroscientists, computer scientists, engineers and physicists, the unsolved question of how the brain computes. It combines a substantial fraction of the European groups working in the field into a consortium of 13 groups from Austria, France, Germany, Hungary, Sweden, Switzerland and the UK. About 80 scientists will join their efforts over a period of 4 years, starting in September 2005. A project of this dimension has rarely been carried out in the context of brain-science related work in Europe, in particular with such a strong interdisciplinary component (web site: http://facets.kip.uni-heidelberg.de/).

7.2.3. ERC NERVI

Participants: Bruno Cessac, Pascal Chossat [CNRS], Olivier Faugeras, Pierre Kornprobst.

Olivier Faugeras responded to the 2008 ERC call “IDEAS”. His project, NerVi, submitted to the “Mathematics and Interfaces” panel, has been accepted and obtained a 5 years funding for a total amount of 1.7 Million Euros.

The project is to develop a formal model of information representation and processing in the part of the neocortex that is mostly concerned with visual information. This model will open new horizons in a well-principled way in the fields of artificial and biological vision as well as in computational neuroscience. Specifically the goal is to develop a universally accepted formal framework for describing complex, distributed and hierarchical processes capable of processing seamlessly a continuous flow of images. This framework features notably computational units operating at several spatiotemporal scales on stochastic data arising from natural images. Mean- field theory and stochastic calculus are used to harness the fundamental stochastic nature of the data, functional analysis and bifurcation theory to map the complexity of the behaviours of these assemblies of units. In the absence of such foundations the development of an understanding of visual information processing in man and machines could be greatly hindered. Although the proposal addresses fundamental problems its goal is to serve as the basis for ground-breaking future computational development for managing visual data and as a theoretical framework for a scientific understanding of biological vision.

8. Dissemination

8.1. Diffusion and Community Services

Romain Brette is a member of the editorial board of Cognitive Neurodynamics and of the programme committee of ICCN’07 (Shanghai). He serves as a regular reviewer for Journal of Computational Neuroscience, Neural Computation, Journal of Physiology (Paris), Cognitive Neurodynamics, Computational Intelligence and Neuroscience, Europhysics Letters and the CNS conferences. He organizes the Theoretical Neuroscience Breakfasts in Paris twice a month, and he is setting up a wiki for theoretical neuroscience teams at Ecole Normale Supérieure. He is a member of two specialists committees at Ecole Normale Supérieure: 27 and 61 (two recruitments of assistant professors in 2007). He is also in charge of the web site and booklet of the computer science curriculum.

Maureen Clerc is a member of two local (Sophia Antipolis) committees: CUMIR and Commission d’Animation Scientifique. She is a member of the Program Committee of RFIA 2008. She was invited to participate in the CRM-Mitacs-INRIA meeting in Montreal in May, and gave an invited colloquium at the Grenoble Jean Kuntzmann colloquium in June. She was invited to give a course at the Interregional School for Functional Brain Imaging (INSERM-CNRS). She animates since 2006 a regional discussion group on MEG and EEG data processing (with B. Burle, B. Torrésani and C. Bénar).

Rachid Deriche is Project committee vice-chairman at INRIA Sophia Antipolis - Méditerranée and member of the Direction of the Sophia Antipolis Research Center (DGSA). Rachid Deriche is Adj. Director at the Doctoral School EDSTIC (http://edstic.i3s.unice.fr/index.html). He has co-organised MICCAI 2008 Diffusion MRI Tutorial : *Technology Trends and unsolved problems" (06/09/2008-NY)* [with P. Basser, NIH, C.F.Westin, Harvard Med. School-Boston, and R.Verma (U.Penn)].

Rachid Deriche is Associate Editor of SIAM Journal on Imaging Sciences (SIIMS), editorial board member at Springer for the book series entitled Computational Imaging and Vision, editorial board member of International Journal of Computer Vision (IJCV). R. Deriche has served since many years as area-chair and/or as program committee member for International Conferences as ICCV, MICCAI,ECCV,CVPR,ISBI and national conferences as AFRIF-AFIA RFIA and serves several international journals and conferences (NeuroImage, IEEE Transactions on Medical Imaging, Magnetic Resonance in Medicine, JMIV, Medical Image Analysis Journal, ISMRM, HBM, ISBI..)

Rachid Deriche has been invited to give a talk at :

- 07/04/08 : Sabanci University - Istambul (Turkey).
- 08/04/08 : Bogazici University - Istambul (Turkey).

- 06/09/08 : MICCAI 2008 Diffusion MRI Tutorial : "Technology Trends and unsolved problems" New-York (USA).
- 24/10/08 : Dept Informatics & Telecoms, University of Athens (Greece).
- 07/11/08 : International Symposium on Computational Medicine (ISCM) - Beijing (China)
- 23/11/08 : JETIM:2008 - 3èmes Journées d'Etudes Algéro-Françaises en Imagerie Médicale - Tipasa (Algeria)
- 09/12/08 : Journée conjointe *Imagerie du tenseur: avancées et nouveaux traitements* GDR Stic-Santé, Thème B: *Signaux et Images en santé* et GDR ISIS, Thème B *Image et Vision*.

Olivier Faugeras is a member of the French Academy of Sciences, the French Academy of Technology. He was on the Administration boards of the Agence Nationale de la Recherche (ANR) and the Fondation d'Entreprise EADS until October 2008. He is on the Editorial board of the International Journal of Computer Vision (IJCV). Together with Quang-Tuan Luong and Steve Maybank he received the Koenderink Prize for the most influential papers published in ECCV from 1990 to 1998 at ECCV 2008. Their paper [71] was presented at ECCV 1992.

Pierre Kornprobst is a member of the comité de suivi doctoral (CSD) in Sophia Antipolis. He has organized a workshop on computational vision (co-organized with Pascal Mamassian) for the Neurocomp 2008 conference. He served as referee for the conference ICPR 2008.

Théo Papadopoulo served as a referee for the conferences MICCAI 2008 and RFIA 2008 (Reconnaissance des Formes et Intelligence Artificielle). He has taken the role of Industrial liaison for the organization of the 2008 European Conference on Computer Vision (ECCV) in Marseille. Since July 2007, he is the task leader of the WP8 work package of the European project FACETS 7.2.2. Théo Papadopoulo is also a member of the local (Sophia Antipolis) committee for software development (CDL).

Five theses were defended at Odyssée this year

- Maxime Descoteaux: High Angular Resolution Diffusion MRI: From Local Estimation to Segmentation and Tractography [11],
- Pierre Maurel: Shape gradients, shape warping and medical applications to facial expression analysis [12],
- Jonathan Touboul: Nonlinear and stochastic models in Neuroscience [33],
- Sylvain Vallaghé: EEG and MEG forward modeling : computation and calibration [14],
- Adrien Wohrer: Model and large-scale simulator of a biological retina with contrast gain control [15].

8.2. Teaching

- Romain Brette is an assistant professor at Ecole Normale Supérieure (Paris). He teaches in the Introduction to scientific computing course and the Computational neuroscience course in the computer science curriculum of Ecole Normale Supérieure. He also mentors several students there.
- Bruno Cessac is Maitre de conférences in Nice University. He is teaching thermodynamics, quantum physics, statistical physics, neural networks dynamics, probability theory,C programming, for physics students.
- Maureen Clerc and Théo Papadopoulo teach "Inverse problems for brain functional imaging" (20H) at ENS Cachan.
- Maureen Clerc is in charge of two modules at Ecole des Ponts: Fourier Analysis and Applications, and Séminaire d'Ouverture and teaches 15H at Ecole des Ponts.
- Rachid Deriche teaches and is in charge of the module *PDE's and Geometric Flows in Computer Vision and Image Processing* in the Master MPRI *Master Parisien de Recherche en Informatique* - University of Paris 7, ENS and Ecole Polytechnique - (15H).

- Olivier Faugeras teaches at ENS the course ”Mathematical methods for neuroscience“ in the Master MVA and the ENS Math/Info section - (24H). Jonathan Touboul and Romain Veltz do exercise sections for this course at ENS - (16H)
- Théo Papadopoulo teaches “Computer Vision” at the Polytechnic Engineering School of the University of Nice-Sophia Antipolis (24H).
- Sandrine Chemla is a teaching assistant of numerical electronics courses (combinatory logic and sequential logic) for first and second year students.
- Émilien Tlapale teaches "Programming in C++", at EPU (Université de Nice-Sophia Antipolis) in the electronic department.
- Jérome Piovano teaches "Sound and Image Signal for the Computer Scientist" (24h) and "Trees and Data Structures" (78h) at the Polytechnic Engineering School of the University of Nice-Sophia Antipolis (24H).
- Sylvain Vallaghé gives practical lectures on "Games and Strategies" at the Polytechnic Engineering School of the University of Nice-Sophia Antipolis.

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