MARIE SKLODOWSKA-CURIE ACTIONS

Co-funding of regional, national and international programmes (COFUND)

DOC2AMU THESIS PROJECT 2018 CALL FOR APPLICATIONS

Temporal networks: from network theory to brain science and neurology

1. GENERAL INFORMATION

Call	2018-20
Topic	Networks
Keywords	Temporal networks; brain networks; neurology

2. THESIS DIRECTOR(S), RESEARCH UNITS AND DOCTORAL SCHOOLS

Thesis director	Alain BARRAT
Research Unit	Centre de Physique Théorique
Doctoral school	ED 352 - Physique et Sciences de la Matière
Thesis co-director	Demian BATTAGLIA
Research Unit	Institut de Neurosciences des Systèmes
Doctoral school	ED 062 - Sciences de la Vie et de la Santé

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1. DESCRIPTION OF THE PHD THESIS PROJECT

1.1 OBJECTIVES OF THE PROJECT BASED ON THE CURRENT STATE OF THE ART

Many natural and man-made systems are conveniently represented by networks: a set of entities represented by nodes, whose interactions or couplings are represented by links. Such representation framework can describe systems as diverse as social networks, protein interaction networks, brain networks or the World-Wide-Web. A wide, interdisciplinary community of scientists is therefore nowadays concerned with research in the field of complex networks, with topics ranging from very theoretical approaches close to graph theory to more applied or field-specific questions. Numerous advances have been obtained in the understanding of complex networks in the last 15 years: how to analyse and characterize datasets coming in the form of networks, how to devise models of networks of relevance in various fields, how structure and function of networks are linked, and how processes depend on the structure of the network on which they take place (for instance, how an epidemic spread depends on the structure of the contacts and mobility in a population).

While most studies of networks have for a long time considered them as static entities, an important development has emerged in recent years, to take into account the fact that many networks evolve over time. The resulting studies of ***temporal (i.e., time-dependent) networks***[1] have been made both possible and necessary thanks to the novel availability of time-resolved datasets and to the need to study the temporal dimension of many phenomena. Although several advances have been made, this field is still largely in its infancy. Many characterization tools have indeed been based on considering temporal networks as series of static snapshots and developed within specific contexts, for instance the one of contact networks of individuals; few models of temporal networks have been proposed; the issues of the extraction of features such as temporal communities or simply of the relevant timescales of evolution of a temporal networks are still largely open; representations and summaries of temporal networks need to be developed, as well as tools to compare different temporal networks datasets among themselves or with models. One of the supervisors (A. Barrat) is pioneer in the recent developments of this field, mainly in the context of temporally resolved contact networks[2].

Neuroscience is one of the fields in which the approach of complex networks has grown strongly in the last decade, culminating in the rise of “connectomics” [3]. Networks appear in the brain in two forms. On the one hand, large-scale initiatives try to map the whole graph of anatomical connectivity; even such a complete knowledge (still far from doable for human brains) would however not suffice to understand how the brain works. On the other hand, the functional connectivity (FC) describes how the activities of different areas of the brain are influencing each other and defines weighted networks between these areas, whose weights capture the amounts of information that the coupled regions exchange[4]. While the first FC studies have considered static networks, it is now clear that the time-dependency of this connectivity (FCD: Functional Connectivity Dynamics) crucially needs to be studied and represents the next frontier in brain science[5]. The co-supervisor D. Battaglia works in this field and has already started developing new tools adapted to this time-evolution of FC networks. He developed a theoretical and modelling framework explaining how dynamic functional networks can stem from the complex transient dynamics of static anatomic networks[6]. He co-designed the first whole-brain scale computational model able to render important aspects of the human brain resting state FCD, beyond

[1] Holme & Saramäki, Phys. Rep. 519, 97 (2013)
[2] Barrat & Cattuto, in *“Temporal Networks”,* Springer (2013), P. Holme, J. Saramãki Eds.
[3] Bullmore & Sporns, Nat Rev Neurosci 10,186 (2009)
[4] Kirst, Timme & Battaglia, Nat Comms 7, 11061 (2016).
[5] Calhoun et al., Neuron 84 :262 (2014)
[6] Battaglia et al.,PLoS Comp Biol 8(3):e1002438 (2012). Palmigiano et al., Nat Neurosci 20 : 1014 (2017).

static FC[7]. Recently, he started developing FCD-based biomarkers of human healthy aging, based on resting state fMRI, showing that aging slows down the spontaneous reconfiguration dynamics of functional networks[8]. The extraction of time-resolved networks avoids misinterpreting temporal as inter-subject variability and bears promise of metrics tracking deviations from healthy aging trajectories with improved sensitivity, with applications e.g. in the non-invasive early diagnosis of dementias.

In this context, the objectives of the present project are to combine approaches coming from statistical physics, theory of networks and neuroscience:

- to reach ***theoretical and methodological developments in the analysis of temporal networks***, making them compliant with the needs of cognitive and clinical neuroscience. In particular, we want to address the following points i) how to conveniently represent temporal networks at various levels of aggregation? ii) how to choose the most relevant time-scale for temporal network analysis? iii) how to properly compare networks observed at different times in different conditions?
- to provide ***pragmatic proofs of concepts of the usefulness of these new approaches applying them to diverse datasets***. To this aim, we will exploit existing multi-modal neuroimaging data (fMRI, EEG, MEG…) from human control subjects as well as rare intracranial EEG from epileptic patients. We will also compare empirical with artificial datasets created using the Virtual Brain software (thevirtualbrain.org) developed at the Institute of Systems Neuroscience (INS).

These objectives can only be reached through an interdisciplinary approach combining tools and methods coming from the expertise and know-how of the two co-supervisors, backed by the inter-sectoral partner.

1.2 METHODOLOGY

The methodology used during the thesis will be **data-driven**: (temporal) networks tools obviously need to be developed ***in relation with*** and ***inspired by*** data, and in fine will be ***applied to*** data. The thread running through the project is thus a strong relation to datasets, both empirical and synthetic (including clinical data, in which temporal network metrics can be directly related to the evolution of dysfunctions in patients, such as aphasia, and thus in perspective inspire new treatment protocols).

The first and most important task is linked with the description, analysis and representation of temporal network data, in particular in the context of FC data. Each dataset gathered in particular conditions is indeed very complex, but is also unique, with some properties that might not be general: it is thus crucial to represent it in a way to discard unimportant details while highlighting the salient features. Understanding which features to retain and which to left out is non-trivial and partially context-dependent. This has been understood and progresses have been made in the context of static networks, but the case of temporal networks has been barely touched. For instance, for contact networks, a framework to generalize the so-called contact matrices (coarse-grained representations that retain only average contact times between groups of individuals) has been put forward: this representation of temporally resolved contact networks, called contact matrices of distributions, keeps information on the statistical distributions of contact durations and has been shown to be an adequate level of description for data-driven simulations of spreading processes, even with noisy or incomplete data[9]. In the same context, a non-negative tensor factorization approach can be used to extract community structure and relevant activity patterns of temporal networks[10]. A fingerprint of these temporal networks can also be extracted from the outcome of spreading processes[11]. A. Barrat has contributed to these efforts, which still need to be adapted, enriched and generalized to other types of temporal networks such as FC data. For instance, memory effects need to be characterized, quantified[12] and taken into account in data representations. Overall, we will construct a hierarchy of data representations with varying level of details, in the spirit of the hierarchy defined[13] for static, unweighted networks, and of a list of summaries of temporal network data that allows to build, for each dataset, its “signature”. The definition of such a signature of a temporal network will be the starting point to build a systematic way of comparing temporal networks, in the spirit of the NetSimile tool[14], built for unweighted, undirected static networks. The ability to compare temporal networks (datasets and models) is indeed crucial at various levels: to understand if datasets gathered in different contexts can be ascribed to the same type of conditions, if a dataset is compatible with a null model, if a model

[7] Hansen et al., NeuroImage 105:525–535 (2015).
[8] Battaglia et al., submitted
[9] Machens et al., BMC Inf. Dis. 13 :185 (2013) ; Génois et al., Nat. Comms 6 :8860 (2015)
[10] Gauvin et al., PLoS ONE 9 :e86028 (2014) ; Gauvin et al., arXiv :1501.02758
[11] Gauvin et al., Sci Rep 3, 3099 (2013).
[12] Vestergaard et al., Phys. Rev. E 90 :042805 (2014)
[13] Orsini et al., Nat Comms 6 :8627 (2015)
[14] Berlingerio et al., arXiv :1209.2684

of temporal network is adequate to represent data and can be used to generate synthetic datasets. Moreover, we will use it to detect timescales in the temporal network, by comparing successive time windows of varying length (as done by Darst et al.[15], with however a too simple comparison tool).

The second task will be to develop models of temporal networks able to produce artificial but plausible streams of functional connectivity dynamics. The modeling task has several aspects:

i. proposing simple generative models of temporal datastreams, as done for contact networks[12] by defining simple interaction rules between nodes

ii. defining hierarchies of null models[11], which then allow to distinguish in datasets which properties are specific ("non-random") and which are generic ("chance level")

iii. generating temporal streams of FC dynamics through the use of Virtual Brain models[16], which realistically simulate the neural dynamics of thalamocortical networks.

The third task will be the application of the theoretical methods to empirical, clinical datasets. We will use our new temporal networks techniques to discriminate different conditions or contexts (e.g. rest vs active or sleep; inter-ictal vs ictal; before or after learning a task) based on their FC dynamics patterns. The temporal network signatures developed by the first task will provide "descriptive biomarkers". We will focus on language dysfunctions such as aphasia that transiently arise at different severities as an effect of epilepsy. Furthermore aphasia can also be induced via electric stimulation in electrode-implanted patients as a routine tool to map language-related regions prior to surgical intervention. It will thus be possible to study how temporal network metrics co-vary and predict symptom severity. A complementary strategy will be to fit the models explored by the second task to the different datasets and use the fitted model parameters themselves as "generative biomarkers".

These three tasks are clearly linked, as the theoretical methods and tools will be data-inspired and their adequacy and usefulness constantly monitored against real datasets. Therefore, we will not limit ourselves to a "plug-and-play" application of pre-existing tools to neural data, but the nature of the data themselves and the pursued biomarking aims will crucially constrain the tools to be designed and prompt unforeseen evolutions of the current state-of-the-art approaches.

1.3 WORK PLAN

In the first semester, the candidate will perform bibliographic work on static and temporal networks in general, on brain networks and FC/FCD, and on the most recent developments of the fields, including literature about the clinical application field of epilepsy neurology. S/he will also learn the methods to deal with temporal networks and FC data recently developed at CPT and INS. The candidate will as well start data analysis, first with preliminary simple techniques. Data analysis and development of new tools for characterizing temporal networks will constitute the bulk of the thesis activities and will thus be an effort of at least two years. The candidate will start with traditional network analysis of aggregated networks at various scales and study the influence of the aggregation temporal scale. S/he will also study the temporal evolution of single links, quantifying how bursty or periodic/tonic are different functional links[17], beyond conventional measures of average link strength. The results will be compared with adequate null models, some in the literature, and others to be defined. This will both provide first data characterizations and show the limitations of such simple tools, giving hints on how to develop richer representations and characteristics. The candidate will then develop summaries of temporal networks that will be proposed as *signature* of a temporal network dataset, and define a systematic comparison between temporal networks. The systematic exploration of different ways of aggregating data will also lead to the definition of a hierarchy of data representations.

In the mean time, the candidate will perform two 2 one-month internships with the non-academic partner (scheduled for months 7 and 19) in order to learn recording techniques, to seize the data richness and limitations, and to better understand the concrete needs of clinical actors via "immersion" in the life of a neurology service and attending to internal medical decision meetings. In months 9-12, we also plan a learning phase towards the use of the Virtual Brain at INS, in order to generate artificial datasets while fully understanding how these data are produced and the data tuning possibilities.

Modeling efforts, including the use of the Virtual Brain to generate artificial data streams, will start in the second year and continue up to the middle of the third year. Concrete application of advanced temporal network approaches to case studies will start in the second year and continue until the end of the thesis. We will analyse human sEEG recordings from intracranial multi-channel electrodes implanted in epileptic patients undergoing pre-surgical evaluation, at the Epileptology service of the Timone hospital (under the direction of the inter-sectoral partner Agnès Trébuchon). For tens of

[15] Darst et al., Sci Rep 6 :39713 (2016)
[16] Deco et al., Nat Rev Neurosci 12 :43 (2011) ; Hansen et al., Neuroimage 105 :525 (2015)
[17] Thompson WH, Fransson P Sci Rep 6:39156 (2016).

patients, sEEG signals have been continuously recorded for the duration of over one week. These recordings stand thus in an intermediate position between “task” and “rest” conditions, since many daily-life activities are performed by the patients (reading, sleep...). Furthermore, these recordings will contain inter-ictal activity, but also several examples of pre-ictal and ictal events. Recordings are paired with movies documenting several hours per day of the subject behavior, and with a diary of basic activities (sleep-wake times, seizures, etc.). Importantly, data have been collected on the language function, monitoring the emergence of aphasic symptoms of different types, either associated to epileptic pathology or even induced (or contrasted) via electric stimulation applied to suitable brain regions in the language system. In this way we will be able to map temporal network changes across behavior types and conditions and in direct relation with clinical interventions and measures of the fluctuating severity of symptoms. In addition, for complementary analyses, additional independent datasets are also available, such as MEG data during sensorimotor tasks at different stages of learning (courtesy of A. Brovelli at the Timone Neuroscience Institute), useful to probe the link between cognitive performance changes and FCD variations. Finally, the last months will be mainly dedicated to thesis writing. The workplan is summarized in the following Gantt chart.

Months	1-6	7-12	13-18	19-24	25-30	31-36
Bibliographic work, becoming familiar with concepts, programming tools, etc						
Internship with non-academic partner						
Data analysis, development of tools						
Learning to use virtual brain						
Modeling						
Case studies *(sEEG/aphasia, MEG/learning)*						
Thesis writing						

Several scientific papers will be published during the thesis. They will be aimed on the one hand at the general community studying networks, through journals such as PloS ONE, Scientific Reports, Journal of Complex Networks, but also to the neuroscience community through journals such NeuroImage, eLife, … In particular, publications will deal with:

- definition of a hierarchy of representations of temporal networks, and their applications to datasets
- definition of a systematic way to compare temporal networks
- applications of these methods to compare datasets of FCD in different conditions and in relation to clinical symptoms and pathological dysfunction
- application of such methods to explore the parameter space of the Virtual Brain and to compare artificial datasets with real datasets

It is impossible to foresee exactly when publications will be possible, as this depends on the rhythm of obtention of new results, which in turn may depend on unforeseen difficulties. However, we consider that the writing of the first papers should start around the end of the first year or the beginning of the second year, with 2 papers published during the second year and 2-3 during the third year.

1.4 SUPERVISORS AND RESEARCH GROUPS DESCRIPTION

The first supervisor, Alain Barrat, is head of the Statistical Physics and Complex Systems team of the Centre de Physique Théorique (CPT, Luminy Campus). The CPT research teams cover a wide range (from cosmology and quantum gravity to statistical physics). The Statistical Physics and Complex Systems team pursues a very strong and successful research direction towards the study of complex networks and interdisciplinary applications, with publications in leading journals of different disciplines (physics, epidemiology, social sciences, interdisciplinary venues).

The second supervisor, Demian Battaglia, is researcher at the Institut de Neuroscience des Systèmes (INS) on the La Timone Campus, within the Theoretical Neuroscience Group (TNG). INS fosters the understanding of the healthy and pathologic brain as a complex multi-scale system, using an integrative synergy of approaches ranging from molecular and cellular to cognitive and computational neurosciences. TNG is in charge of the development of the Virtual Brain neuroinformatics platform. Demian Battaglia is responsible for a research line on Functional Connectivity Dynamics within TNG.

CPT and INS will ensure availability of office space, desktop and laptop to doctoral candidates, and attendance to important conferences. The supervisors are also applying jointly to local and national funding opportunities. The present project, for its applications to aphasia, is compatible with the possibility of future cofounding by the convergence Institute on Language, Communication and the Brain (ILCB). Our results will also increase the chances of success of future ANR applications by the supervisors, who are already involved in an exploratory project (mini-funding by the CNRS Interdisciplinary mission in 2017: “Infiniti- BrainTime”).

2. 3I DIMENSIONS AND OTHER ASPECTS OF THE PROJECT

2.1INTERDISCIPLINARY DIMENSION

Both supervisors have a strong experience both in supervising PhD students and in interdisciplinary collaborations (including interdisciplinary collaborations involving students). Each supervisor will first dispense to the candidate a specific training, respectively concerning complex networks and functional connectivity, and bring him/her up to date on the latest developments in the field. Alain Barrat will then supervise more specifically the aspects related to the analysis, representation and modeling of temporal networks as seen from the point of view of statistical physics, while Demian Battaglia will supervise the application of these methods to real data in the neuroscience domain. Battaglia will also provide training to the candidate to use the Virtual Brain at INS. Given the data-driven nature of the project, these supervisions will in fact be performed jointly and in tight synergy, also facilitated by the former PhD training of Demian Battaglia in statistical physics.

As the laboratories of the supervisors are on two separate campuses, the doctoral candidate will benefit from office space in both laboratories and spend time in each in rapid alternation, for instance one week in each. This will be particularly important at the beginning of the PhD so that the doctoral candidate becomes rapidly familiar with both environments and interacts with both teams. Moreover, both supervisors will carefully communicate all the opportunities of assisting to seminars of interest in each laboratory, to expose the candidate as much as possible to the most up to date research in their fields. In a later stage, longer stays in one laboratory or the other may become more adequate, depending on workplan needs. In any case, joint weekly meetings with both supervisors will be the rule to ensure good communication and progresses.

2.2 INTERSECTORAL DIMENSION:

The non-academic partner, Agnes Trébuchon, is a neurologist in the Epileptology and General Neurophysiology teams of the Clinical Neurophysiology team of the Timone Hospital, with specialization of language-related dysfunctions in neurological diseases and epilepsy. This partner will play several roles in the project. On the one hand, she will provide datasets that will be crucial in the development of the data-driven thesis project. On the other hand, she will bring expertise in clinical neurophysiology, intracranial recordings, electric stimulation, cognitive assessments… She will therefore be closely associated to the research on data analysis and on the application to case studies.

Both supervisors consider moreover that it is absolutely crucial, when one works in a data-driven field, to have a fundamental grasp of the nature of the data and of how it has been collected, including an understanding of potential limitations of the data-gathering techniques and of the real needs of the clinical partners. Therefore, the candidate will spend two one-month internships in the Epileptology service (M7: early exposure; M19: exploring the clinical valorization of achieved results). This will allow direct contact with sEEG recording facilities, participation to group meetings… The proposed project is adequate for the DAS "Santé-Alimentation" of the SRI for the region PACA, because of its emphasis on the development of novel diagnostic tools…

2.2INTERNATIONAL DIMENSION:

Both supervisors, as well as the inter-sectoral partner, have many international collaborations to which the doctoral candidate would be naturally exposed. In particular, both Alain Barrat and Demian Battaglia have collaborations with the ISI Foundation in Turin, an excellence center for research on complex systems in which an important research activity is devoted to complex networks. In particular, several ISI scientists are working on temporal networks on the one hand and on brain networks on the other hand. The doctoral candidate will therefore be able to spend time (several weeks or months) at ISI Foundation to interact and work with the ISI scientists on these topics. Demian Battaglia is furthermore actively cooperating with experimental partners in the USA (Montana State University, Vanderbilt University) or Germany (ESI, Frankfurt; BCCN, Göttingen).

Both supervisors moreover regularly participate to international conferences in their fields. The doctoral candidate will be invited to submit abstracts and participate to the annual conference on complex networks NetSci, as well as to the annual conference on complex systems CCS, the Brain Connectivity Workshop, the Human Brain Mapping Organization (OHBM) and Society for Neuroscience (SFN) annual meetings…

3. RECENT PUBLICATIONS

-C. Vestergaard, E. Valdano, M. Génois, C. Poletto, V. Colizza, A. Barrat, Impact of spatially constrained sampling of temporal contact networks on the evaluation of the epidemic risk, European Journal of Applied Mathematics 27, 941 (2016)
-M. Génois, C. Vestergaard, C. Cattuto, A. Barrat, Compensating for population sampling in simulations of epidemic spread on temporal contact networks, Nature Communications 6:8860 (2015)
-L. Gauvin, A. Panisson, A. Barrat, C. Cattuto, Revealing latent factors of temporal networks for mesoscale intervention in epidemic spread, preprint arXiv:1501.02758
-A. Machens, F. Gesualdo, C. Rizzo, A. E. Tozzi, A. Barrat, C. Cattuto, An infectious disease model on empirical networks of human contact: bridging the gap between dynamic network data and contact matrices, BMC Infectious Diseases 13:185 (2013)
-A. Barrat, C. Cattuto, Temporal networks of face-to-face human interactions, in *"Temporal Networks",* Springer (2013), P. Holme, J. Saramãki Eds.
-A. Barrat, M. Barthélemy, A. Vespignani, Dynamical processes on complex networks (Cambridge, 2008).
- A. Palmigiano, T. Geisel, F. Wolf, D. Battaglia, Flexible information routing by transient synchrony. Nature Neuroscience 20:1014–1022 (2017).
-C. Kirst, M. Timme, D. Battaglia, Dynamic information routing in complex networks, Nature Communications 7:11061 (2016).
-E.C.A. Hansen*, D. Battaglia*, A. Spiegler, G. Deco, V.K. Jirsa, Functional connectivity dynamics: modeling the switching behavior of the resting state, NeuroImage 105:525–535 (2015). *[*equal contributions]*
-D. Battaglia, T. Boudou, E.C.A. Hansen, S. Chettouf, A. Daffertshofer, A.R. McIntosh, J. Zimmermann, P. Ritter, V. Jirsa, Functional Connectivity Dynamics of the Resting State across the Human Adult Lifespan, in review for NeuroImage; preprint posted on BioRxiv
-D. Battaglia, A. Witt, F. Wolf, T. Geisel, Dynamic Effective Connectivity of Inter-Areal Brain Circuits, PLoS Comp Biol 8(3):e1002438 (2012).

4. EXPECTED PROFILE OF THE CANDIDATE

The candidate is expected to have a solid background in statistical physics and some knowledge of neurosciences, complex systems and networks. For example, s/he could have followed a Master's degree in computational neurosciences. Solid programming skills are required, with a good knowledge of unix/linux environment and of advanced programming languages such as python or matlab. Previous experience in data mining and analysis would be a plus. The candidate should demonstrate his/her strong will to pursue research through interdisciplinary work mixing theoretical and more applied approaches, with in particular a strong interest in data-driven approaches.

5. SUPERVISORS' PROFILES

Alain Barrat is CNRS Senior Researcher ("Directeur de Recherches") at the Centre de Physique Théorique (CPT) in Marseille (Campus de Luminy) since 2008, after 10 years as CNRS researcher in the Laboratoire de Physique Théorique in Orsay, France. He is head of the "statistical physics and complex systems" team of the CPT, Academic editor of PLoS ONE, Associate editor of Network Science, member of the Advisory Board of Journal of Physics A, Vice-president of the Complex Systems Society.
Alain Barrat is a statistical physicist by training. Since more than 10 years, his research focuses on the interdisciplinary frontiers of statistical physics and in particular on the field of complex networks. He is an internationally recognized specialist of complex networks and of the attached dynamical processes. His most cited article in the field has received more than 1200 citations, while 16 others have had more than 100 citations. He has strongly contributed to the development of the field of weighted networks and is currently a pioneer in the field of temporal networks, in particular to measure and describe human contacts, with applications to the study of epidemics. He is co-author of more than

125 publications (h-index 41) and of the book “Dynamical processes on complex networks” (Cambridge, 2008), which has become a reference in the field.
He has already supervised 6 thesis, each completed in three years and having led to several peer-reviewed publications. The students were:
1-Luca Dall’Asta (Oct. 2003-July 2006), currently researcher at the Polytechnic Institute of Turin, Italy. 7 peer-reviewed publications during the PhD:

-Statistical theory of Internet exploration, Phys. Rev. E 71:036135 (2005)
-Vulnerability of weighted networks, J. Stat. Mech. P04006 (2006).
-Exploring networks with traceroute-like probes: theory and simulations, Theoretical Computer Science 355, 6 (2006).
-Agreement dynamics on small-world networks, Europhys. Lett. 73, 969 (2006)
-Topology Induced Coarsening in Language Games, Phys. Rev. E 73:015102(R) (2006)
-Non-equilibrium dynamics of language games on complex networks, Phys. Rev. E 74:036105 (2006)
-What is the real size of a sampled network? The case of the Internet, Phys. Rev. E 75:056111 (2007)

2-Aurélien Gautreau (Oct. 2005-July 2008), currently professor at Cachan IUT (Institut universitaire de technologie). 3 peer-reviewed publications during the PhD:

-Arrival Time Statistics in Global Disease Spread, J. Stat. Mech. L09001 (2007)
-Global disease spread: statistics and estimation of arrival times, J. Theor. Biol. 251, 509 (2008)
-Microdynamics in stationary complex networks, Proc. Natl. Acad. Sci. USA 106, 8847 (2009)

3-Paolo Bajardi (Sept. 2008-Nov. 2011), currently Data Scientist in a start-up in Turin, Italy. 8 peer-reviewed publications during the PhD:

-Seasonal transmission potential and activity peaks of the new influenza A(H1N1): a Monte Carlo likelihood analysis based on human mobility, BMC Medicine 7, 45 (2009)
-Mobility Networks, Travel Restrictions, and the Global Spread of 2009 H1N1 Pandemic, PLoS ONE 6(1): e16591 (2011).
-Modeling the critical care demand and antibiotics resources needed during the Fall 2009 wave of influenza A(H1N1) pandemic, PLoS Currents: Influenza. Dic 4:RRN1133 (2009).
-Modeling vaccination campaigns and the Fall/Winter 2009 activity of the new A(H1N1) influenza in the Northern Hemisphere, Emerging Health Threats Journal 2:e11 (2009)
-Estimate of Novel Influenza A/H1N1 cases in Mexico at the early stage of the pandemic with a spatially structured epidemic model, PLoS Currents: Influenza. Nov 11:RRN1129 (2009)
-Dynamical patterns of cattle trade movements, PLoS ONE 6(5):e19869 (2011)
-Optimizing surveillance for livestock disease spreading through animal movements, J. R. Soc. Interface 9, 2814 (2012)
-Real time numerical forecast of global epidemic spreading: case study of 2009 A/H1N1pdm, BMC Medicine 10, 165 (2012)

4-Juliette Stehlé (Sept. 2009-Nov. 2012), currently statistician-economist at the French National Institute of Statistics and Economic Studies (INSEE). 7 peer-reviewed publications during the PhD:

-Dynamical and bursty interactions in social networks, Phys. Rev. E 81:035101(R) (2010)
-What's in a crowd? Analysis of face-to-face behavioral networks, J. Theor. Biol. 271:166-180 (2011)
-High-resolution measurements of face-to-face contact patterns in a primary school, PLoS ONE 6(8):e23176 (2011)
-Simulation of a SEIR infectious disease model on the dynamic contact network of conference attendees, BMC Medicine 9:87 (2011)
-Social network dynamics of face-to-face interactions, Phys. Rev. E 83:056109 (2011)
-Empirical temporal networks of face-to-face human interactions, EPJ Special Topics 222:1295 (2013)
-Gender homophily from spatial behavior in a primary school: a sociometric study, Social Networks 35:604 (2013)

5-Anna Machens (Oct. 2010-Oct. 2013), currently Data Scientist in Germany. 2 peer-reviewed publications during the PhD.

-An infectious disease model on empirical networks of human contact: bridging the gap between dynamic network data and contact matrices, BMC Infectious Diseases 13:185 (2013)
-Immunization strategies for epidemic processes in time-varying contact networks, J. Theor. Biol. 337:89 (2013)

6-Julie Fournet (Oct. 2013-Sept. 2016), currently employed in a start-up (CDI). 5 peer-reviewed publications during the PhD.

-Contact patterns among high school students, PLoS ONE 9(9):e107878 (2014)
-Data on face-to-face contacts in an office building suggest a low-cost vaccination strategy based on community linkers, Network Science 3, 326 (2015)
-Contact patterns in a high school: a comparison between data collected using wearable sensors, contact diaries and friendship surveys, PLoS ONE 10(9):e0136497 (2015)
-Epidemic risk from friendship network data: an equivalence with a non-uniform sampling of contact networks, Sci. Rep. 6:24593 (2016)
-Estimating the epidemic risk using non-uniformly sampled contact data, Sci. Rep. 7:9975 (2017)

Alain Barrat is currently supervising one PhD student (Antoine Moinet), in co-supervision (co-tutelle) with Romualdo Pastor-Satorras (UPC, Barcelona, Spain) since October 2015, and another one (Valeria Gelardi), in co-supervision with Nicolas Claidière (LPC, AMU) since October 2017.

Demian Battaglia is a CNRS Junior Researcher ("Chargé de Recherches") in the Theoretical Neuroscience Group at the Institut de Neurosciences des Systèmes (INS) in Marseille (Campus Timone) since 2015. He was previously Marie-Curie fellow in the same lab, independent Bernstein Fellow at the Max Planck Institute for Dynamics and Self-organization in Göttingen (Germany) and postdoc in the Laboratory for Neurophysics and Physiology at the University Paris Descartes. After obtaining his PhD in Statistical Physics in 2005 at SISSA (Trieste, Italy), he oriented his research toward the study of complex dynamics in multi-scale neural circuits and its role in establishing a flexible bridge between structural and functional connectivity. His most recent research interest focus on "computational chronnectomics", i.e the modelling of large-scale Functional Connectivity Dynamics (FCD), and the development of FCD metrics for biomarking applications, e.g. in aging. He is Review editor for Frontiers in Computational Intelligence and member of the direction board of the Mediterranean Neuroscience Society. He authored research articles on journals such as Nature Communications, NeuroImaging, Journal of Neuroscience, PLoS Computational Biology, Physical Review Letters… which received over 300 citations overall (ISI web of science), and contributed 6 invited chapters to specialized monographs. He has organized four international workshops.
He has already officially co-directed 3 PhD thesis at the University of Göttingen (with Prof. Theo Geisel). His student direction work always led to peer-reviewed publications. The students were:

1- Olav Stetter (Jan. 2010 – Dec. 2013, U Göttingen), currently CTO of the startup Free Machine (Munich, Germany). 3 peer-reviewed publications stemming from PhD work with DB:
- First Connectomics Challenge: From Imaging to Connectivity. The Journal of Machine Learning Research: W&CP 46:1–22 (2015)
- Transfer entropy reconstruction and labeling of neuronal connections from simulated calcium imaging. PLoS ONE 9(6):e98842 (2014)
- Model-free reconstruction of excitatory neuronal connectivity from calcium imaging signals. PLoS Comp Biol 8(8):e1002653 (2012)

2- Markus Helmer (Sep. 2012 – Sep. 2015, U Göttingen), currently postdoc at Yale University (USA). 1 peer-reviewed publication (plus 2 submitted) stemming from PhD work with DB:
-Model-Free Estimation of Tuning Curves and Their Attentional Modulation, Based on Sparse and Noisy Data. PLoS ONE 11(1):e0146500 (2016)
-Gender bias in scholarly peer-review, *resubmitted after minor revision to* eLife.
-Connectome of a model canonic cortical circuit flexibly shapes layer-dependent multi-frequency oscillations, *in review for* PLoS Computational Biology; preprint: bioRxiv 10.1101/026674

3- Agostina Palmigiano (Sep. 2013 – January 2017, U Göttingen), currently postdoc at Columbia University (USA). 2 peer-reviewed publications stemming from PhD work with DB:
- Controlling the oscillation phase through precisely timed closed-loop optogenetic stimulation: a computational study. *Front Neural Circuits* 7:49 (2013)
- Dynamic information routing at the edge of synchrony, *resubmitted after revision to* Nature Neuroscience

Markus Helmer and Agostina Palmigiano spent extensive time as guests at INS during their PhD, after Demian Battaglia relocated from Göttingen to Marseille.
In addition Demian Battaglia tutored one PhD student at INS (under the supervision of V. Jirsa):

4- Enrique Hansen (tutored from October 2013 to March 2015, at INS), 1 peer-reviewed publication (plus 1 submitted) stemming from PhD work with DB:
- Functional connectivity dynamics: modeling the switching behavior of the resting state. *NeuroImage* 105:525–535 (2015)
- Functional Connectivity Dynamics of the Resting State across the Human Adult Lifespan, *submitted to* Proc Nat Ac Sci USA; preprint posted on BioRxiv

At AMU, Demian Battaglia is currently co-supervising two PhD students at AMU: Mohammed Arbabyazd (with Viktor Jirsa) and Diego Lombardo (with Mira Didic), and a third one at University Paris Sud: Shruti Naïk (with Ghislaine Dehaene-Lambertz), in addition to tutoring specific projects of a fourth student at AMU: Wesley Clawson (with Christoph Bernard). He supervised 2 master students at AMU (Thomas Boudou, Julie Falque). He plans to obtain "HDR" in the academic year 2018/2019 at AMU.

AVIS DES DIRECTEURS DES LABORATOIRES CONCERNES PAR LE PROJET DE THESE

Avis du directeur du laboratoire du directeur de thèse, M. MARTIN Thierry

X Favorable ☐ Défavorable

Commentaires :

Le porteur de projet Alain Barrat dirige une équipe phare du laboratoire. Son activité aux interfaces de la physique mérite le plus grand soutien.

Fait à Marseille, le 08/01/2018

Signature

Thierry MARTIN
Directeur du
Centre de Physique Théorique

Avis du directeur du laboratoire du co-directeur de thèse, M. JIRSA Viktor

X Favorable ☐ Défavorable

Commentaires :

Fait à Marseille, le 8/1/2018

Signature

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Marseille, le 08/01/2018

To whom it may concern,

it is with pleasure that I accept to be the inter-sectoral partner for the Doc2Amu project proposed by Alain Barrat and Demian Battaglia, centered on the temporal network analysis of time-series of neuronal activity. I will be happy sharing with the two PIs data coming from intracranial recordings in epileptic patients gathered at the Clinical Neurophysiology service of la Timone hospital and interacting with the PhD candidate during the following years whenever the project is accepted.

Best wishes.

Professeur Agnès TREBUCHON