4th INTERNATIONAL WORKSHOP ON NEURODYNAMICS (NDY'26)

A workshop on Neuroscience and Dynamical systems

Castro Urdiales, Cantabria, Spain
May 26-29, 2026

Scientific committee

- Alessandro Torcini
- Christian Bick
- Stephen Coombes
- Ernest Montbrió
- Joaquín J. Torres
- Roberto Barrio

Organizing committee

Computational Dynamics group

- Roberto Barrio
- M. Ángeles Martínez
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- Esther Barrio
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- Ana Mayora-Cebollero
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Contents

1 INTRODUCTION

Neuroscience is nowadays one of the most collaborative and active scientific research fields as it has been increasingly involving the participation of experts from other disciplines. In particular, computational and mathematical aspects of neuroscience are currently playing an important role both in modeling and replicating experimental findings and in explaining the underlying mechanisms of neurophysiological or cognitive processes. Differential equations are ubiquitous in the modeling of such phenomena and, consequently, nonlinear dynamics and dynamical systems techniques become fundamental sources of new mathematical and computational tools to study neuroscience models.

The aim of this Fourth Workshop on Neurodynamics, NDy'26 (previous editions were NDy'23 NDy'18, NDy'14) is to present an overview of successful achievements in this rapidly developing collaborative field by putting together different types of applications of nonlinear dynamics (geometrical tools in dynamical systems, numerical methods, computational schemes, dynamical measures,...) to different problems in neuroscience (mononeuronal dynamics, network activity, cognitive problems,...). Additional emphasis will be put on experimental findings seeking for theoretical explanations, and therefore this meeting is focussed on using mathematics as the primary tool for elucidating the fundamental mechanisms responsible for experimentally observed behavior in the applied neurosciences. Importantly, it will draw attention to those pieces of mathematical theory which are likely to be relevant to future studies of the brain. The final goal is spreading together mathematical methodology and neuroscience challenges and stimulating future cross-collaborations among participants, being Mathematical Neuroscience the generic topic for NDy'26.

2 PROGRAMME

	Tuesday	Wednesday	Thursday	Friday
9:30-10:00		C. Bick	R. Barrio	D. Moreno Soto
10:00-10:30		T. Manos	A. Mayora	A. Carballosa Calleja
10:30-11:00		S. Chien	C. Vich Llompart	V. Bolelli
11:00-11:30		*Coffee break*	*Coffee break*	*Coffee break*
11:30-12:00		S. Coombes	A. Torcini	B. Pietras
12:00-12:30		H. Schmidt	D. Pazó	G. Oleaga
12:30-13:00		A. Oujbara	B. Seoane	M. Martínez-Saito
13:00-13:30		J. Recalde	C. Mayora	
13:30-16:30	16:00 Registration	LUNCH	LUNCH	LUNCH
16:30-17:00	Á. Byrne	M. G. Pedersen	V. Makarov	
17:00-17:30	H. Sheheitli	B. Donmez	D. Noriega	
17:30-18:00	U. Ernst	E. Alnuwaysir	I. Topal Kement	
18:00-18:30	L. Pérez			
20:30		**SOCIAL DINNER**		

All the talks will be placed at the CIEM center, 4 Maria Aburto street (see the map at the end of the program).

3 COMMITTEES

3.1 Scientific Committee

Roberto Barrio
Universidad de Zaragoza, Spain.

Christian Bick
Vrije Universiteit Amsterdam, The Netherlands

Stephen Coombes
University of Nottingham, UK.

Ernest Montbrió
Universitat Pompeu Fabra (UPF), Spain

Alessandro Torcini
CY Cergy Paris Université, France

Joaquín J. Torres
Universidad de Granada, Spain

3.2 Organizing Committee

Computational Dynamics Group (CoDy)
`http://cody.unizar.es/`

Roberto Barrio (Chair), Universidad de Zaragoza, Spain.

Esther Barrio, Universidad de Zaragoza, Spain.
Jorge A. Jover-Galtier, Universidad de Zaragoza, Spain.
Álvaro Lozano-Rojo, Universidad de Zaragoza, Spain.
M. Ángeles Martínez, Universidad de Zaragoza, Spain.
Ana Mayora-Cebollero, Universidad de Zaragoza, Spain.
Carmen Mayora-Cebollero, Universidad de Zaragoza, Spain.
Javier Pardos, Universidad de Zaragoza, Spain.
Lucía Pérez, Universidad de Oviedo, Spain.
Sergio Serrano, Universidad de Zaragoza, Spain.
Rubén Vigara, Universidad de Zaragoza, Spain.

4 ABSTRACTS

Shear and Symmetry Breaking in an Oscillator Model of Parkinsonian Gait Freezing

E. Alnuwaysir [1,2], **K. Tsaneva-Atanasova** [1,2], **J. Sieber** [1], **P. Ashwin** [1]

1. Department of Mathematics and Statistics, University of Exeter, Stocker Road, Exeter EX4 4PY, UK.
2. Living Systems Institute, University of Exeter, Stocker Road, Exeter EX4 4PY, UK.
   Email: ea544@exeter.ac.uk, k.tsaneva-atanasova@exeter.ac.uk, j.sieber@exeter.ac.uk, p.ashwin@exeter.ac.uk

Abstract

This research investigates the freezing of gait (FOG) in Parkinson's Disease (PD) through mathematical modelling and time-series analysis. We used data from stepping-in-place experiments by Nantel et al. and modelled transitions from regular stepping to freezing as stochastic escapes between dynamic states. Our modelling starts from a generalised Hopf (GH) bifurcation normal form, which we modify by introducing symmetry-breaking forcing and shear. The GH normal form captures bistability between oscillatory motion and steady states. Our modification matches the distortions introduced by Hilbert or Takens embeddings. We employ numerical continuation with COCO to determine the effect of symmetry breaking and assess how well it matches the data [1, 2, 3].

References

[1] Julie Nantel, Camille De Solages, and Helen Bronte-Stewart: Repetitive stepping in place identifies and measures freezing episodes in subjects with Parkinson's disease, *Gait & Posture*, 34(3) (2011), 329–333.

[2] Ai Wang, Jan Sieber, William R. Young, and Krasimira Tsaneva-Atanasova: Time Series Analysis and Modeling of the Freezing of Gait Phenomenon, *SIAM Journal on Applied Dynamical Systems*, 22(2) (2023), 825–849.

[3] Jennifer Creaser, Krasimira Tsaneva-Atanasova, and Peter Ashwin: Sequential Noise-Induced Escapes for Oscillatory Network Dynamics, *SIAM Journal on Applied Dynamical Systems*, 17(1) (2018), 500–525.

Tonic-clonic seizure transitions as bifurcations in a neural field model

R. Barrio[1], **O. Cattell**[2], **A. Mayora-Cebollero**[1], **R. O'Dea**[2], **S. Coombes**[2]

1. Department of Applied Mathematics, CoDy, University of Zaragoza, Spain. Email: `rbarrio@unizar.es, amayora@unizar.es`

2. School of Mathematical Sciences, University of Nottingham, Nottingham, UK. Email: `Oliver.Cattell@nottingham.ac.uk`, `Reuben.Odea@nottingham.ac.uk, Stephen.Coombes@nottingham.ac.uk`

Abstract

Epilepsy is a dynamic complex disease involving a paroxysmal change in the activity of millions of neurons, often resulting in seizures. Tonic-clonic seizures are a particularly important class of these and have previously been theorised to arise in systems with an instability from one temporal rhythm to another via a quasi-periodic transition [1]. We show that a recently introduced class of next generation neural field models has a sufficiently rich bifurcation structure to support such behaviour [2]. This is used to seed a more exhaustive numerical bifurcation analysis that highlights the preponderance of the model to generate torus bifurcations. Since the neural field model is derived from a biophysically meaningful spiking tissue model we are able to highlight the neurobiological mechanisms that can underpin tonic-clonic seizures as they relate to levels of excitability, electrical and chemical synaptic coupling, and the speed of action potential propagation.

References

[1] Ermentrout, G. B., Cowan, J. D.: Secondary Bifurcation in Neuronal Nets, *SIAM Journal on Applied Mathematics*, Vol. 39, No. 2 , 1980.

[2] Cattell, O., Mayora-Cebollero, A., O'Dea, R. D., Barrio, R., Coombes, S.: Understanding tonic-clonic seizure transitions as secondary bifurcations in a neural field model, *Proc R Soc A*, In press, 2026.

Dimension reduction for adaptive network dynamics

C. Bick [1,2]

1. Amsterdam Center for Dynamics and Computation, Department of Mathematics, Vrije Universiteit Amsterdam, the Netherlands.
   Email: `c.bick@vu.nl`

2. Systems and Networks Neuroscience, Amsterdam Neuroscience, the Netherlands.

Abstract

Adaptivity of network connections is a key property of neural systems, which contributes, for example to learning. However, if all network connections adapt independently of one another the resulting dynamical system is high-dimensional. Here we discuss ways to reduce the dimension of network dynamical systems with adaptive connections. On the one hand, we consider mean-field approximations of adaptive network dynamics for large networks [1]. On the other hand, we discuss how "constraints" of adaptivity - for example keeping the average weight constant - can reduce the dimensionality of adaptive network dynamical systems [2].

References

[1] Duchet, B., Bick, C., Byrne, Á.: Mean-field approximations with adaptive coupling for networks with spike-timing-dependent plasticity. *Neural Computation* **35** (2023) 1481–1528.

[2] Martens, E.A., Bick, C.: Multiple Timescale Dynamics of Network Adaptation with Constraints. *Chaos* **35** (2025) 103141

Realizing cyclic-sequential dynamics in neural population models

V. Bolelli [1], **L. Greco** [1], **D. Prandi** [2]

1. L2S, University of Paris-Saclay, CentraleSupèlec, Gif-sur-Yvette, France. Email:bolellivirginia@gmail.com

2. CNRS, L2S, University of Paris-Saclay, CentraleSupèlec, Gif-sur-Yvette, France.

Abstract

We present a mathematical framework for cyclic and sequential patterns of brain activity based on heteroclinic dynamics in neural-field models. Specifically, we consider a class of Amari-type neural-field equations and first show that low-dimensional models, in which each variable represents a neural state, do not sustain heteroclinic cycles under biologically plausible constraints on equilibria.

To overcome this limitation, we embed heteroclinic dynamics into higher-dimensional neural population systems. Using a universal approximation result, we show that Lotka–Volterra vector fields, which generically support robust heteroclinic cycles, can be realized by neural networks interpretable as high-dimensional neural-field models. This yields a lifting of the original low-dimensional dynamics into a higher-dimensional system governed by biologically plausible Amari equations.

When appropriately projected, the high-dimensional dynamics exhibit cyclic–sequential behavior. Moreover, we establish the existence of sequences with tunable, constant residence times near equilibria, thereby avoiding the asymptotic slowing typical of classical heteroclinic trajectories. As a case study, we apply the framework to reproduce sequential transitions between cognitive states observed during focused-attention meditation. This provides a mathematically consistent description of cyclic–sequential dynamics in neural populations.

Pattern formation in a next generation neural field model with plasticity

Á. Byrne[1], **N. Fennelly**[1], **D. Avitabile**[2]

1. School of Mathematics and Statistics, University College Dublin, Ireland.
2. Amsterdam Center for Dynamics and Computation, Vrije Universiteit Amsterdam, the Netherlands.

Abstract

Synaptic plasticity plays a fundamental role in neuronal dynamics, governing how connections between neurons evolve in response to experience. In this work, we extended a network model of θ-neuron oscillators to include a realistic form of adaptive plasticity, which adjust coupling strengths based on the relative phases of θ-neuron oscillators [1]. We compare two distinct implementations of this plasticity: pairwise updates to individual coupling strengths and global updates applied to the mean coupling strength. We derive a mean-field approximation and assess its accuracy by comparing it to θ-neuron simulations across various stability regimes. Through bifurcation analysis and the calculation of maximal Lyapunov exponents, we uncover interesting phenomena such as bistability and chaotic dynamics via period-doubling and boundary crisis bifurcations [2]. We also study the spatially extended network and explore the existence and stability of spatiotemporal patterns. Through both a Turing instability analysis and numerical continuation we uncover states above and beyond those seen in a standard neural field model.

References

[1] Duchet, B., Bick, C., Byrne, Á.: Mean-Field Approximations With Adaptive Coupling for Networks With Spike-Timing-Dependent Plasticity, *Neural Computation*, 35(9) (2023), 1481–1528.

[2] Fennelly, N., Neff, A., Lambiotte, R., Keane, A., Byrne, Á.L.: Mean-field approximation for networks with synchrony-driven adaptive coupling, *Chaos*, 35(1) (2025), 013152.

On the Scaling of Neural Population Dimensionality: Insights from SVCA

Alejandro Carballosa[1,2], **Alessandro Torcini**[1]

1. Laboratoire de Physique Théorique et Modélisation, CY Cergy Paris Université, CNRS UMR 8089, Cergy-Pontoise, France.

2. Institut du Cerveau - Paris Brain Institute, Sorbonne Université, Inserm U1127–CNRS UMR 7225, Paris, France.

Abstract

Neuronal recordings have become *large scale* thanks to recent technological advances in the last decade, enabling the simultaneous measurement of activity from thousands of neurons. In this direction, a key theoretical question in the field is whether the dimensionality of the system remains constant as more neurons are included in the analysis or if it changes according to a given law. Some earlier studies, based on Principal Component Analysis (PCA) and in the context of few tens of neurons, gave weight to the former hypothesis and made theoretical predictions for a bounded dimensionality with system size. In contrast, recent findings exploiting the previously mentioned large scale datasets and based on a method called Shared Variance Component Analysis (SVCA), have reported the existence of power-law structures in the variance spectra that apparently make the system's dimensionality grow unboundedly with the number of analyzed neurons. Furthermore, while the first, most relevant dimensions can be decoded from the behavior of the animal, the interpretation of these new additional dimensions is yet unclear and somehow linked to internal variables.

In this talk, we aim to review and reconcile these seemingly conflicting observations. Using both synthetic models and some of the previous experimental datasets, we show that SVCA effectively captures collective dynamics as reliable interpretable features. We explore the scaling laws observed in the data and we derive an analytical relationship between the exponent of the power law SVC-spectra and the embedding dimensionality. In sum, our results predict that, despite apparent growth at intermediate scales, dimensionality ultimately saturates for sufficiently large system sizes.

VIP-Mediated Attentional Modulation of Persistent Activity in a Cortical Microcircuit Model

Sh. Chien[1], **J. Hlinka**[1,2], **T. Knösche**[3], **H. Schmidt**[1]

1. Institute of Computer Science, The Czech Academy of Sciences, Czechia.
   Email: `chien@cs.cas.cz`
2. National Institute of Mental Health, Klecany, Czechia.
3. Max Planck Institute for Human Cognitive and Brain Sciences, Germany.

Abstract

Persistent neuronal activity is a proposed neural mechanism supporting the maintenance of information in working memory (WM). Attention is known to influence WM performance and the stability of internal representations. However, how attentional signals modulate the circuit mechanisms that generate persistent activity remains insufficiently explored in computational models. In this study, we investigate whether modulatory input to vasoactive intestinal peptide (VIP) interneurons can regulate the emergence of persistent activity in a biologically constrained cortical microcircuit model. We employed a cortical microcircuit model consisting of excitatory (E) and inhibitory interneuron populations (PV, SOM, and VIP) distributed across cortical layers L2/3, L4, L5, and L6. Three classes of long-range inputs were implemented: (i) lateral input, (ii) modulatory input, and (iii) bottom-up input. We systematically varied key parameters to examine their influence on the emergence of persistent activity. The model exhibits bistability with respect to bottom-up input. Bistability emerges across a range of parameter configurations, including variations in VIP interneuron cell count, recurrent connectivity within the E2/3 population, recurrent connectivity within the E4 population, and the strength of modulatory input. The size of the bistable region is sensitive to these parameters, particularly the modulatory input to VIP2/3 neurons. Notably, stronger modulatory input reduces the minimum bottom-up input required to sustain persistent activity. These findings provide a potential circuit-level mechanism by which attention may enhance working memory stability.

Revisiting the Haken Lighthouse Model: Bridging Spiking and Non-Spiking Neural Networks

S. Coombes

School of Mathematical Sciences, University of Nottingham, Nottingham, NG7 2RD, UK.

Email: `stephen.coombes@nottingham.ac.uk`

Abstract

Simple spiking neural network models built from integrate-and-fire (IF) units display rich emergent behaviour but are difficult to analyse, especially in terms of pattern formation. Rate-based models and coupled phase oscillators are more tractable but miss important dynamical features of spiking systems. To bridge these paradigms, Hermann Haken introduced the Lighthouse model, a synergetic framework capturing synchronisation, travelling waves, and neural pattern formation. We revisit the Lighthouse model and develop new mathematical results that clarify self-organisation in spiking networks. We derive linear stability conditions for phase-locked spiking states in Lighthouse networks defined on graphs with realistic alpha-function synapses and axonal delays. Extending this graph-based analysis to spatially continuous (non-local) networks, we formulate a Turing-type instability criterion for emergent spiking patterns. We further show that localised spiking bump solutions – difficult to analyse in IF networks – arise naturally in the Lighthouse model and examine their stability against wandering dynamics. These results reinforce the Lighthouse model as a powerful framework for studying structured neural interactions and self-organisation, advancing the synergetic perspective on spiking neural dynamics [1].

References

[1] Coombes, S.: Revisiting the Haken Lighthouse Model, *The European Physical Journal Special Topics: In Memoriam Hermann Haken: Synergetics and Self-organisation in Complex Systems*, 2025. `https://doi.org/10.1140/epjs/s11734-025-01841-3`

Reconstructing resonant phase oscillator interactions from noisy time series

B. Dönmez, B. Rink

Department of Mathematics, Vrije Universiteit Amsterdam, Amsterdam, the Netherlands.
Email: b.donmez@vu.nl, b.w.rink@vu.nl

Abstract

We present a novel method for reconstructing networks and hypernetworks of coupled phase oscillators from noisy time series. Noise and uncertainty can make it hard or impossible to distinguish different oscillator networks based on observed dynamical behavior. Thus, our method does not aim to determine exact phase equations for the oscillators, but instead recovers their first- and second-order resonant normal form. This normal form contains crucial information on the underlying network and yields accurate approximations of the dynamics. We provide rigorous estimates on the accuracy of the reconstructed normal form and illustrate the method with numerical examples.

Routing by spontaneous synchronization

M. Schünemann, U. Ernst

Computational Neurophysics Lab, Department of Theoretical Physics, University of Bremen, Germany.

Email: `maikschuenemann@gmail.com, udo@neuro.uni-bremen.de`

Abstract

Selective attention allows to process stimuli which are behaviorally relevant, while attenuating distracting information. However, it is an open question what mechanisms implement selective routing, and how they are engaged in dependence on behavioral need. Here we introduce a novel mathematical framework for selective processing by spontaneous synchronization. Input signals become organized into 'avalanches' of synchronized spikes which propagate to target populations. Selective attention enhances spontaneous synchronization and boosts signal transfer by a simple disinhibition of a control population, without requiring changes in synaptic weights.

Specifically, we consider a generic situation in which two separate, recurrently coupled populations A and B are driven by two different, competing stimuli. Both populations are sending their outputs to a receiving population C. In dependence on attention, either the input signal driving A, or the input signal driving B shall be routed to C.

Our framework is fully analytically tractable and provides a complete understanding of all stages of the routing mechanism, yielding closed-form expressions for input-output correlations. In particular, we identify an optimal recurrent coupling strength for the sending populations which balances the effects of decreasing stimulus information and increasing signal transfer when enhancing synchronicity in the sending populations [arXiV:2305.13914].

Interestingly, although gamma oscillations can naturally occur through a recurrent dynamics, we can formally show that the routing mechanism itself does not require such oscillatory activity and works equally well if synchronous events would be randomly shuffled over time. Furthermore, we explain a range of physiological findings in a unified framework and make specific predictions about putative control mechanisms and their effects on neural dynamics.

Chaotic Selectivity in High-Dimensional Neurons

V.A. Makarov[1], **J. Makarova**[2]

1. Department of Applied Mathematics and Mathematical Analysis,
Universidad Complutense de Madrid, Madrid, 28040, Spain.
Email: `vmakarov@ucm.es`

2. Dept. of Translational Neuroscience, CNC, CSIC, Av. de León, 1,
Alcalá de Henares, Madrid, 28805, Spain.
Email: `julia.samuseva@cajal.csic.es`

Abstract

Reflexive artificial neural networks often outperform humans on tasks that require matching input data to outputs, such as the classification of images. However, a core characteristic of general intelligence is the ability to handle situations in which the "right" answer isn't always clear, which poses a challenge for AI.

In this work, we build on the concept of a high-dimensional brain [1] to introduce a new form of reflective learning. This approach extends selective and associative learning to chaotic learning. Unlike traditional methods, chaotic learning allows a single neuron to respond differently to identical stimuli depending on the context. It is grounded in the local chaotic dynamics of the learning process. The introduced discrete-time model is simple, making it particularly appealing for hardware implementation.

Through simulations, we illustrate how various types of learning can emerge in a neuron. The model exhibits learning properties similar to those of more complex neural networks, including the emergence of extreme selectivity and associative memories.

References

[1] Tyukin, I., Gorban, A.N., Calvo, C., Makarova, J., Makarov, V.A.: High-dimensional brain: A tool for encoding and rapid learning of memories by single neurons. *Bull. Math. Biol.* **81** (2019) 4856-4888.

Modeling Neural-Level Seizure Dynamics with Arbor-TVB: Whole-Brain Network Mechanisms and Intervention Strategies

T. Manos

ETIS Lab, ENSEA, CNRS, UMR8051, CY Cergy-Paris University, Cergy, France.
Email: `thanos.manos@cyu.fr`

Abstract

Epileptic seizure generation and propagation require a multi-scale framework linking cellular mechanisms to whole-brain dynamics. In this study, we first use The Virtual Brain (TVB) framework with the Epileptor model to examine how the location and connectivity of the Epileptogenic Zone (EZ) shape focal seizures in the mouse brain. Focusing on the hippocampus, we evaluate strategies to limit seizure initiation and prevent propagation. Simulations of tissue resection, anti-seizure drug effects, and neurostimulation identify interventions that reduce hyperexcitability while preserving overall network function [1]. We then introduce a co-simulation framework coupling the biophysically detailed neural simulator Arbor with TVB, bridging micro-scale neuronal dynamics and macro-scale brain activity. Arbor models single neurons and local circuits, while TVB captures whole-brain dynamics informed by structural connectivity. This integration reveals how local biophysical processes influence global brain states, offering new insights into seizure mechanisms and potential intervention targets [2].

References

[1] Courson J., Quoy M., Timofeeva Y., Manos T.: An exploratory computational analysis in mice brain networks of widespread epileptic seizure onset locations along with potential strategies for effective intervention and propagation control. *Front. Comput. Neurosci.* **18** (2024) 1360009.

[2] Hater T., Courson J., Lu H., Diaz-Pier S., Manos T.: Arbor-TVB: a novel multi-scale co-simulation framework with a case study on neural-level seizure generation and whole-brain propagation, *Front. Comput. Neurosci.* **19** (2026) 1731161.

Hierarchical inference in the brain as a chain of 7 "neurons": criticality, activity and prediction errors, power-laws, and Up-Down states

M. Martinez-Saito

Institute of Cognitive Neuroscience, HSE University, Russian Federation.
Email: `mmartinezsaito@gmail.com`

Abstract

We describe a chain of unidirectionally coupled adaptive excitable elements slowly driven by a stochastic process from one end and open at the other end, as a minimal toy model of unresolved irreducible uncertainty in a system performing inference through a hierarchical model. Threshold potentials adapt slowly to ensure sensitivity without being wasteful. Activity and energy are released as intermittent avalanches of pulses with a distribution largely independent of the exogenous input form. We find that subthreshold bistability closely resembles empirical measurements of intracellular membrane potential, and suggest that critical cortical cascades emerge from a trade-off between metabolic power consumption and performance requirements in a critical world, and that the temporal scaling patterns of brain electrophysiological recordings ensue from weighted linear combinations of subthreshold activities and pulses from different hierarchy levels.

The Role of Synaptic Dynamics in Mean-Field Models of Coupled Neural Populations

A. Mayora-Cebollero [1], **R. Barrio** [1], **J.A. Jover-Galtier** [1], **C. Mayora-Cebollero** [1], **L. Pérez** [2], **S. Serrano** [1]

1. Department of Applied Mathematics, Computational Dynamics group and IUMA, University of Zaragoza, Spain.
   Email: `amayora@unizar.es`; `rbarrio@unizar.es`; `jorgejover@unizar.es`; `cmayora@unizar.es`; `sserrano@unizar.es`
2. Department of Mathematics, University of Oviedo, Spain.
   Email: `perezplucia@uniovi.es`

Abstract

The dynamical study of mean-field models of coupled neural populations allows us to analyse the different regimes that emerge when varying model parameters or when specific properties are included or omitted. The Montbrió-Pazó-Roxin mean-field model (*Physical Review X*, 2015) and the Dumont-Gutkin mean-field model (*PLoS Computational Biology*, 2019) describe the dynamics of heterogeneous all-to-all coupled QIF spiking neural networks without and with synaptic dynamics, respectively. These two models are linked through a parameter related to synaptic coupling. In this presentation [1, 2], we investigate the different dynamical regimes that arise when the value of this parameter is varied, and the mechanisms that create or destroy them. Our analysis combines several techniques, including spike-counting sweeping, Lyapunov exponents, and numerical continuation.

References

[1] Barrio, R., Jover-Galtier, J. A., Mayora-Cebollero, A., Mayora-Cebollero, C., Serrano, S.: Synaptic dependence of dynamic regimes when coupling neural populations. *Physical Review E* **109(1)** (2024) 014301.

[2] Mayora-Cebollero, A., Barrio, R., Li, L., Mayora-Cebollero, C., Pérez, L.: Dynamics of coupled neural populations: The role of synaptic dynamics. *Chaos: An Interdisciplinary Journal of Nonlinear Science* **35(6)** (2025) 063140.

Deep Learning for Dynamical Analysis in Computational Neuroscience

C. Mayora-Cebollero[1], **R. Barrio**[1], **Á. Lozano**[2], **A. Mayora-Cebollero**[1]

1. Department of Applied Mathematics, Computational Dynamics group and IUMA, University of Zaragoza, Spain.
   Email: `cmayora@unizar.es`; `rbarrio@unizar.es`; `amayora@unizar.es`

2. Department of Mathematics, Computational Dynamics group and IUMA, University of Zaragoza, Spain.
   Email: `alozano@unizar.es`

Abstract

Deep Learning is the set of techniques that use Artificial Neural Networks (loosely inspired by their biological counterparts) to learn from complex data. In recent years, Deep Learning has been applied to perform dynamical systems analyses such as chaos detection [1, 2] and the approximation of the full Lyapunov exponents spectrum [3]. Beyond achieving competitive results for these studies, Deep Learning also provides several advantages such as time savings and the ability to work with partial information. In this presentation, we explore the use of Deep Learning to analyze chaotic dynamics in mean-field models of coupled neural populations.

References

[1] Barrio, R., Lozano, Á., Mayora-Cebollero, A., Mayora-Cebollero, C., Miguel, A., Ortega, A., Serrano, S., Vigara, R.: Deep Learning for chaos detection. *Chaos: An Interdisciplinary Journal of Nonlinear Science* **33(7)** (2023) 073146.

[2] Mayora-Cebollero, C., Fenton, F.H., Halprin, M., Herndon, C., Toye, M.J., Barrio, R.: Deep Learning for analyzing chaotic dynamics in biological time series: Insights from frog heart signals. *Neurocomputing* **660** (2026) 131820.

[3] Mayora-Cebollero, C., Mayora-Cebollero, A., Lozano, Á, Barrio, R.: Full Lyapunov exponents spectrum with Deep Learning from single-variable time series. *Physica D: Nonlinear Phenomena* **472** (2025) 134510.

Towards a Timescale-specific Subspace for Brain Inter-area Communication

D. Moreno Soto [1,2,3], **L. Schutzeichel** [2,3,4], **S. Musall** [4], **M. Helias** [2,3], **D. Dahmen** [3]

1. Dept. of Computer Science, Dept. of Biology, RWTH Aachen University, Germany.
   Email: morenosoto@netsci.rwth-aachen.de
2. Dept. of Physics, RWTH Aachen University, Germany.
3. Institute for Advanced Simulation 6, Jülich Research Centre, Germany.
4. Institute for Biological Information Processing 3, Jülich Research Centre, Germany.

Abstract

Brain-wide neural function involves communication between distributed neuronal networks through mechanisms that still remain hazy. Local networks display diverse intrinsic timescales of activity that are crucial to their function, but our understanding of how these timescales couple during interactions between different brain areas is still in its infancy. Additionally, it is unclear how the operation at criticality, a property of neural networks known to contribute to their computational capabilities, influences inter-area communication. We amalgamated the inter-areal picture with a novel form of criticality, devoid of neuronal avalanches, which arises from disordered connections and entails a rich repertoire of timescales [1]. Using linear response theory, we developed an inter-areal formalism for feedforward signal relay between recurrent networks operating in this new critical regime. This formalism supports the existence of a communication subspace composed of the eigenmodes of the interacting networks. The structure of the coupling between eigenmodes predominantly preserves local timescale hierarchies and is consistent with the nature of the tasks performed by the system. Furthermore, this inter-areal model exhibits a regime of high expressivity in signal transmission. Altogether, this approach links the communication subspace hypothesis to critical dynamics, advancing towards a timescale-specific theory of brain inter-area communication.

References

[1] Dahmen, D. *et al.*: Second type of criticality in the brain uncovers rich multiple-neuron dynamics. *Proceedings of the National Academy of Sciences* **116** (2019) 13051–13060.

Hopf-Hopf bifurcations and chaos in a coupled FitzHugh-Nagumo system

F. Drubi, S. Ibáñez, D. Noriega

Department of Mathematics, University of Oviedo, Spain.
Email: noriegadiego@uniovi.es

Abstract

Given the following system of two linearly coupled FitzHugh-Nagumo oscillators:

$$\begin{cases} x_1' &= c(y_1 + x_1 - \frac{x_1^3}{3}) + \alpha_1(x_2 - x_1), \\ y_1' &= -\frac{1}{c}(x_1 - a + by_1) + \alpha_2(y_2 - y_1), \\ x_2' &= c(y_2 + x_2 - \frac{x_2^3}{3}) + (\alpha_1 + \varepsilon_1)(x_1 - x_2), \\ y_2' &= -\frac{1}{c}(x_2 - a + by_2) + (\alpha_2 + \varepsilon_2)(y_1 - y_2). \end{cases}$$

the emergence of codimension-two Hopf-Hopf bifurcations under certain restrinctions over the parameters is discussed. Following [1], a classification of non-resonant cases is performed; among others, two in which the bifurcation diagram includes invariant 2 and 3-tori are present.

Rich dynamical behavior is unveiled in this exploration, including quasiperiodic dynamics [2] and chaotic regions [3], both closely related to the synchronization manifold. In particular, in the chaotic regions boundary and interior crises are observed, where the attractor suddenly expands: these jumps are linked to transitions of the attractor to almost-synchronization phases.

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A Dynamic Fast Marching Method for Efficient Exploration of Time-evolving Environments

G.E. Oleaga, D. Ortega-Lozano, V.A. Makarov

Department of Applied Mathematics and Mathematical Analysis,
Universidad Complutense de Madrid, Madrid, 28040, Spain.
Email: goleaga@ucm.es, dorteg03@ucm.es, vmakarov@ucm.es

Abstract

Exploration in environments containing both static and moving obstacles is a fundamental challenge in physics and engineering with applications in robotics. The Fast Marching Method (FMM) is an efficient numerical solver for the Eikonal equation and a powerful tool for modeling wavefront propagation in static scenarios. However, we show that it fails in the presence of moving obstacles, leading to unreliable trajectories [1].

To mitigate this problem, we introduce a novel method, called the Dynamic Fast Marching Method (DFMM), that enables wave-based robust exploration in environments of arbitrary dimension and complexity, even in the presence of time-evolving constraints. The DFMM preserves the computational efficiency of the classical FMM while enabling a fast and reliable global search for collision-free trajectories in dynamic situations. Furthermore, the same framework naturally provides an effective interception strategy for pursuing moving targets in cluttered dynamic environments, thereby extending its versatility.

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Mathematical Modeling of Fear: Synchronization in the Amygdala–Prefrontal Cortex Circuit

Abdeltif Oujbara

Department of Mathematics; Normandie Univ.; LMAH UR 3821, Université Le Havre Normandie, 25 rue Philippe Lebon, 76600 Le Havre, Normandie, France.

Email: oujbara95abdeltif@gmail.com

Abstract

In this presentation, I will discuss the dynamics of an amygdala pyramidal cell described by a two-compartment Hodgkin–Huxley-type model. Special attention will be given to the impact of coupling between the soma and dendrite, and to how this cellular model can serve as a basis for studying synchronization in neural networks connecting the amygdala and the prefrontal cortex.

Dimensionality reduction scheme for populations of populations of QIF neurons

D. Pazó[1], **R. Cestnik**[2]

1. Instituto de Física de Cantabria (IFCA), Universidad de Cantabria-CSIC, Spain.
   Email: pazo@ifca.unican.es
2. Centre for Mathematical Science, Lund University, Sweden

Abstract

The dynamics of large populations of fully coupled quadratic integrate-and-fire (QIF) neurons can be described by firing-rate equations consisting of only a few ordinary differential equations (ODEs) [1].

In this contribution, we go one step further to consider a fully coupled network of the mentioned firing-rate equations, which represents a population of QIF neurons with clustered substructure. We report on an additional reduction of this system to a small set of ODEs [1].

Expressed in mathematical language, our reduction theory applies to ensembles of complex Riccati equations, while the theory in Ref. [1] applies to ensembles of real Riccati equations (or QIF neurons).

References

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Dissecting emerging slow rhythms in delay-coupled neural oscillators

X. Qie [1], **M. Martin** [2], **M.G. Pedersen** [2]

1. School of Mathematics, South China University of Technology, Guangzhou, China. Email: `xinxinqie77@gmail.com`

2. Department of Information Engineering, University of Padova, Italy. email: `matteo.martin.2@phd.unipd.it, mortengram.pedersen@unipd.it`.

Abstract

Synaptic transmission delays are ubiquitous in neural circuits and can fundamentally alter the dynamical repertoire of coupled oscillators. A striking yet underappreciated consequence of delayed coupling is the emergence of slow modulatory rhythms that have no counterpart in the intrinsic dynamics of isolated neurons. Here we demonstrate that weak delayed coupling in small inhibitory networks introduces an effective slow–fast structure in the phase-difference dynamics, generating low-frequency components that are absent in the intrinsic cellular dynamics.

The origin of this generic phenomenon is analyzed by numerical continuation and bifurcation analysis. To do so, we employ phase reduction based on phase response curves to derive a phase-difference model with delay for mutually inhibitory coupled oscillators, where the individual units are given by the FitzHugh–Nagumo model, the Morris–Lecar model, or a next-generation neural mass model. We use phase planes to study multistability and limit cycles, which correspond to slow modulation of fast oscillations in the full model. Treating the synaptic delay as a bifurcation parameter, we apply numerical continuation to construct delay-dependent bifurcation diagrams. The analysis reveals Hopf, heteroclinic, and saddle-node-of-periodics bifurcations that cause and organize slow rhythmic behavior. Our analysis provides a systematic approach to the search for limit cycles in phase-reduction models corresponding to delay-induced slow rhythms in the original model.

Dynamical landscape in neuron and cardiac models

L. Pérez[1], **R. Barrio**[3], **S. Ibáñez**[2]

1. Department of Mathematics, University of Oviedo, Spain.
   Email: `perezplucia@uniovi.es`
2. Department of Mathematics, University of Oviedo, Spain.
   Email: `mesa@uniovi.es`
3. Department of Applied Mathematics, University of Zaragoza, Spain.
   Email: `barrio@unizar.es`

Abstract

Neuronal and cardiac models exhibit a substantial overlap in their underlying dynamical mechanisms, despite the distinct biological scales they represent. For instance, bursting behaviour, multi-scale dynamics and canard phenomena can be found in both cases. In this talk, we will focus on the geometric mechanisms and the bifurcation landscape that underlie common cardiac and neuron behaviour.

AudioPrism: Oscillatory dynamics for multi-scale temporal processing in speech recognition

B. Pietras [1,2], **P. Carvalho** [1,2], **I. Dubinin** [1,2], **W. Singer** [1,2,3], **F. Effenberger** [1,2]

1. Natural Intelligence (NISYS GmbH), Frankfurt am Main, Germany.
   Email: `bastian@nisys.ai`
2. Ernst Strüngmann Institute, Frankfurt am Main, Germany.
3. Max Planck Institute for Brain Research, Frankfurt am Main, Germany.

Abstract

Oscillatory dynamics underlie key computational mechanisms in the brain —resonance, synchronization, and fading memory [1]— yet remain largely unexploited in artificial neural networks. We present AudioPrism, a minimal architecture of damped harmonic oscillators (DHOs) for speech recognition.

AudioPrism mirrors two-stage auditory processing. A *prism layer* of uncoupled DHOs with log-spaced natural frequencies decomposes raw audio via resonance —without Fourier transforms— mimicking cochlear tonotopy. The prism transmits the envelope, approximating a Mel-spectrogram. A *harmonic oscillator recurrent network* (HORN) of coupled DHOs with cortical δ–γ frequencies then integrates these features across timescales. After training, the network self-organizes a high-to-low frequency cascade mirroring the $\gamma \to \theta/\delta$ hierarchy of auditory cortex; low-frequency reverberations provide the fading memory critical for classification.

Without the prism, networks perform at chance level on raw audio. With it, AudioPrism achieves consistently high performance, being fast, stable, noise robust and highly parameter efficient. Moreover, it allows for almost perfect zero-shot transfer learning, demonstrating robust, invariant speech representations. Finally, its continuous-time formulation shows potential for energy-efficient analog-electronic hardware implementation [2].

References

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Adaptive geometry of cognitive maps in a memory-augmented neural network

J. Recalde, S. Cheng

Institut für Neuroinformatik, Ruhr University Bochum, Germany.

Abstract

Animals use internal models of the world to guide flexible behavior. In neuroscience, these models are often described as cognitive maps, which are primarily associated with the hippocampal–entorhinal system. Although originally viewed as metric representations of physical space, experimental evidence shows that hippocampal representations are often more complex: they can be fragmented, distorted, or organized by non-spatial variables. Here, we study how such representational geometry emerges in a memory-augmented neural network (MANN) [1] trained with reinforcement learning to solve goal-directed navigation and memory tasks. The model combines recurrent dynamics with a fast associative memory, allowing the agent to autonomously store and retrieve goal locations from egocentric sensory input. We show that this memory system is necessary for flexible hidden-goal navigation and gives rise to structured internal representations resembling cognitive maps. Their geometry adapts to task-relevant distinctions: open environments produce metric maps, barriers induce compartmentalized representations, ambiguous environments can collapse states, and context-dependent tasks organize non-spatial variables.

Importantly, this geometry guides behavior. When the environment changes, the agent makes systematic errors that reflect its learned belief about the world, while novel states can be incorporated into the existing map. Together, these results suggest that MANNs can form adaptive cognitive maps whose geometry reflects task-relevant distinctions and guides behavior, while reproducing several regimes observed in the hippocampus.

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A Macroscopic Model of Spiking Neural Networks with Spike-Timing-Dependent Plasticity

H. Schmidt [1,*], **R. Gast** [2,*], **A. Kennedy** [2]

1. Institute of Computer Science, Czech Academy of Sciences, Prague, Czech Republic.

2. Department of Neuroscience, Scripps Research, San Diego, CA, US.

[*] Contributed equally.

Abstract

The human brain consists of approximately 10^{14} synapses, produced from a genome of about 20,000 protein-coding genes. How can the developing brain ensure that local circuits wire up in a way that supports their function, despite this bottleneck in genetic encoding? We study the role of interaction between synaptic plasticity rules and cellular physiology in producing useful connectivity in neural populations. We leverage two key aspects of biological neural networks: 1) neurons and the synapses connecting them are inherently diverse in their structure and electrophysiological properties, and 2) synapses are highly plastic and subject to activity-dependent changes in strength, which can be mathematically formalized by spike-timing-dependent plasticity (STDP) rules.

We address this question in networks of quadratic integrate-and-fire (QIF) neurons endowed with STDP. We develop a multi-population mean-field method that incorporates spike synchronization, allowing it to reproduce synaptic weight evolution in heterogeneous spiking neural networks – something conventional rate models fail to capture. We find that such connectivity patterns are the natural result of an interaction between neural heterogeneity and STDP. We demonstrate that this model can flexibly store associative memory items, and encode memory sequences with repeating items [1].

References

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Uncovering statistical structure in large-scale neural activity with Restricted Boltzmann Machines

B. Seoane [1,2]

1. Departamento de Física Teórica, Universidad Complutense de Madrid, 28040 Madrid, Spain. Email: `beseoane@ucm.es`

2. GISC - Grupo Interdisciplinar de Sistemas Complejos 28040 Madrid, Spain.

Abstract

Large-scale electrophysiological recordings now enable simultaneous monitoring of thousands of neurons across multiple brain regions, revealing structured variability in population activity. Understanding how such collective patterns emerge from microscopic interactions requires models that are both scalable and interpretable. Here, we use RBMs to model the activity of $\sim$ 1500–2000 simultaneously recorded neurons from the Allen Institute Visual Behavior Neuropixels dataset, spanning multiple cortical and subcortical regions of the mouse brain. RBMs accurately reproduce high-order and global empirical statistics while remaining interpretable: they provide effective interactions between neurons, including higher-order terms, and uncover dominant coordination patterns with clear anatomical organization. Analysis of the learnt landscape further enables unsupervised identification of task-related brain states. Finally, Monte Carlo sampling of the model captures the global relaxation dynamics observed in the data. These results establish RBMs as scalable and interpretable tools for extracting statistical structure from large-scale neural recordings, linking collective neural activity to brain organization and behavior.

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Coupled beta and high-frequency oscillations emerge from synchronized bursting in a minimal model of the subthalamic nucleus

H. Sheheitli [1,2], **L.A. Johnson** [1], **J. Wang** [1], **J.E. Aman** [1], **J.L. Vitek** [1]

1. Department of Neurology, University of Minnesota, Minneapolis, MN, USA. Email: `shehe003@umn.edu`
2. Department of Psychiatry & Behavioral Sciences, University of Minnesota, Minneapolis, MN, USA.

Abstract

Local field potentials from the subthalamic nucleus (STN) in Parkinson's disease exhibit exaggerated beta oscillations (13–30 Hz) coupled to high-frequency oscillations (HFOs, 200–400 Hz), with HFO amplitude modulated by beta phase. This phase-amplitude coupling (PAC) is a robust biomarker of the parkinsonian state [1], yet no biophysical model has explained how it emerges, what determines the HFO frequency, or how HFOs can exist without beta modulation in the medicated STN.

We present a minimal model consisting of a heterogeneous population of excitatory Izhikevich neurons [2] with recurrent coupling, parameterized by intrinsic excitability and synaptic coupling strength. The two-dimensional parameter landscape reveals three regimes: asynchronous tonic firing, asynchronous bursting, and synchronous bursting. Synchronous bursting produces beta-HFO PAC as a collective phenomenon. Asynchronous bursting yields HFO power without PAC, corresponding to the medicated state. The synchronization transition depends on baseline excitability, ranging from sharp co-emergence of bursting and synchrony to a two-stage process where burst recruitment precedes synchronization. HFO peak frequency varies continuously across the parameter landscape, accounting for the clinically observed slow-to-fast HFO shift with medication.

The work provides a dissection of how multiple-timescale mesoscopic LFP spectral features map onto the microscopic neuronal operating regime, and offers a mechanistic lens for dynamics-based interpretation of patient-specific spectral signatures.

References

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Coarse-Grained Brain Dynamics Reveal Altered Scaling Regimes in Early Psychosis

I. Topal[1], **G. Montaña-Valverde**[1], **W. Hinzen**[1,2]

1. Department of Translation & Language Sciences, Universitat Pompeu Fabra, Carrer Roc Boronat, 138, Barcelona, 08018, Spain.
   Email: irem.topal@upf.edu
2. Institut Català de Recerca i Estudis Avançats (ICREA), Barcelona, Spain.
   Email: wolfram.hinzen@upf.edu

Abstract

The brain criticality hypothesis states that large-scale neural activity operates near a regime characterized by scale invariance and emergent collective dynamics. Such regimes are associated with nontrivial fixed points and the emergence of effective low-dimensional descriptions of high-dimensional activity. Here, we analyze resting-state fMRI data from the HCP Early Psychosis cohort through the lens of coarse-grained neural dynamics. Using a phenomenological renormalization group (PRG) approach [1], we iteratively construct coarse-grained descriptions of brain activity and examine their statistics under coarse-graining transformations. This reveals the emergence of a non-Gaussian fixed-point distribution together with robust scaling behaviour across renormalization steps, consistent with an underlying scale-invariant dynamical regime. We further observe dynamical scaling, indicating long-range dependencies and slow collective modes. Importantly, we find significant differences between healthy individuals and patients, suggesting a shift in the underlying dynamical organization of brain activity in early psychosis. These results support the view that neuropsychiatric conditions reflect alterations in the system's position within a space of dynamical regimes, with scaling exponents providing quantitative markers of large-scale brain dynamics.

References

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A theory for self-sustained balanced states in absence of strong external currents

A. Torcini[1], **D. Angulo Garcia**[2]

1. Laboratoire de Physique Théorique et Modélisation, UMR 8089, CY Cergy Paris Université, CNRS, Cergy-Pontoise, France.
   Email: `alessandro.torcini@cyu.fr`
2. Universidad Nacional de Colombia, Facultad de Ciencias Exactas y Naturales, Manizales, Colombia.
   Email: `dangulog@unal.edu.co`

Abstract

Recurrent neural networks with balanced excitation and inhibition exhibit irregular asynchronous dynamics, which is fundamental for cortical computations. Classical balance mechanisms require strong external input currents in order to sustain finite firing rates, thus raising concerns about their biological plausibility [1]. Here, we investigate an alternative mechanism based on short-term synaptic depression (STD) acting on excitatory-excitatory synapses, which dynamically balances the network activity without the need of strong external driving. We characterize the dynamics of a densely connected recurrent network made up of N rate-neuron models encompassing STD. Depending on the synaptic strength J_0, the network exhibits two distinct regimes: at sufficiently small J_0, it converges to a homogeneous fixed point, while for sufficiently large J_0 *Rate Chaos* emerges. For finite networks, we observe a *transition region* at intermediate J_0, where the system passes from the homogeneous fixed point to Rate Chaos following different routes to chaos. The characterization of the Rate Chaos has been performed by means of Dynamical Mean Field approaches. This analysis revealed that the new balancing mechanism is able to sustain finite irregular activity even in the thermodynamic limit, and that balancing occurs via dynamic cancellation of the correlations in the synaptic input currents. Our findings show that STD provides an intrinsic self-regulating mechanism for balanced networks, sustaining irregular yet stable activity without the need of biologically unrealistic strong external currents [2].

References

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Disentangling excitatory and inhibitory synaptic conductances from neuronal spiking activity

R.M. Delicado-Moll[1], **A. Guillamon**[2], **A.E. Teruel**[1], **C. Vich**[1]

1. Departament de Matemàtiques i Informàtica, and Institute of Applied Computing and Community Code (IAC3), Universitat de les Illes Balears, Spain. Email: `catalina.vich@uib.es`

2. Departament de Matemàtiques, Universitat Politècnica de Catalunya, Spain.

Abstract

Estimating the synaptic inputs received by neurons is a central problem for understanding functional connectivity and neural dynamics. Separating the temporal contributions of excitatory (g_E) and inhibitory (g_I) synaptic conductances is particularly challenging because these quantities cannot be directly measured in vivo and must instead be inferred from observable activity such as the membrane potential. Many existing inverse methods rely on linear approximations valid only in subthreshold regimes or require multiple experimental trials, limiting their applicability to spiking activity and noisy recordings.

Here we present a computational method to estimate the time course of g_E and g_I from a single membrane potential trace in the spiking regime. Using a base neuronal model fitted to reproduce the intrinsic activity of a target neuron without synaptic input, we compute a mapping between constant conductance pairs, the spike period, and the amplitude of the peak membrane potential, enabling conductance estimation directly from the observed spike frequency and peak amplitudes.

We validate the method using in silico experiments with a broad range of conductance dynamics, including different oscillation frequencies and phase relationships between excitation and inhibition. The estimator reliably reconstructs both conductance components while remaining robust to measurement noise and requiring only a single recording.

These results provide a framework for inferring local excitatory and inhibitory synaptic inputs from spiking activity, offering a practical tool for studying synaptic balance and neural dynamics across different neuronal models.

5 PARTICIPANTS

A

Eman Alnuwaysir
Department of Mathematics and Statistics, University of Exeter, Stocker Road, Exeter EX4 4PY, UK.
Living Systems Institute, University of Exeter, Stocker Road, Exeter EX4 4PY, UK.
ea544@exeter.ac.uk

B

Esther Barrio
CSIC, CoDy and University of Zaragoza, Spain.
esther.barrio@idaea.csic.es

Roberto Barrio
Department of Applied Mathematics, CoDy, University of Zaragoza, Spain.
rbarrio@unizar.es

Christian Bick
Amsterdam Center for Dynamics and Computation, Department of Mathematics, Vrije Universiteit Amsterdam, the Netherlands.
c.bick@vu.nl

Virginia Bolelli
L2S, University of Paris-Saclay, CentraleSupèlec, Gif-sur-Yvette, France.
bolellivirginia@gmail.com

Áine Byrne
School of Mathematics and Statistics, University College Dublin, Ireland.
aine.byrne@ucd.ie

C

Alejandro Carballosa Calleja
Laboratoire de Physique Théorique et Modélisation, CY Cergy Paris Université, CNRS UMR 8089, Cergy-Pontoise, France.
acarball@cyu.fr

Shih-Cheng Chien
Institute of Computer Science, The Czech Academy of Sciences, Czechia.
chien@cs.cas.cz

Stephen Coombes
School of Mathematical Sciences, University of Nottingham, Nottingham, NG7 2RD, UK.
stephen.coombes@nottingham.ac.uk

D

Bengi Donmez
Department of Mathematics, Vrije Universiteit Amsterdam, Amsterdam, the Netherlands.
b.donmez@vu.nl

E

Udo Ernst
Computational Neurophysics Lab, Department of Theoretical Physics, University of Bremen, Germany.
udo@neuro.uni-bremen.de

I

Santiago Ibáñez
Department of Mathematics, University of Oviedo, Spain.
mesa@uniovi.es

J

Jorge Jover
Department of Applied Mathematics, Computational Dynamics group and IUMA, University of Zaragoza, Spain.
jorgejover@unizar.es

L

Álvaro Lozano
Department of Mathematics, Computational Dynamics group and IUMA, University of Zaragoza, Spain.
alozano@unizar.es

M

Valeriy Makarov
Department of Applied Mathematics and Mathematical Analysis, Universidad Complutense de Madrid, Madrid, 28040, Spain.
vmakarov@ucm.es

Thanos Manos
ETIS Lab, ENSEA, CNRS, UMR8051, CY Cergy-Paris University, Cergy, France.
thanos.manos@cyu.fr

M. Ángeles Martínez
Department of Applied Mathematics, IUMA and Computational Dynamics group, University of Zaragoza, Spain.
gelimc@unizar.es

Mario Martínez-Saito
Institute of Cognitive Neuroscience, HSE University, Russian Federation.
mmartinezsaito@gmail.com

Ana Mayora
Department of Applied Mathematics, Computational Dynamics group and IUMA, University of Zaragoza, Spain.
amayora@unizar.es

Carmen Mayora
Department of Applied Mathematics, Computational Dynamics group and IUMA, University of Zaragoza, Spain.
cmayora@unizar.es

Daniel Moreno Soto
Dept. of Computer Science, Dept. of Biology, RWTH Aachen University, Germany.
morenosoto@netsci.rwth-aachen.de

N

Diego Noriega
Department of Mathematics, University of Oviedo, Spain.
noriegadiego@uniovi.es

O

Gerardo Oleaga
Department of Applied Mathematics and Mathematical Analysis, Universidad Complutense de Madrid, Madrid, 28040, Spain.
goleaga@ucm.es

Abdeltif Oujbara
Department of Mathematics; Normandie Univ.; LMAH UR 3821, Université Le Havre Normandie, 25 rue Philippe Lebon, 76600 Le Havre, Normandie, France.
oujbara95abdeltif@gmail.com

P

Javier Pardos
ITA, CoDy and University of Zaragoza, Spain.
javpard@unizar.es

Diego Pazó
Instituto de Física de Cantabria (IFCA), Universidad de Cantabria-CSIC, Spain.
pazo@ifca.unican.es

Morten Gram Pedersen
Department of Information Engineering, University of Padova, Italy.
mortengram.pedersen@unipd.it

Lucía Pérez
Department of Mathematics, University of Oviedo, Spain.
perezplucia@uniovi.es

Bastian Pietras
Natural Intelligence (NISYS GmbH), Frankfurt am Main, Germany.
bastian@nisys.ai

R

Jon Recalde
Institut für Neuroinformatik, Ruhr University Bochum, Germany.
jon.recaldefeo@rub.de

S

Julia Samuseva
Dept. of Translational Neuroscience, CNC, CSIC, Av. de León, 1, Alcalá de Henares, Madrid, 28805, Spain.
julia.samuseva@cajal.csic.es

Helmut Schmidt
Institute of Computer Science, Czech Academy of Sciences, Prague, Czech Republic.
schmidt@cs.cas.cz

Beatriz Seoane
Departamento de Física Teórica, Universidad Complutense de Madrid, 28040 Madrid, Spain.
beseoane@ucm.es

Sergio Serrano
Department of Applied Mathematics, Computational Dynamics group and IUMA, University of Zaragoza, Spain.
sserrano@unizar.es

Hiba Sheheitli
Department of Neurology, University of Minnesota, Minneapolis, MN, USA.
shehe003@umn.edu

T

Irem Topal Kement
Department of Translation & Language Sciences, Universitat Pompeu Fabra, Carrer Roc Boronat, 138, Barcelona, 08018, Spain.
irem.topal@upf.edu

Alessandro Torcini
Laboratoire de Physique Théorique et Modélisation, UMR 8089, CY Cergy Paris Université, CNRS, Cergy-Pontoise, France.
alessandro.torcini@cyu.fr

V

Catalina Vich Llompart
Departament de Matemàtiques i Informàtica, and Institute of Applied Computing and Community Code (IAC3), Universitat de les Illes Balears, Spain.
catalina.vich@uib.es

Rubén Vigara
Department of Applied Mathematics, IUMA and Computational Dynamics group, University of Zaragoza, Spain.
rvigara@unizar.es

6 OTHER INFORMATION

All the talks (and reception) will take place at the CIEM center, 4 Maria Aburto street.

Lunches

Lunch will be served at Hotel Las Rocas, located at 1 Flaviobriga Street, at 14:00 on Wednesday and Thursday. On Friday, lunch will be served at Club Náutico de Castro-Urdiales at 13:30.

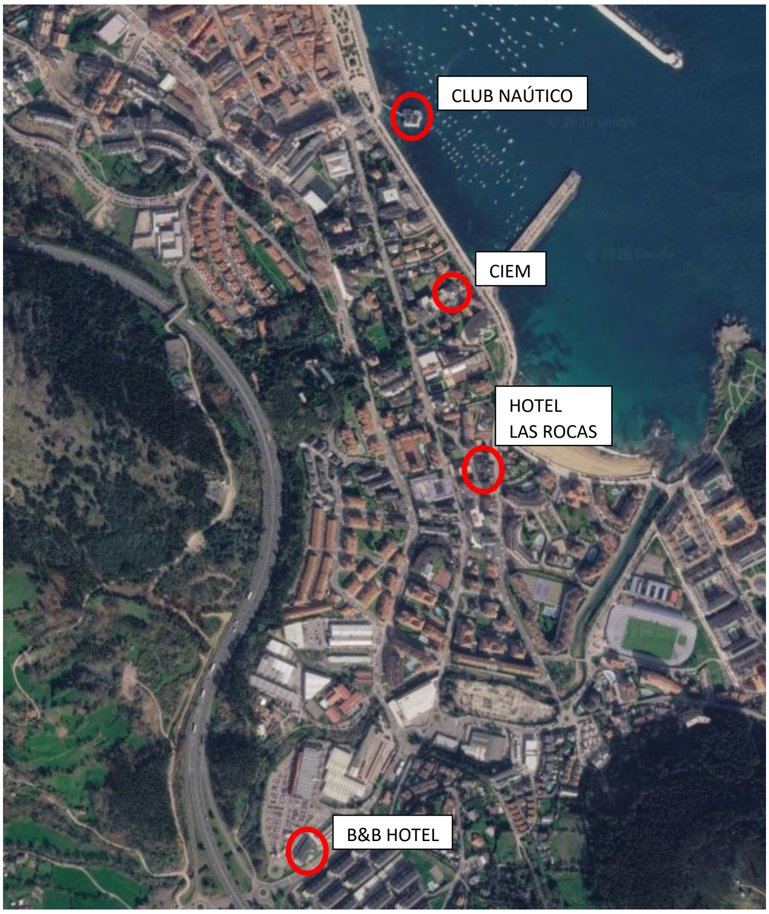

Figure 1: Location of the CIEM center, Hotel Las Rocas, B&B Hotel and Club Náutico de Castro-Urdiales.

Social Dinner

The social dinner will take place on Wednesday, May 27, at 20:30, at Hotel Las Rocas, located at 1 Flaviobriga Street.