Modeling phase synchronization
of interacting neuronal populations

From phase reductions to collective behavior
of oscillatory neural networks

Bastian Pietras
This dissertation has been accomplished within the COSMOS project. That project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 642563.

The research presented in this dissertation was performed at the Faculty of Behavioural and Movement Sciences, Vrije Universiteit Amsterdam, Amsterdam Movement Sciences, The Netherlands, and at the Department of Physics, The University of Lancaster, United Kingdom.
VRIJE UNIVERSITEIT

Modeling phase synchronization of interacting neuronal populations
From phase reductions to collective behavior of oscillatory neural networks

ACADEMISCH PROEFSCHRIFT

ter verkrijging van de graad Doctor aan de Vrije Universiteit Amsterdam en The University of Lancaster, op gezag van de rector magnifici prof.dr. V. Subramaniam en prof.dr. M.E. Smith, in het openbaar te verdedigen ten overstaan van de promotiecommissie van de Faculteit der Gedrags- en Bewegingswetenschappen op donderdag 20 december 2018 om 9.45 uur in de aula van de universiteit, De Boelelaan 1105

door

Bastian Pietras

tegenwoordig te Herford, Duitsland
promotoren: prof.dr. A. Daffertshofer
          prof.dr. A. Stefanovska

copromotor: prof.dr. P.V.E. McClintock
MODELING PHASE SYNCHRONIZATION
OF INTERACTING NEURONAL POPULATIONS

FROM PHASE REDUCTIONS TO COLLECTIVE BEHAVIOR
OF OSCILLATORY NEURAL NETWORKS

Bastian Pietras, MSc

THESIS SUBMITTED FOR A
double PhD degree
undertaken at

Vrije Universiteit Amsterdam
Departament of Human Movement Sciences
Vrije Universiteit Amsterdam
Amsterdam, NL

Lancaster University
Department of Physics
Lancaster University
Lancaster, UK

December 2018
»Gut, daß du fragst!« sagte er lachend. »Man muß immer fragen, man muß immer zweifeln.«

Herrmann Hesse – *Demian* (1919)
Foreword

“The Greek word for ‘everything that is the case’, what we could call ‘the universe’, is COSMOS.

And at the moment [...], Cosmos is Chaos and only Chaos because Chaos is the only thing that is the case.

A stretching, a tuning up of the orchestra . . . ”


The dissertation at hand, entitled “Modeling phase synchronization of interacting neuronal populations”, originated within a subproject of the European Union funded Horizon 2020 Marie Skłodowska-Curie Innovative Training Network “Complex Oscillatory Systems: Modeling and Analysis (COSMOS)”. I was privileged to first delve into this COSMOS at a workshop on “Dynamics of Coupled Oscillators: 40 years of the Kuramoto Model” in the summer of 2015. During that time, I was trying to tame one of these ancient Greek mythological creatures, a so-called chimera, as part of my Master project. A chimera is told to be a fire-breathing hybrid of a lion, a goat and a snake. It is a beast that is composed of incongruous parts. Its figurative counterpart in terms of nonlinear dynamics, a chimera state, emerges as some structured, coherent pattern out of Chaos, to stick to the notion of Greek mythology. It is partly ordered, partly chaotic – a mixture of incongruous dynamical behavior. A chimera thus gives Order to Chaos.

My endeavor to break into this extraordinary cosmos was triggered through the putative role of chimera states in explaining (pathological) brain dynamics. The functioning of our brain crucially relies on a well-coordinated flow and processing of information. The exchange of information within and across distinct brain areas is believed to occur between a few synchronized parts, while most other brain areas remain unsynchronized and their activity uncorrelated. A concerted succession of synchronized brain activity in distributed parts of the brain is key for communication and coordination. From a dynamical systems perspective, the co-occurrence of synchrony and chaos, of coherence and incoherence, can be viewed as a chimera state. Such a state is highly sensitive: it can form spontaneously, but it can also collapse within a fraction of a second. As such, the dynamics of chimera states are considered particularly relevant for the functioning of our brain. Different parts of the brain interact in a temporally and spatially complex pattern of synchrony. This interplay culminates eventually, like in an orchestra, in our personal cerebral symphony. But disturbing the carefully balanced
arrangement of individual neurons, of neural assemblies and circuits, can make the orchestra play out of tune, and lead to neurological disorders.

Relatively little is known about how different constituents of this cerebral orchestra shape the emergent collective dynamics and influence the overall performance. Different roles can be ascribed to particular parts of the brain. As in a musical orchestra, every part contributes to the ensemble with a specific timbre, pitch and dynamic range. In this way, the different parts of the brain are assigned their neural instruments to join the cerebral symphony. Being part of this orchestra, however, comes along with responsibilities: to obediently and willingly be a part of the whole, and to put one’s own aspirations as a soloist on hold. Every instrument, every neural assembly has to play their assigned role and in harmony with all the others. Still, perturbations can disturb this harmonic balance and affect individual performances. Sometimes, one instrument’s failing goes unnoticed. But that of another can have drastic effects. In principle, the more exposed an instrument, the stronger the impact on the ensemble. The degree of exposure is determined through a variety of factors: the composition and instrumentation as well as the harmonization and accompaniment of the symphony. Similar principles hold for the different components of neural circuits and assemblies. Neurons within a neural circuit can be more or less influential in the circuit dynamics. And some neural assemblies can have a stronger or weaker impact on brain-wide dynamics than others. Understanding how neuronal dynamics interact across scales and shape collective behavior is a timely and urgent issue. Which factors determine the specific properties of a neural instrument, which factors determine their exposure? And, how does the interplay of neural assemblies and circuits result in the cerebral symphony that defines the functioning of the brain?

With my dissertation I aim to shed light on the latter and to get a glimpse of the mathematical principles according to which brain rhythms emerge from a myriad of neuronal oscillations. It is my humble approach towards unraveling the mechanisms that underpin the ensemble performance of the cerebral symphony and my stepping stone into the field of neuroscience.

Bastian Pietras