Phase synchronization and intermittent behavior in healthy and Alzheimer-affected human brain-based neural network

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Outline

Introduction and motivation

The investigation of biological systems by using physics conceptions is a trending topic. Nowadays, it is known that anomalous dynamical properties can be related to neural diseases as Parkinson, epilepsy and Alzheimer [1,2]. In this scenario, the main objective of this work consists of the study of the dynamical properties of a neural network:

- Mathematical modeling of neural behavior,
- complex networks approach,
- Kuramoto order parameter and recurrence quantification analysis.

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[1] L. D. Iasemidis, J. C. Sackellares, Neuroscientist **2**, 118 (1996)

[2] L. Aron, B. A. Yankner, Nature **540**, 207 (2016)

Introduction and motivation

Previously studies have shown the existence of anomalous synchronization, intermittent transitions, and sensibility to initial conditions in small-world thermally sensitive neural networks.

PHYSICAL REVIEW E **96**, 012320 (2017)

Detection of nonstationary transition to synchronized states of a neural network using recurrence analyses

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Nonstationary transition to phase synchronization of neural networks induced by the coupling architecture

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Suppression of anomalous synchronization and nonstationary behavior of neural network under small-world topology

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Research paper

Synchronization domains in two coupled neural networks

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Objectives

- To investigate the synchronization characteristics of a network of networks based on human brain connectome;
- To investigate the intermittency properties of the neural system;
- To study the influence of external connectome of a healthy and Alzheimer-affected human brain.

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Phase synchronization and intermittent behavior in healthy and Alzheimer-affected human-brain-based neural network

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Mathematical model

To simulate the non-identical bursting neurons it is used the Rulkov map[3]:

$$\begin{aligned} x^j_{t+1,i} &= \frac{\alpha^j_i}{1+(x^j_{t,i})^2} + y^j_{t,i} + I^j_{\mathrm{int},t,i} + I^j_{\mathrm{ext},t}, \\ y^j_{t+1,i} &= y^j_{t,i} - \beta x^j_{t,i} + \gamma, \qquad \alpha^j_i \in [4.15, 4.25], \ \ \beta = \gamma = 0.001. \end{aligned}$$

The coupling equations are given by:

$$I^j_{\mathrm{int},t,i} = \frac{\varepsilon_{\mathrm{int}}}{\chi} \sum_{k=1}^{N} e_{i,k} x^j_{t,k}, \qquad I^j_{\mathrm{ext},t} = \varepsilon_{\mathrm{ext}} \sum_{k=1}^{M} g^{j,k} \overline{V}^k_t,$$

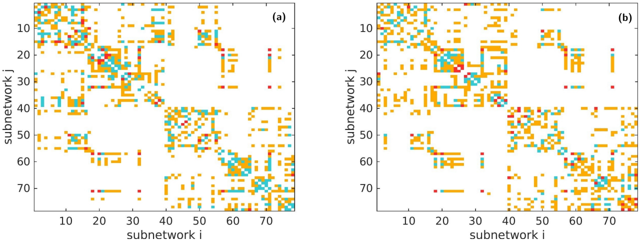
where $N = 250$, $M = 78$, and $\overline{V}^k_t$ is the mean field of subnetwork k.

[3] N. F. Rulkov, Physical Review Letters, **86**, 183 (2001)

Connection architecture

The network of networks depicts two levels of connection architecture.

- The internal connection scheme is given by a small-world network following the Newman-Watts route[4].
- The external coupling scheme is based on the human brain connectome from healthy and Alzheimer-affected patients[5,6].



[4] M. E. J. Newman, D. J. Watts, Physical Review E, **60**, 7332 (1999)

[5] C.Y. Lo, P.N. Wang, K.H. Chou, J. Wang, Y. He, C.P. Lin, Journal of Neuroscience, **30**, 16876 (2010)

[6] F. A. S. Ferrari, R. L. Viana, A. S. Reis, K. C. Iarosz, I. L. Caldas, A. M. Batista, Physica A, **496**, 162 (2018)

Analysis procedures

Two approaches are used to perform the analyses of this work:

- To investigate the synchronization characteristics, it is used the Kuramoto order parameter[7], which need (individual) information of each neuron, where a phase association is necessary.
- To investigate the intermittency properties, it is used the recurrence quantification analysis (determinism)[8], which needs a time series that represent the dynamical system. Here, it is used the time series of the mean field of the systems, described as:

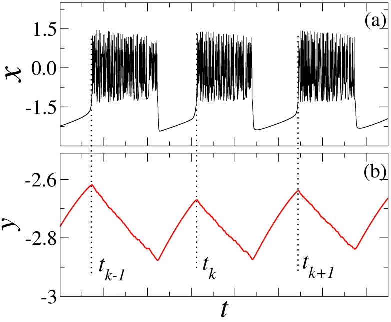
$$\overline{V}_t^k = \frac{1}{N}\sum_{i=1}^{N} x_{t,i}^k, \qquad \overline{V}_{\mathrm{global},t} = \frac{1}{NM}\sum_{i=1}^{N}\sum_{k=1}^{M} x_{t,i}^k.$$

[7] Y. Kuramoto, Chemical Oscillations, Waves, and Turbulence, Vol. 19 (Springer, Berlin, 2012)

[8] N. Marwan, M. C. Romano, M. Thiel, and J. Kurths, Physics Reports, 438, 237 (2007)

Kuramoto order parameter

The Kuramoto order parameter is able to evaluate phase synchronization of the network by the association of a phase to its neurons[9].



$$\theta_i^j(t) = 2\pi k_i^j + 2\pi \frac{t - t_{k,i}^j}{t_{k+1,i}^j - t_{k,i}^j},$$

$$R^j(t) = \left| \frac{1}{N} \sum_{k=1}^{N} \mathrm{e}^{i\theta_k^j(t)} \right|,$$

$$R_{\mathrm{g}}(t) = \left| \frac{1}{MN} \sum_{j=1}^{M} \sum_{k=1}^{N} \mathrm{e}^{i\theta_k^j(t)} \right|.$$

[9] M. V. Ivanchenko, G. V. Osipov, V. D. Shalfeev, J. Kurths. Physical Review Letters, 2004.

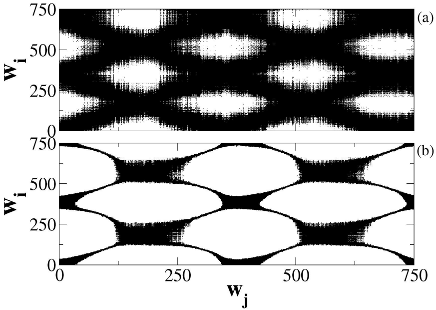
Recurrence quantification analysis

The recurrence quantification analysis (RQA) is a tool to analyze dynamical systems, which is based on the recurrence matrix.

$$\mathbf{R}_{ij}(\mu) = \Theta(\mu - ||\mathbf{w}_i - \mathbf{w}_j||), \quad \mathbf{w}_i \in \mathbb{R},\, i, j = 1, 2, \cdots, S.$$

In the RQA scenario, the determinism is able to investigate synchronization of networks[10].

$$\Delta(\ell_{\min}, \mu) = \frac{\sum_{\ell=\ell_{\min}}^{S} \ell P(\ell, \mu)}{\sum_{\ell=1}^{S} \ell P(\ell, \mu)},$$



where, $\mu = 0.11$ is chosen from the maximization of $d[\Delta(\mu)]/d\mu$.

[10] R. C Budzinski, B. R. R. Boaretto, T. L. Prado, S. R. Lopes, Chaos, Solitons and Fractals, 123, 35, 2019

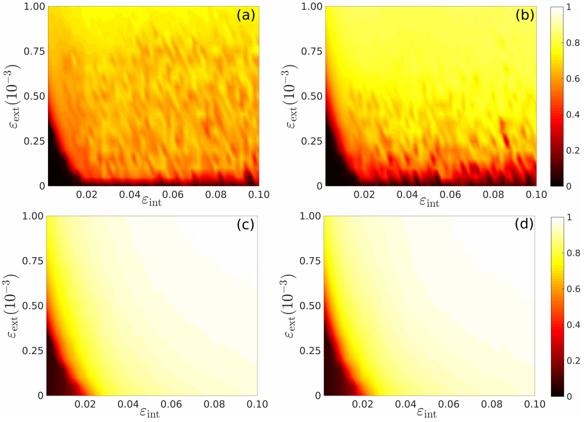
Phase synchronization

In order to investigate the phase synchronization, it is considered the temporal average (after a transient time) of Kuramoto order parameter for each subnetwork and for the entire system.

$$\langle R\rangle^j = \frac{1}{t_\mathrm{f}-t_0}\sum_{t=t_0}^{t_\mathrm{f}} R^j(t),$$

$$\overline{\langle R\rangle} = \frac{1}{M}\sum_{j=1}^{M}\langle R\rangle^j,$$

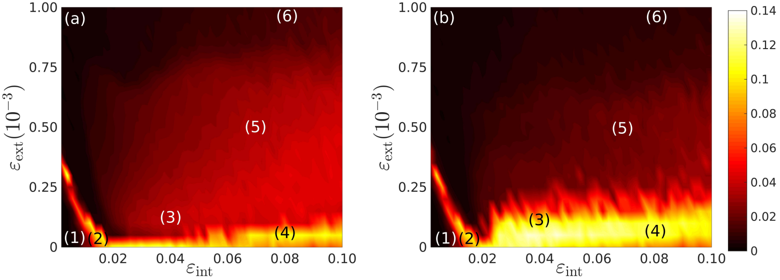
$$\langle R\rangle_\mathrm{g} = \frac{1}{t_\mathrm{f}-t_0}\sum_{t=t_0}^{t_\mathrm{f}} R_\mathrm{g}(t).$$



Intermittency characteristics

In order to investigate the intermittent behavior of the network of networks, it is possible to use the temporal standard deviation of the determinism[11].

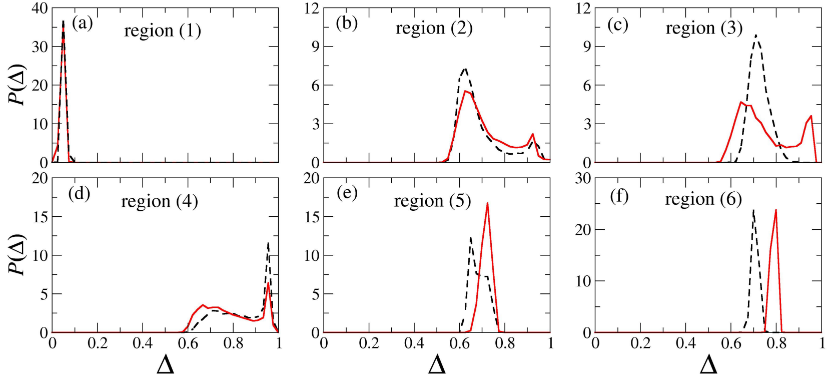
$$\sigma(\Delta) = \sqrt{\frac{1}{T}\sum_{i=1}^{T}[\Delta(i) - \langle\Delta\rangle]^2}.$$



[11] R. C. Budzinski, B. R. R. Boaretto, K. L. Rossi, T. L. Prado, J. Kurths, S. R. Lopes, Physica A, **507**, 321, 2018

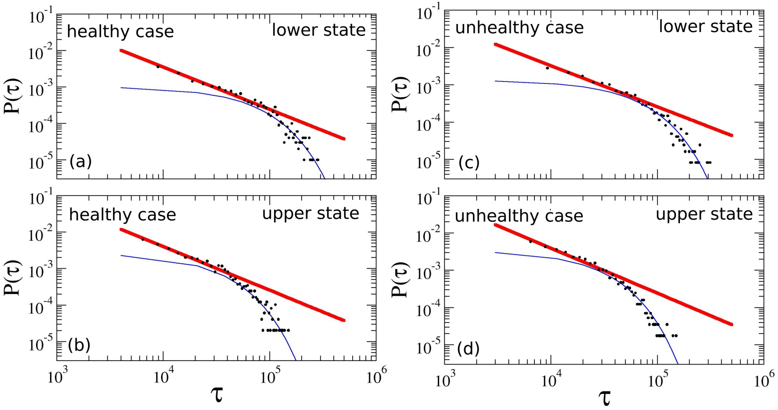
Intermittency characteristics

Considering a long time series of the determinism of global network mean field it is possible to analyze the PDF of Δ.



Intermittency characteristics

To the region (2), both networks depict the existence of two states of Δ. It is possible to evaluate the time of existence of each state.



Final considerations

It is analyzed a network of networks composed of $19\,500$ bursting neurons based on the human brain of healthy and Alzheimer-affected patients.

- **Phase synchronization:** It is observed a similar level of phase synchronization of subnetworks. On the other hand, considering the entire system (global), the Alzheimer-affected human brain depicts a higher level of phase synchronization;
- **Intermittent behavior:** By using of the determinism of the network mean field it is observed that both networks depict intermittent behavior, however, the unhealthy case depicts a higher level of intermittency. Besides that, the two cases show the existence of two-states intermittency.

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