Spiking models of metastable activity: theory and applications

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The goal of this project is to acquire familiarity with the theory and practice of attractor networks generating metastable dynamics. Participants will learn to perform network simulations and analyze single-trial population activity using hidden Markov models.

Background. Metastable brain dynamics are characterized by abrupt, jump-like modulations so that the neural activity in single trials appears to unfold as a sequence of discrete, quasi-stationary 'states'.[1] Evidence that cortical neural activity unfolds as a sequence of metastable states is accumulating at fast pace. Metastable activity occurs both in response to an external stimulus and during ongoing, self-initiated activity. Metastable states are increasingly found to support internal representations that are not locked to external triggers, including states of deliberations, attention and expectation. Decoding stimuli or decisions via metastable states can be carried out trial-by-trial, shifting our perspective from traditional concepts based on trial-averaging to models based on dynamic ensemble representations. Recent theoretical work has started to characterize the mechanistic origin and potential roles of metastable representations.

Part I - Theory

We will discuss recent experimental and theoretical findings on metastable activity; its potential role for representing internal states as well as relevant task variables; and how it may arise in biologically realistic models. We will introduce the basic concepts in the theory of attractor networks of spiking neurons as a model of metastable activity.[2,3]

Part II - Simulations

Participants will learn how to simulate recurrent networks of spiking neurons with clustered connectivity. We will provide a demo[4,5] for students to play with and discover how these networks respond to stimuli and other external perturbations.

Part III - Statistical methods

We will introduce hidden Markov models (HMM) as a tool to analyze attractor dynamics in spiking networks. Participants will fit a Poisson-HMM to population spike trains from network simulations, compare the model statistics between different conditions and decode stimuli from HMM-state sequences.

Modeling challenges:

1 – Can we generate metastable activity in a clustered network model of CA1, where E-to-E connectivity is set to zero (or to a very low value)?

2 – Can we generate metastable activity in a clustered network model with inhibitory cell-type specific connectivity (VIP, PV, SOM)?
3 – The attractor networks we simulated so far generate random sequences during spontaneous activity. Can we generate state sequences where the identity and order of states is fixed?
4 - Can we generate a model where, after stimulus offset, stimulus-specific states are reactivated stochastically at random times with a delay?

References

1. La Camera, G., Fontanini, A. & Mazzucato, L. Cortical computations via metastable activity. *Curr. Opin. Neurobiol.* **58**, 37–45 (2019).
2. Litwin-Kumar, A. & Doiron, B. Slow dynamics and high variability in balanced cortical networks with clustered connections. *Nat. Neurosci.* **15**, 1498–1505 (2012).
3. Mazzucato, L., Fontanini, A. & La Camera, G. Dynamics of multistable states during ongoing and evoked cortical activity. *J. Neurosci.* **35**, 8214–8231 (2015).
4. Mazzucato, L., Fontanini, A. & La Camera, G. Demo for simulating clustered networks in Ref. 4. Available at: https://github.com/mazzulab/expectation-spiking-net.
5. Mazzucato, L., La Camera, G. & Fontanini, A. Expectation-induced modulation of metastable activity underlies faster coding of sensory stimuli. *Nat. Neurosci.* (2019). doi:10.1038/s41593-019-0364-9

Background readings

Zucchini, W., MacDonald, I.L. and Langrock, R., 2017. *Hidden Markov models for time series: an introduction using R*. Chapman and Hall/CRC.