Towards a unifying view of metastability in Neuroscience

Summary

Several works in the Neuroscience literature discuss the idea of metastable brain dynamics. These include evidence from a wide variety of experiments and analysis, and suggest important cognitive and sensory functional roles of metastability. A careful comparison between works reveals, however, that the meaning ascribed to metastability can vary widely and is not necessarily always compatible: it varies from a regime with successive states being accessed, to one with integration and segregation of neurals regions, to one with variability of synchronization. The definitions differ also concering specific criteria for metastability, such as e.g. whether time-scale separation between different processes is necessary or not. These inconsistencies in meaning can lead to confusion in the literature, hindering the comparison of different works and hampering advancements towards a clear description of metastability. To improve this situation, we provide a mini-review of the different meanings of metastability, discuss their commonalities and differences, and use insights from Physics and Dynamical Systems Theory to suggest a refined general definition of metastability in Neuroscience that involves the succession of distinct activity patterns and includes several other definitions in the literature as specific types of metastability. The properties, functional roles, and possible dynamical mechanisms of those types of metastability are discussed. We illustrate each case with concrete examples, and also study a model displaying several types of metastability over its parameter range. Future works can also examine the emergence of the different types of metastability presented here in experimental data, and create a more comprehensive understanding of this behavior in the brain. We believe that this work can help to make studies on metastability more precise, facilitate the understanding of the current literature, and also serve as a didactic introduction to the topic.

Additional detail

The dynamical regime of metastability as a regime for brain dynamics has been of increasing interest in Neuroscience due to its putative functional roles in cognitive, sensory and motor tasks [1, 2, 3]. It has, over time, acquired distinct meanings in the literature, which are not always compatible. The main meanings we have identified are summarized in Fig. 1.

A significant amount of works choose a definition of metastability as a succession of system states, which is either similar to the meaning used in Physics, where a metastable state is one apparent (transient) equilibrium, that may be accessed before an eventual transition to a final real equilibrium state or similar to the meaning in dynamical systems theory in which recurrent metastable states are visited in a regular or irregular succession. Other, more specific criteria associated with metastability are (i) the spontaneity (or not) of the transitions (whether the transitions occur with or without external perturbation); (ii) recurrence (or not) of the patterns; (iii) separation (or not) of time-scales. Each case can play a distinct functional role, and occur due to distinct dynamical mechanisms. In the literature observations and arguments for several such cases can be identified.

Considering this, we propose the following general definition of metastability: a regime with the successive expression of distinct activity patterns, whereby an activity pattern has to be reliable (last for a sufficiently long time) and stereotyped (well-defined in space and time).

For concreteness, we mention three works with experimental or computational evidence for metastability in neural circuits that fit to our definition. Firstly, authors in [2] observe successions of four distinct states, identified by using a Hidden Markov Model applied to the firing rates of

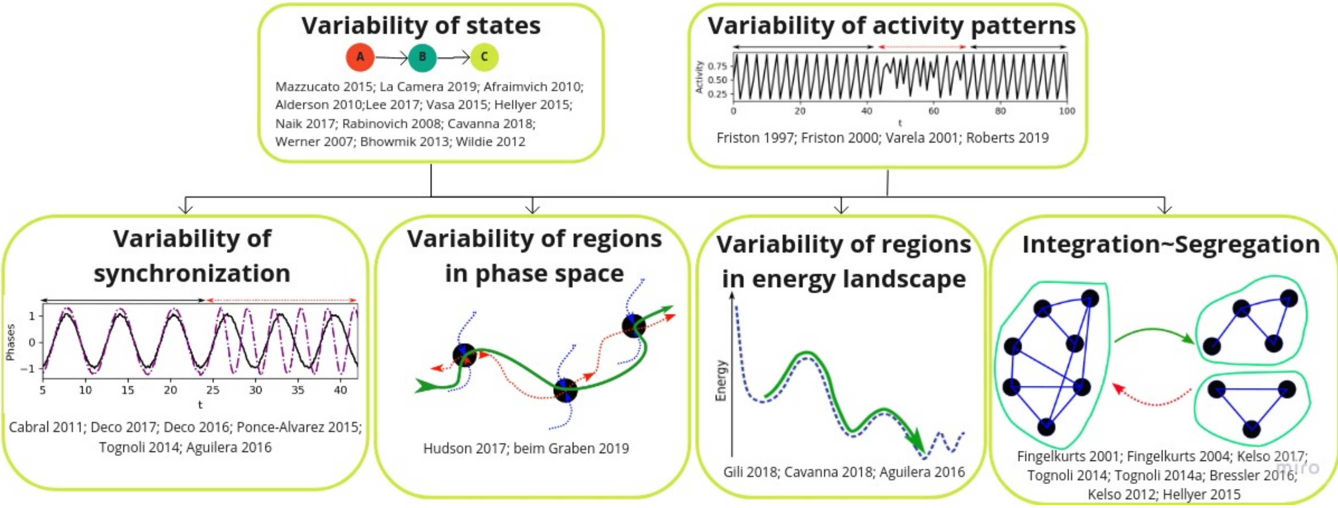

Figure 1: Meanings of metastability found in the Neuroscience literature.

10 neurons in the gustatory cortex of a rat. Secondly, the works which identify (micro)states from EEG data by applying k-means clustering to scalp field potential distribution maps [4]. Thirdly, we mention the observations done in [5], who produce, in a realistic model with 513 uniformly sized cortical and subcortical regions, sequences of distinct types of waves similar to those observed in experiments such as resting-state MEG. Moreover, we note that metastability can be observed on a neuronal scale, as well as on a brain region scale.

Furthermore, we discuss how each specific criterion, mentioned previously, can be related to a distinct type of metastable behavior. We mention here briefly spontaneous metastability and nonspontaneous metastability. The former allows for a rich exploration of the system's dynamical repertoire naturally, without extra energy expenditure necessary for inducing the transitions; it can be mechanistically implemented in several ways, such as in heteroclinic cycles [6] or in a chaotic saddle containing different activity patterns [7]. The latter can allow for favorable responsiveness to external stimuli, and can be implemented in, for instance, a multistable system, where the perturbations induce transitions between attractors [8]. These types of metastability will be studied in models, over distinct parameter ranges.

References

[1] Andrew A. Fingelkurts and Alexander A. Fingelkurts. Making complexity simpler: Multivariability and metastability in the brain, jul 2004.

[2] Giancarlo La Camera, Alfredo Fontanini, and Luca Mazzucato. Cortical computations via metastable activity. *Current Opinion in Neurobiology*, 58:37–45, jul 2019.

[3] Emmanuelle Tognoli and J. A.Scott Kelso. The Metastable Brain. *Neuron*, 81(1):35–48, jan 2014.

[4] R D Pascual-Marqui, C M Michel, and D Lehmann. Segmentation of brain electrical activity into microstates: model estimation and validation. *IEEE Trans. Biomed. Eng.*, 42(7):658–665, 1995.

[5] James A Roberts, Leonardo L Gollo, Romesh G Abeysuriya, Gloria Roberts, Philip B Mitchell, Mark W Woolrich, and Michael Breakspear. Metastable brain waves. *Nature Communications*, 10(1):1056, mar 2019.

[6] Mikhail I. Rabinovich, Ramón Huerta, Pablo Varona, and Valentin S. Afraimovich. Transient cognitive dynamics, metastability, and decision making. *PLoS Computational Biology*, 4(5):1000072, may 2008.

[7] Gerrit Ansmann, Klaus Lehnertz, and Ulrike Feudel. Self-induced switchings between multiple space-time patterns on complex networks of excitable units. *Physical Review X*, 6(1):011030, mar 2016.

[8] Andrew E. Hudson. Metastability of neuronal dynamics during general anesthesia: Time for a change in our assumptions? *Frontiers in Neural Circuits*, 11:58, 2017.