Definition and Quantification of Metastability in Neuroscience

Kalel Luiz Rossi

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This version is an early draft, for the authors to read and discuss.

1 Definitions of Metastability

Scanning the neuroscience literature, we extracted definitions of metastability used either explicitly or implicitly by authors. If multiple definitions could be identified, all of them were extracted.

1.1 Definition 1a - Variability of states

Metastability here denotes the regime with a successive expression of the system's states over time.

A state can be concretely described as a set of variables or measurements characterizing or representing the system, like neuronal firing rates [La Camera et al., 2019], a degree of phase synchronization [Alderson et al., 2020, Lee and Frangou, 2017, Váša et al., 2015, Hellyer et al., 2014], saddle-sets in phase space [Rabinovich et al., 2008] or simply quasi-equilibrium points in phase-space [Cavanna et al., 2018]. It can also be left as an abstract concept [Werner, 2007]. [Shanahan, 2010, Bhowmik and Shanahan, 2013, Wildie and Shanahan, 2012] confine to synchronized states, in which case metastability is characterized by migrations between synchronized states.

Since each of these states is successively replaced by another, none of them are equilibria. They are either transiently stable (were stable, but a change of parameters made them unstable), or are simply unstable states that are visited for some time ("attractor-like" [Váša et al., 2015, Hellyer et al., 2014]). In either case, they are generally called metastable states (metastates).

[La Camera et al., 2019] requires that the transitions between states be abrupt, "jump-like".

1.2 Definition 1b - Variability of activity patterns

Metastability here denotes the regime with a successive expression of activity patterns over time [Friston, 1997, Friston, 2000, Varela et al., 2001]. Karl

Friston requires these activity patterns to be "distinct, self-limiting and stereotyped" [Friston, 1997], referring to them as transients.

Activity of the system can be observed as a set of numbers describing, or reflecting the system's behavior. It can be the time series of average membrane potential of neurons in various regions [Roberts et al., 2019]*, time series of membrane potentials [Friston, 1997, Friston, 2000]*, or local-field potentials (LFPs) [Friston, 2000].

The patterns can be temporal or even spatial. In [Roberts et al., 2019], successive waves of electric potential are identified in whole-brain models, each denoting a spatial pattern, and their succession denotes metastability. In [Friston, 2000], the frequency composition of the system's activity is seen to change in time.

Each pattern can naturally reflect, or represent, the system's state, so that definitions 1a and 1b can be equivalent.

1.3 Definition 1c - Variability of synchronization or phase configurations

Metastability here refers directly to the variability in time of degrees of synchronization, or to oscillation phases, with no mention of states. It can denote a (i) variability of the global degree of phase synchronization [Cabral et al., 2011, Deco et al., 2017]; (ii) variability of the states of phase configurations (how synchronization fluctuates between nodes) [Deco and Kringelbach, 2016, Deco et al., 2017]; (iii) variability in the relative phases of nodes [Ponce-Alvarez et al., 2015];

All these cases can be viewed as a subset of definitions 1a or 1b if the synchronization measure defines or reflects a system's state or activity pattern.

1.4 Definition 1d - Variability of regions in phase-space

Metastability here refers directly to a regime with transitions between regions in phase space [Hudson, 2017, beim Graben et al., 2019]. The trajectory of the system spends time in certain regions, and then moves to other regions. Each region can be an attractor, in which case the trajectory is only near it, not inside [Hudson, 2017]

Points in phase space are defined by the system's dynamical variables, which then represent its state [Cavanna et al., 2018, beim Graben et al., 2019]. Thus, this definition is a phase-space view of definition 1a.

1.5 Definition 1e - Variability of regions in energy landscape

Metastability here refers to a regime with transitions between local minima of energy in an energy landscape. This is the definition in neuroscience closest to the one in physics. In this case, the system transitions from one state to another due to either external perturbations or to another dimension in the landscape [Shankar Gupta et al., 2018, Cavanna et al., 2018].

If the energy value describes a system's state, or represents its activity pattern, then this definition can be considered a specific case of 1a and 1b.

1.6 Definition 2 - Regime for integration and segregation of neural assemblies

Metastability is often viewed as a dynamic regime that naturally implements the dual need for integration and segregation in the brain. The most common approach is to define metastability through one of the previous definitions, and consider integration-segregation as a consequence. However, [Fingelkurts and Fingelkurts, 2001, Fingelkurts and Fingelkurts, 2004] define metastability directly as the regime with this tendency of integration-segregation. According to their theory of Operational Architectonics, this tendency produces the cognitive or behavioral processes in the brain and, therefore, metastability the regime behind them. These processes are constituted by a succession of different acts, each of which can is called a metastable state.

1.7 Discussion

So far, I think the best definition involves the successive expression of activity patterns. Patterns meaning "a reliable sample of traits, acts, tendencies, or other observable characteristics of a person, group, or institution (merriam webster)"

Advantage: Activity patterns are general, yet still concrete. They avoid the term "state", which is carried with lots of meanings from various areas.

Questions:

- In the definition, do states, or activity patterns, have to characterize the system completely (fully)? uniquely?
- What exactly is an activity pattern?
- Are definitions 1a and 1b really equivalent?
- Should metastability be endogenous ([Hellyer et al., 2014]) aka spontaneous ([Shanahan, 2010]), or can it be forced?. Related, the difference between metastability and multistability with noise is presented in: [Roberts et al., 2019, Ponce-Alvarez et al., 2015]; ponce-alvarez seems to allow it: "metastability does not require noise, is result of heterogenous frequencies and nonlinear interactions";
- Does the activity need to be active? Can the system be in a resting state?
- Should the separation of time-scales be explicity required? That is, the period between activity patterns have a minimal/maximal duration?
- Can jumps between metastates be continuous, or only abrupt?
- Should a recurrence in the activity patterns/states be required?

References

[Alderson et al., 2020] Alderson, T. H., Bokde, A. L., Kelso, J. A., Maguire, L., and Coyle, D. (2020). Metastable neural dynamics underlies cognitive performance across multiple behavioural paradigms. *Human Brain Mapping*, 41(12):3212–3234.

[beim Graben et al., 2019] beim Graben, P., Jimenez-Marin, A., Diez, I., Cortes, J. M., Desroches, M., and Rodrigues, S. (2019). Metastable Resting State Brain Dynamics. *Frontiers in Computational Neuroscience*, 13:62.

[Bhowmik and Shanahan, 2013] Bhowmik, D. and Shanahan, M. (2013). Metastability and Inter-Band Frequency Modulation in Networks of Oscillating Spiking Neuron Populations. *PLoS ONE*, 8(4):e62234.

[Cabral et al., 2011] Cabral, J., Hugues, E., Sporns, O., and Deco, G. (2011). Role of local network oscillations in resting-state functional connectivity. *Neuroimage*, 57(1):130–139.

[Cavanna et al., 2018] Cavanna, F., Vilas, M. G., Palmucci, M., and Tagliazucchi, E. (2018). Dynamic functional connectivity and brain metastability during altered states of consciousness. *NeuroImage*, 180(Pt B):383–395.

[Deco and Kringelbach, 2016] Deco, G. and Kringelbach, M. L. (2016). Metastability and Coherence: Extending the Communication through Coherence Hypothesis Using A Whole-Brain Computational Perspective. *Trends in Neurosciences*, 39(3):125–135.

[Deco et al., 2017] Deco, G., Kringelbach, M. L., Jirsa, V. K., and Ritter, P. (2017). The dynamics of resting fluctuations in the brain: Metastability and its dynamical cortical core. *Scientific Reports*, 7(1):3095.

[Fingelkurts and Fingelkurts, 2001] Fingelkurts, A. A. and Fingelkurts, A. A. (2001). Operational architectonics of the human brain biopotential field: Towards solving the mind-brain problem.

[Fingelkurts and Fingelkurts, 2004] Fingelkurts, A. A. and Fingelkurts, A. A. (2004). Making complexity simpler: Multivariability and metastability in the brain.

[Friston, 1997] Friston, K. J. (1997). Transients, metastability, and neuronal dynamics. *NeuroImage*, 5(2):164–171.

[Friston, 2000] Friston, K. J. (2000). The labile brain. {II}. Transients, complexity and selection. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, 355(1394):237–252.

[Hellyer et al., 2014] Hellyer, P. J., Shanahan, M., Scott, G., Wise, R. J., Sharp, D. J., and Leech, R. (2014). The control of global brain dynamics: Opposing actions of frontoparietal control and default mode networks on attention. *Journal of Neuroscience*, 34(2):451–461.

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

[La Camera et al., 2019] La Camera, G., Fontanini, A., and Mazzucato, L. (2019). Cortical computations via metastable activity. *Current Opinion in Neurobiology*, 58:37–45.

[Lee and Frangou, 2017] Lee, W. H. and Frangou, S. (2017). Linking functional connectivity and dynamic properties of resting-state networks. *Scientific Reports*, 7(1):16610.

[Ponce-Alvarez et al., 2015] Ponce-Alvarez, A., Deco, G., Hagmann, P., Romani, G. L., Mantini, D., and Corbetta, M. (2015). Resting-State Temporal Synchronization Networks Emerge from Connectivity Topology and Heterogeneity. *PLoS Computational Biology*, 11(2):e1004100.

[Rabinovich et al., 2008] Rabinovich, M. I., Huerta, R., Varona, P., and Afraimovich, V. S. (2008). Transient cognitive dynamics, metastability, and decision making. *PLoS Computational Biology*, 4(5):1000072.

[Roberts et al., 2019] Roberts, J. A., Gollo, L. L., Abeysuriya, R. G., Roberts, G., Mitchell, P. B., Woolrich, M. W., and Breakspear, M. (2019). Metastable brain waves. *Nature Communications*, 10(1):1056.

[Shanahan, 2010] Shanahan, M. (2010). Metastable chimera states in community-structured oscillator networks. *Chaos*, 20(1):13108.

[Shankar Gupta et al., 2018] Shankar Gupta, D., Fingelkurts, A. A., Kröger, M., Zürich, E., Gili, T., Spalletta, G., and Ciullo, V. (2018). Metastable States of Multiscale Brain Networks Are Keys to Crack the Timing Problem. *Frontiers in Computational Neuroscience — www.frontiersin.org*, 12:75.

[Varela et al., 2001] Varela, F., Lachaux, J. P., Rodriguez, E., and Martinerie, J. (2001). The brainweb: phase synchronization and large-scale integration. *Nature Reviews. Neuroscience*, 2(4):229–239.

[Váša et al., 2015] Váša, F., Shanahan, M., Hellyer, P. J., Scott, G., Cabral, J., and Leech, R. (2015). Effects of lesions on synchrony and metastability in cortical networks. *NeuroImage*, 118:456–467.

[Werner, 2007] Werner, G. (2007). Metastability, criticality and phase transitions in brain and its models. *BioSystems*, 90(2):496–508.

[Wildie and Shanahan, 2012] Wildie, M. and Shanahan, M. (2012). Metastability and chimera states in modular delay and pulse-coupled oscillator networks. *Chaos*, 22(4):43131.