Can Fractal and Complexity Measures of Electrophysiological Signals Be Used to Study Experience?

Daniel Borek (Ghent University, Faculty of Psychology and Educational Sciences, Department of Data-Analysis)

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- Complexity and information-theoretic approaches to brain signal were popularized in consciousness research by Integrated Information Theory, but they can be applied without requiring IIT formalism or assumptions [1].
- Biomarkers based on these approaches have been successful in discriminating states of consciousness, while much effort has been directed toward studying the content.
- Conscious experience is rich and has a high-dimensional structure [2], which makes the problem well-suited for the next set of tools arising from dynamical systems, statistical physics and complexity science.

Quantifying changes in brain signal

- EEG complexity measures can capture intricate neuronal processes that may not be detectable through linear methods
- Many complexity metrics are interrelated; however, entropy exhibits a less straightforward relationship. Further details are provided in [3]

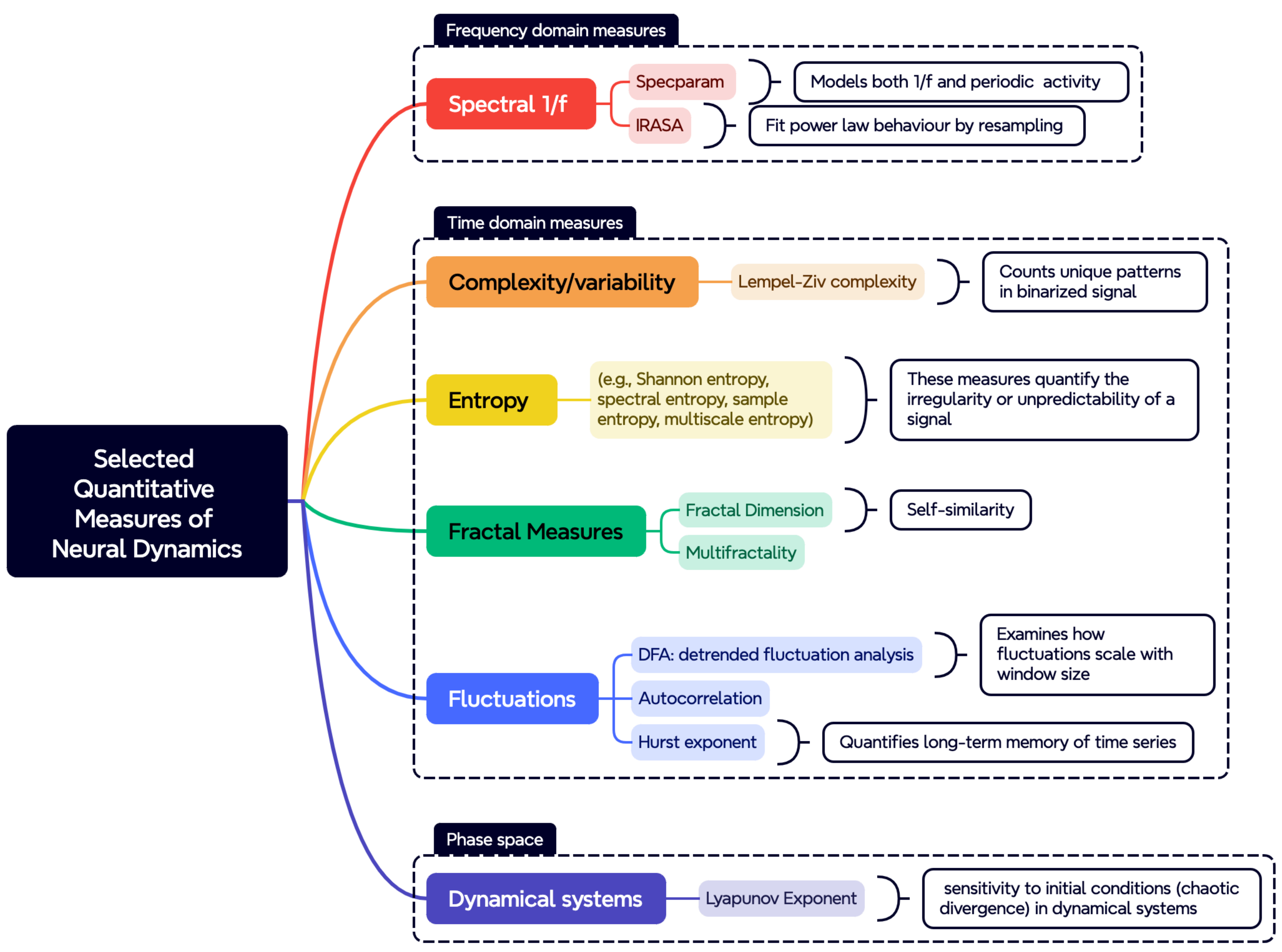

Figure 1: Selected measures of complexity and criticality.

Complexity measures for EEG and brain states

- These measures are increasingly used to differentiate states of consciousness, such as distinguishing between minimally conscious and vegetative states or identifying sleep phases ([4], [5]).
- They are also applied in psychedelic research—for example, in the "entropic brain" hypothesis, which suggests that psychedelics enhance the complexity and richness of neural communication.
- Different metrics vary in how they account for oscillatory activity and the 1/f component of the signal.
- They are particularly well-suited for examining the influence of pharmacological agents known to alter consciousness, such as anesthetics and psychedelics.
- Increased entropy or fractal dimension is often associated with positive affective states (e.g., during psychedelic experiences) and greater cognitive flexibility, whereas reduced complexity is typically observed in conditions such as depression.

Brain criticality, power laws and 1/f noise

- Decades of evidence point to the synchronization of oscillatory neural signals as one of the key mechanisms underlying information integration and selection [6].
- "When oscillations are present, they often appear as 'bumps' superimposed on the 1/f slope of the power spectrum." The power spectrum follows a power-law relationship between power and frequency, where power decreases exponentially with increasing frequency. The slope of the 1/f relationship carries important information [7]
- Criticality is the singular state of complex systems poised at the brink of a phase transition between order and randomness, a special kind of collective behavior observed in many-bodied systems [8].
- The presence of power laws and scale-free distributions in phenomena such as neuronal avalanches is frequently interpreted as evidence of criticality in brain dynamics. Critical brain hypothesis states that global neuronal dynamics of the healthy brain operate at the boundary of a critical phase transition between an ordered and a disordered phase [8]

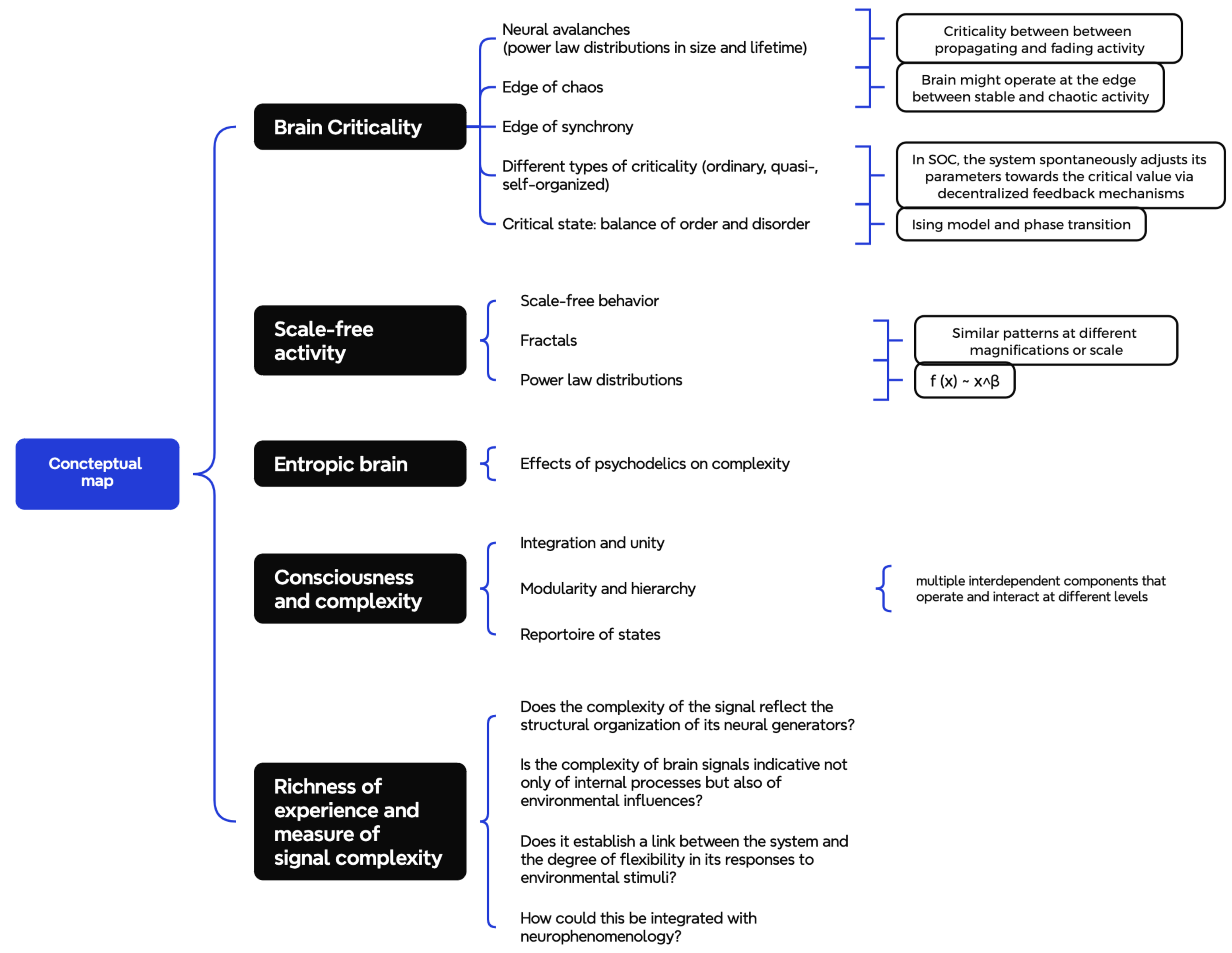

Figure 2: Selected concepts related to complexity and criticality.

Mechanisms?

- Frequently involvement of modulation of NMDA of GABA receptors within the excitation–inhibition framework, offering a mechanistic explanation for altered subjective experiences in conditions such as schizophrenia and ADHD.
- Changes in E:I will also affect oscillatory activity
- Complexity metrics and criticality theory offers its own explanatory framework
  - Emphasis on self-organization and emergent properties arising from collective neural behavior
  - Multi-scale integration guided by universal principles such as scale invariance and power-law distributions.
  - A shift in focus from where functions are localized to how dynamic processes give rise to specific capabilities; Recognition of non-linear causality .

Challenges

- The relationship is non-linear: greater complexity is not always optimal. Intermediate states between chaos and excessive order may best support flexible, adaptive responses to the environment.
- While many measures are closely related, their interrelationships are not always well understood.
- Methodological factors—such as signal preprocessing, recording length, or choice of metaparameters—can significantly influence complexity estimates.
- While power-law behavior is commonly associated with criticality, it can also result from non-critical processes, making it an insufficient marker on its own. Surrogate data testing is essential to rule out spurious findings—and should be accompanied by biologically plausible theoretical grounding from the outset.

Possible directions

- Connecting variations in brain dynamics with qualitative experience via neurophenomenology
- Relating metrics to experience in non-normative states (e.g., time perception in psychiatric disorders, neurodivergence).
- Examining how pre-stimulus complexity influences perception and awareness, including potential links to environmental complexity.
- Applying multilevel hierarchical models across diverse populations and datasets to identify group-level differences.
- Are these metrics just "informational fumes"— epiphenomena rather than causal?

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