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

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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]

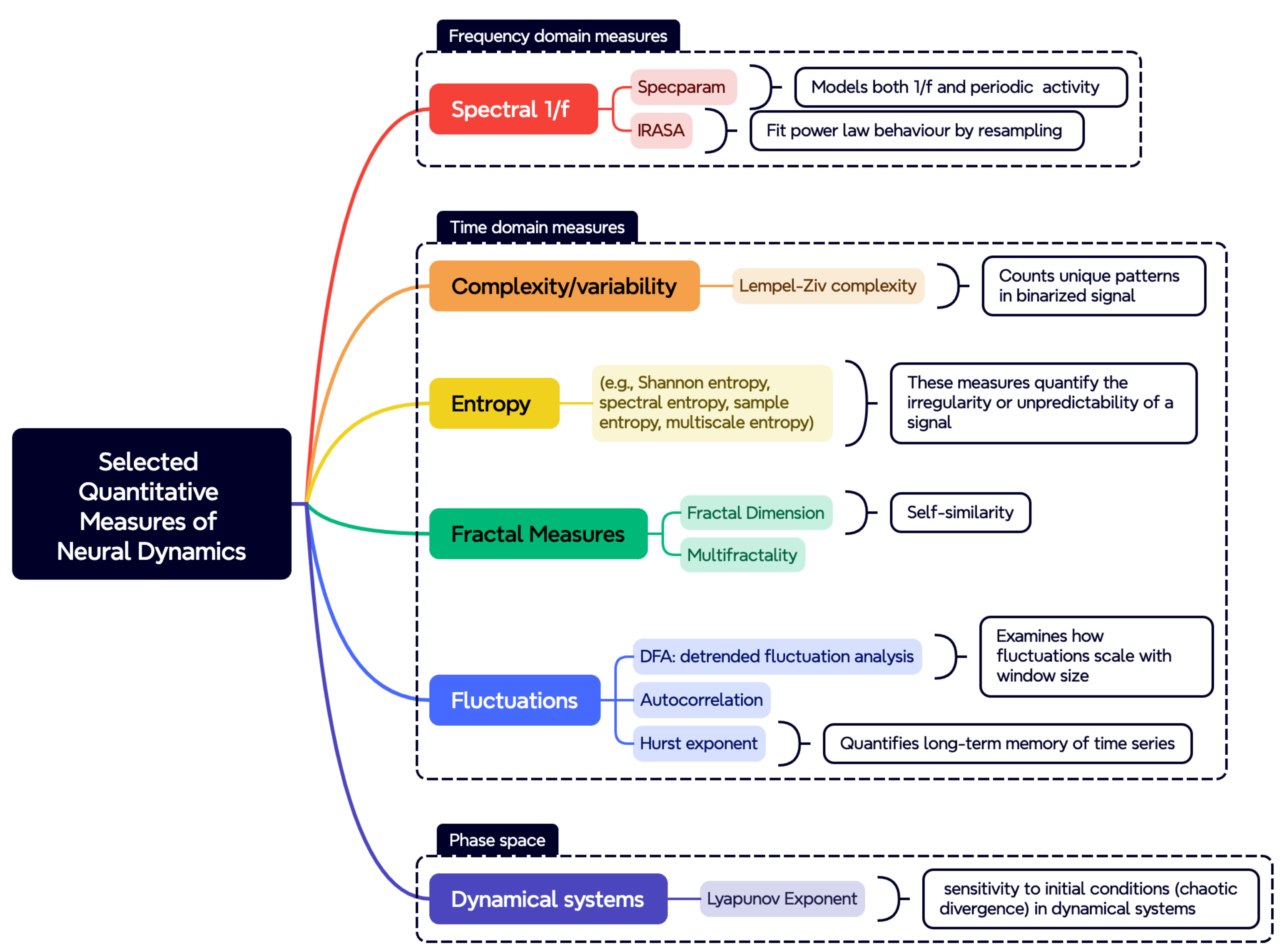

Figure 1: Selected measures of complexity and criticality.

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.
- "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 [4]

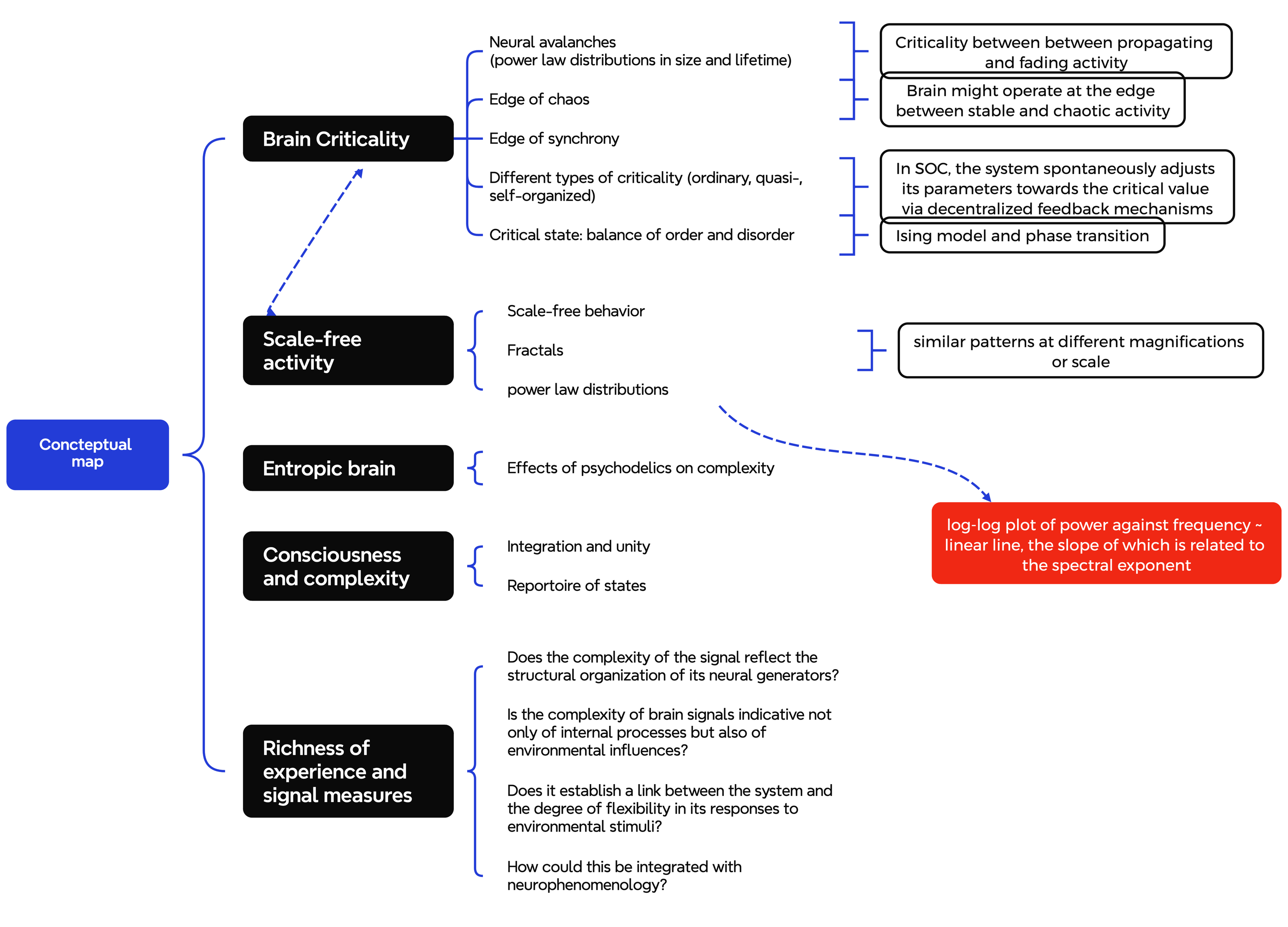

Figure 2: Selected measures of complexity and criticality.

- 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 [5].
- 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 [5]

Complexity measures for EEG and brain states

- recently there are several reviews on topic ([6], [7])

Method	Interpretation and limitations	Clinical Applications	Possible further studies
Auto-correlation decay time	Correlation of the signal to itself, with a certain time-lag,	Correlates with knee frequency [2]; relationship with age persists after accounting for exponent	—
Hurst Exponent	Quantifies long-term memory of time series	Measures statistical dependence between distant points	More influenced by oscillations
DFA (Detrended Fluctuation Analysis)	Examines how fluctuations scale with window size	Removes overall trends first	—
Fractal Dimension metrics (Higuchi, Katz, Petrosian)	Measure signal complexity and self-similarity	Katz fractal dimension less affected by oscillations	—
Lempel-Ziv Complexity	Counts unique patterns in binarized signal	Less affected by oscillations	—
Entropy measures (ApEn, SampEn, PE, WPE)	Quantify signal unpredictability	Sample entropy less affected by oscillations	Permutation entropy strongly influenced by oscillations
Spectral Parameterization (SpecParam/FOOOF)	[Models both periodic and aperiodic components]	Handles knees and broad peaks well; directly separates oscillations from background	More complex modeling approach
IRASA	Separates components through resampling	Directly separates oscillations from background	Less effective with knees or non-scale-free signals

Currently, these measures are being used to differentiate states of consciousness (e.g., distinguishing between minimally conscious and vegetative states, identifying sleep phases) and are also applied in research on psychedelics (e.g., the "entropic brain" hypothesis, where stimulants increase the complexity and richness of neuronal communication).

Increased entropy or fractal dimension often correlates with positive affective states (e.g., psychedelics) and cognitive flexibility, whereas reduced complexity is observed in conditions such as depression. These patterns frequently involve NMDA receptors modulation (excitation-inhibition framework), providing a mechanistic link to various conditions that alter subjective experience, including schizophrenia and ADHD. Additionally, age-related changes in spectral slope correlate with cognitive reserve capacity, suggesting that variations in brain dynamics may # fundamentally shape phenomenological experience across the lifespan.

Possible mechanisms

Summary

- This presentation doesn want to be exaustive iterarture review, rather want to discuss plausibility of linking this dynamics altering experience - ADHD, autism, schisophrenia, time perception
- There are many ways to measure the complexity and variability of brain signals, which are often closely related.
- The relationship is not linear, more complexity or dynamics isn'r always better; intermediate states between chaos and excessive order enable the brain to respond flexibly and adaptively to environmental demands.
- The most plausible underlying mechanism is the balance between excitation and inhibition
- Surrogate data testing is essential for distinguishing genuine criticality from spurious findings
- Although power-law behavior is a hallmark of criticality, it can also emerge from non-critical processes, making it an insufficient criterion on its own

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