Complexity, Entropy and Criticality: Assessing States of Consciousness Under Anesthesia

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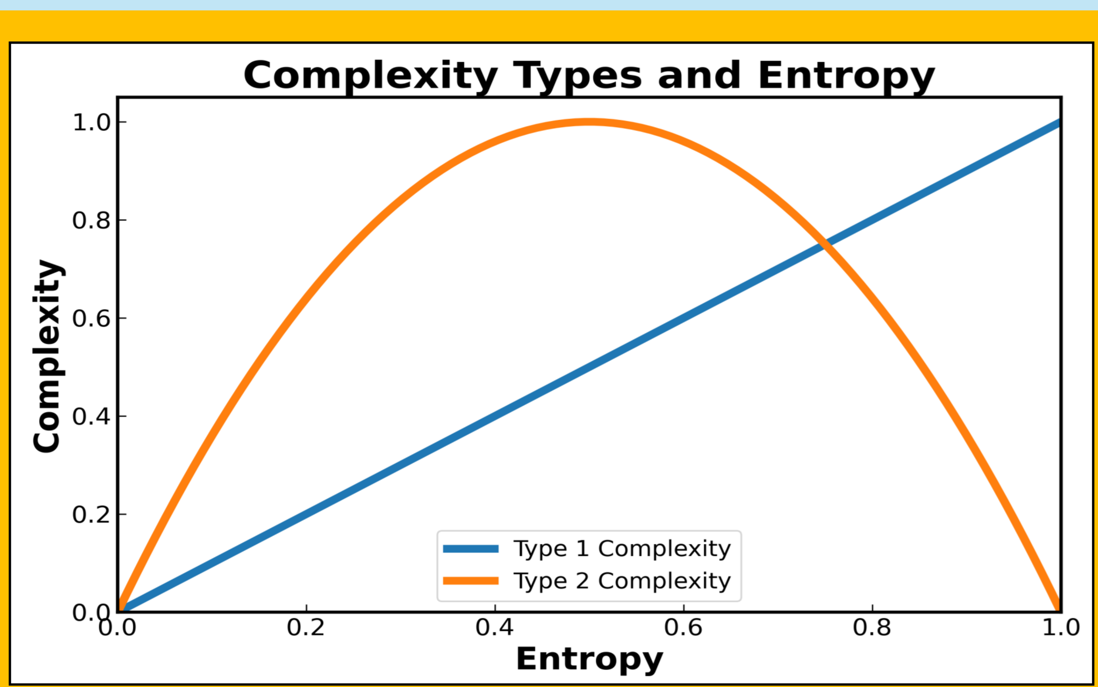
1. BACKGROUND

- Assessments of consciousness using neuroimaging have increasingly focused on features of brain **complexity** and **entropy**[1,2,3].
- The measures of a system's complexity can vary in its relationship with the system's entropy[4,5]:
  - **Type 1 complexity**: A positive linear relationship with entropy.
  - **Type 2 complexity**: A parabolic relationship with entropy.
- A complexity measure with an entropy measure can be used to construct the **complexity-entropy causal plane**, which can disentangle the chaoticity and stochasticity of a signal by quantifying the degree of organization with respect to its randomness[6,7].
- The complexity-entropy plane has been used to assess neural dynamics and may provide valuable insights into the neural dynamics that underlie different **levels of consciousness**[8].

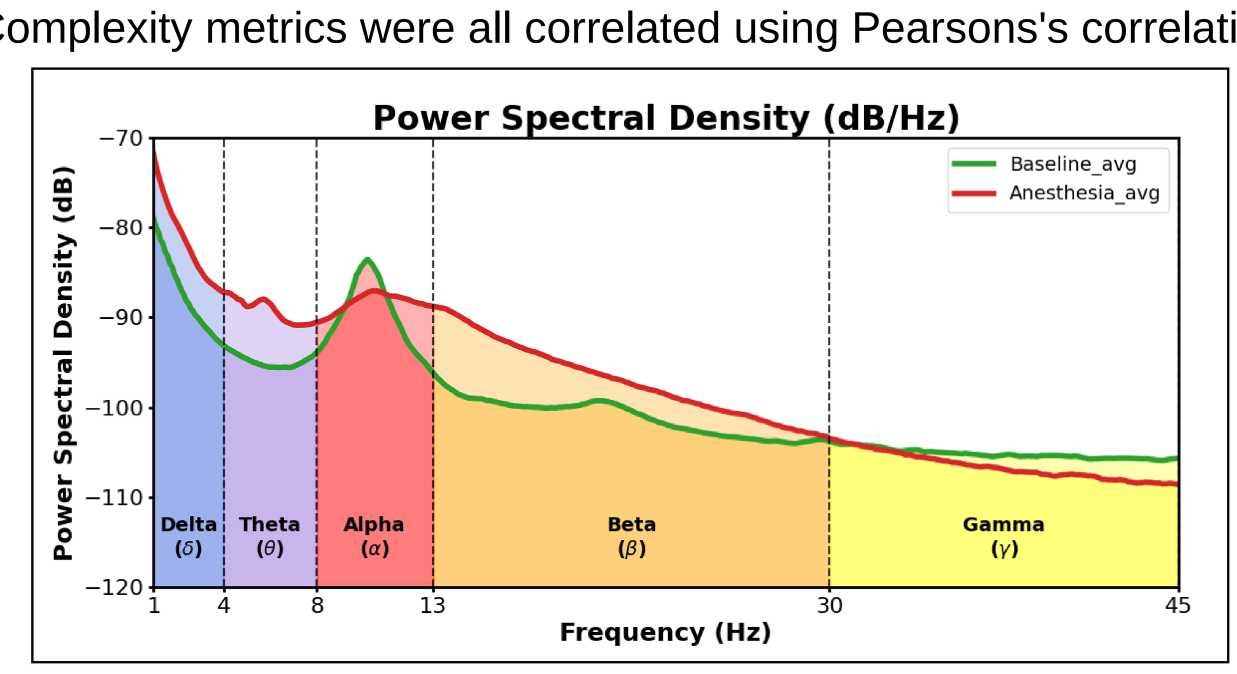


2. HYPOTHESIS

The complexity-entropy plane can effectively differentiate between varying levels of consciousness in participants undergoing sedation with propofol, a GABAergic anesthetic.

3. METHODS

- EEG data was collected during an anesthetic protocol involving healthy participants (**n=9**).
- To assess states of consciousness we analyzed two phases; a resting-state baseline prior to sedation—**the conscious state**—and a steady-state under propofol sedation—**the unconscious state**.
- The complexity-entropy plane is constructed with statistical complexity[9], measuring disequilibrium, and permutation entropy, measuring ordinal patterns in phase space using the OrdPy[10] software package.
- Parameter selection and other complex systems-related metrics, such as Lempel-Ziv complexity (type 1), aperiodic slope of the power spectral density, Higuchi fractal dimension and Hurst exponent (estimated by detrended fluctuation analysis) were assessed using the Neurokit[11] software package.
- Values are whole brain averaged, for each participant and for each condition. These values are then averaged to assess group differences.
- Complexity metrics were all correlated using Pearsons's correlation.



4. RESULTS

1. Conscious states effectively distinguished on the Complexity-Entropy Causal Plane.

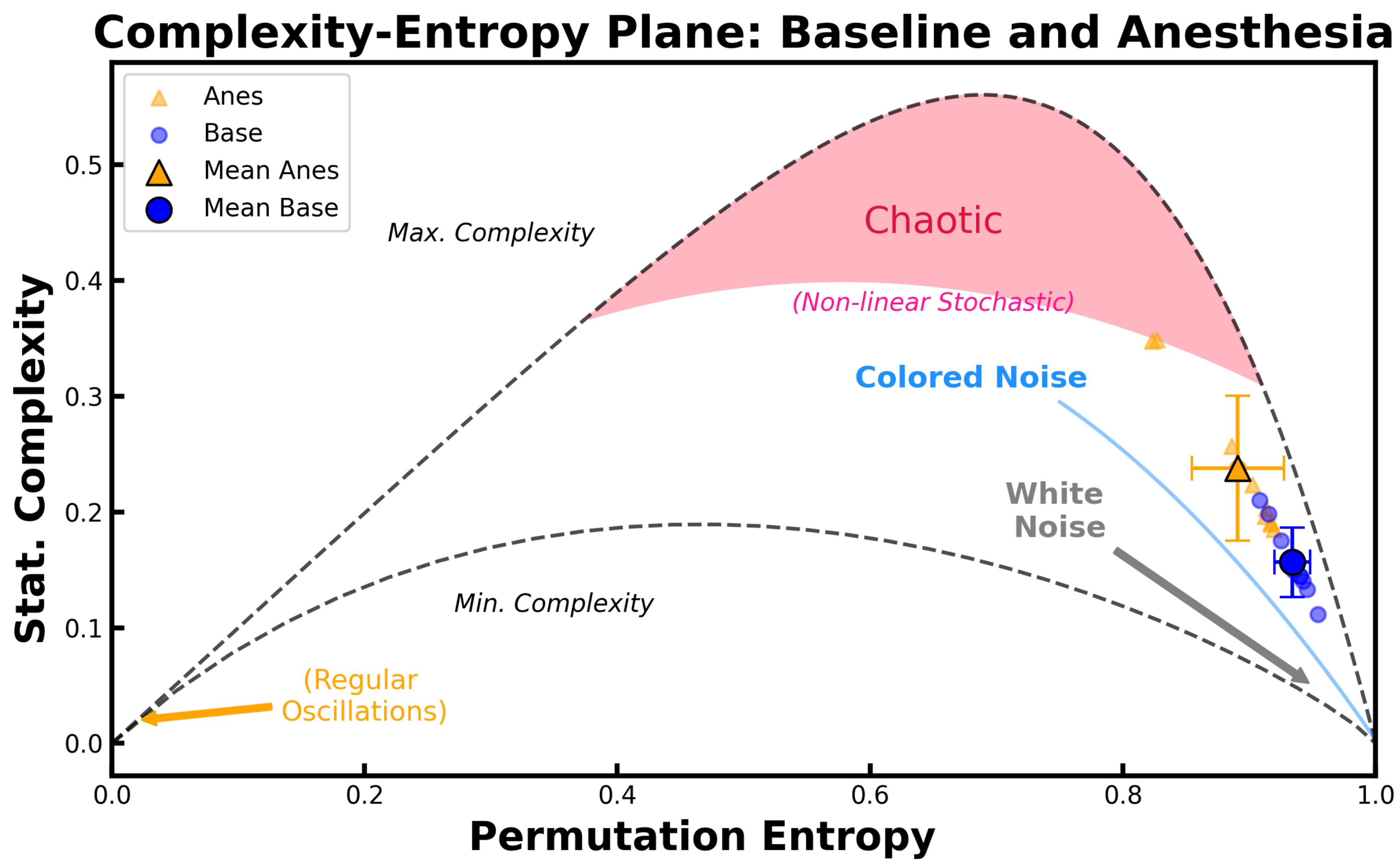


Figure: Background adapted from Zanin & Olivares (2021). Orange represents anesthetic state and blue represents baseline state. Large yellow triangle and large blue circle, both with error bars (standard error) are condition group averages.

2. Type II complexity reduces variability across conditions compared to type I.

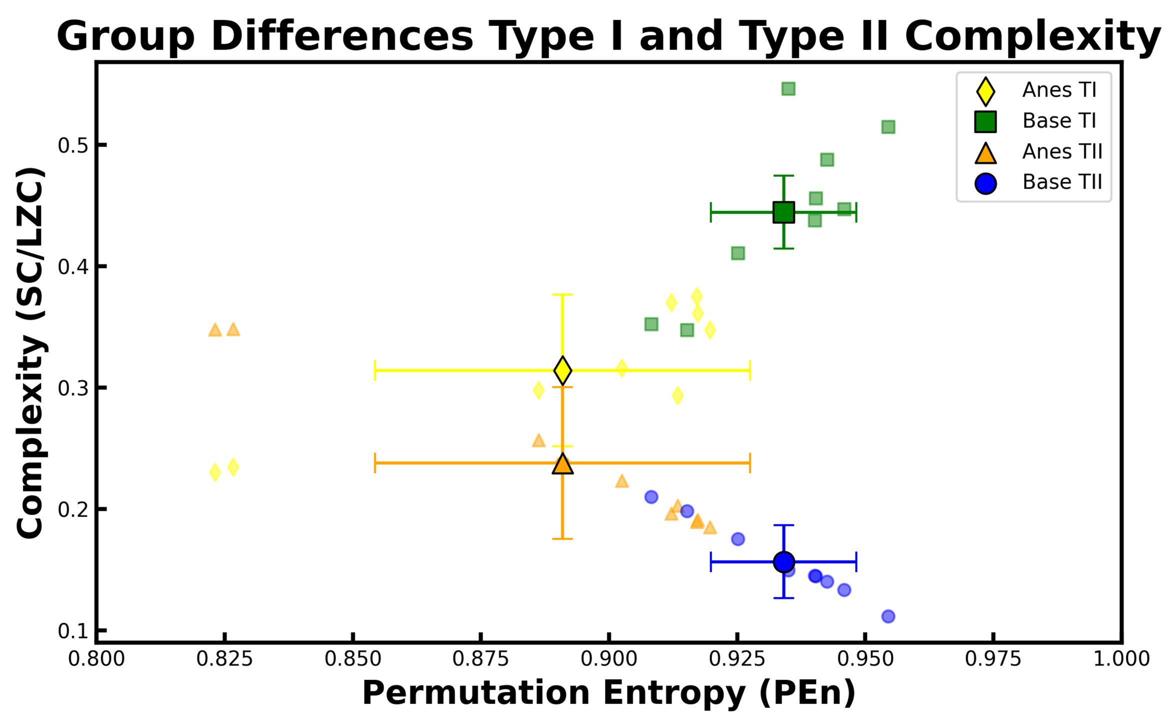
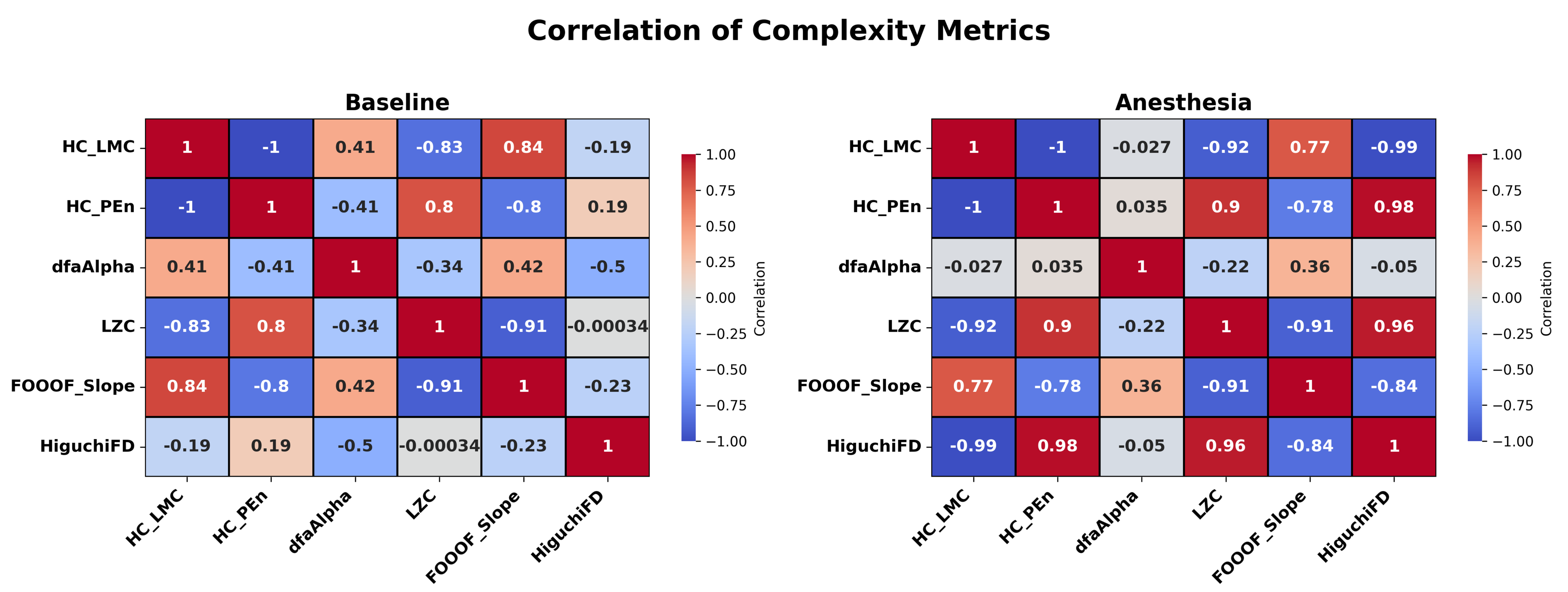


Figure: Complexity values plotted against permutation entropy. Type I measure; yellow-anesthesia and green-baseline. Type II measure; orange-anesthesia and blue-baseline. Condition group averages in larger marker with error bars (standard error)

3. Complexity-related metrics show strong correlations and variability across conditions.



5. CONCLUSION

- We explored how measures of brain complexity and entropy, mapped onto the complexity-entropy causal plane, reflect transitions to anesthetically induced unconsciousness.
- Preliminary results suggest the complexity-entropy plane differentiates levels of consciousness and highlights the frameworks potential to investigate the neural dynamics of consciousness.
- Compared to type I, a type II complexity-entropy plane provides an interpretable description of the physiological signal, characterizing its chaotic and stochastic components.
- Type II complexities, are less biased by the entropy/randomness of the signal.
- Complexity related metrics show strong correlations and variance between conditions, suggesting these metrics provide additional information about the physiological system.
- The framework in conjunction with these metrics provide an opportunity to explore edge of chaos criticality of neurobiological systems to describe conscious level.

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