# What Brain Rhythms Reveal About Functional Brain Connectivity

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## 1. Introduction

Recordings of ongoing neural activity with EEG and MEG exhibit oscillations of specific frequencies over a non-oscillatory background. The oscillations appear in the power spectrum as a collection of frequency bands that are evenly spaced on a logarithmic scale, thereby preventing mutual entrainment and cross-talk. **We hypothesized that if we were able to construct abstract networks, or "virtual brains", whose dynamics were similar to EEG/MEG recordings, those networks would share structural features among themselves, and also with real brains**. Applying mathematical techniques for inverse problems, we have reverse-engineered network architectures that generate characteristic dynamics of actual brains, including spindles and sharp waves, which appear in the power spectrum as frequency bands superimposed on a non-oscillatory background dominated by low frequencies. We show that all reconstructed networks display similar topological features (e.g. structural motifs) and dynamics. We have also reverse-engineered putative diseased brains (epileptic and schizophrenic), in which the oscillatory activity is altered in different ways, as reported in clinical studies. These reconstructed networks show consistent alterations of functional connectivity and dynamics.

## 2. Methods

Macroscopic brain activity was modeled as a linear multivariate stochastic system, which in its continuous version in time is equivalent to an Ornstein-Uhlenbeck process

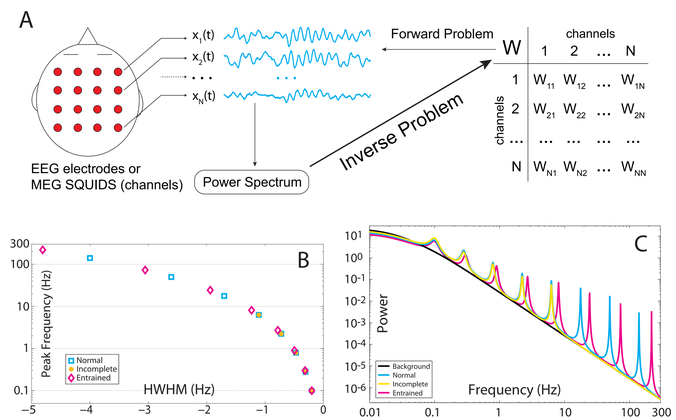



**Figure 1: Reverse-engineering Virtual Brains. (A)** Schematic representation of EEG/MEG recordings and the forward and inverse problems. **(B)** Eigenvalues defining the peak frequency and half width at half maximum in the power spectrum. **(C)** Power spectrum.

If W is known, the Ornstein-Uhlenbeck process can be integrated numerically to simulate EEG or MEG recordings; this is the forward problem of calculating the dynamics from the connectivity matrix. The solution to the inverse problem is more difficult: What is the underlying architecture, W, which gives rise to a particular power spectrum? We note that **the peaks of the power spectrum are determined by the eigenvalues of the connectivity matrix**. In particular, the real part of the complex eigenvalues describes the half width at half maximum (HWHM) and the imaginary part describes the peak frequency. Thus, the eigenvalues of W can reciprocally be inferred from the power spectrum. **This reduces our network reconstruction problem to an inverse eigenvalue-problem** (IEP), which consists in finding a matrix with a given set of eigenvalues.

## 3. Results: Dynamics

We have reconstructed networks that generate brain dynamics in five different scenarios: 1) **Normal** - whose spectrum has evenly spaced frequency bands on a logarithmic scale. 2) **Entrained** - whose spectrum has frequency bands that are rational multiples of each other leading to phase-locking. 3) **Incomplete** - whose spectrum lacks high-frequency peaks, as observed in patients with cognitive deficits. 4) **Background** - whose dynamics lacks rhythmic oscillations. 5) **Random** - where the frequency peaks had been randomly shuffled.

**Figure 2: Examples of connectivity matrices.** Virtual brains from different groups display different patterns of functional connectivity.

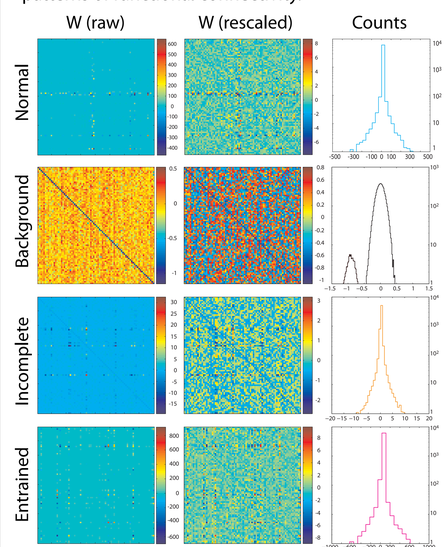
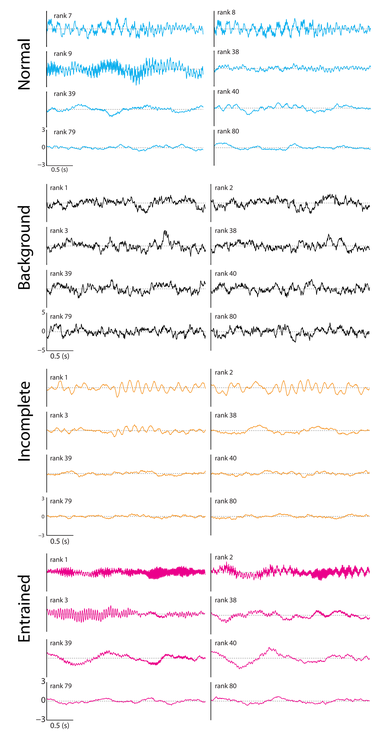



**Figure 3: Virtual Brains display realistic dynamics.** Dynamics from different groups look quite different. Traces from strongly connected nodes display more complicated patterns and contain more frequency components. Some transient oscillations are reminiscent of *sharp waves* and *spindles*.




## 4. Results: Spectral Features of the Normal Group

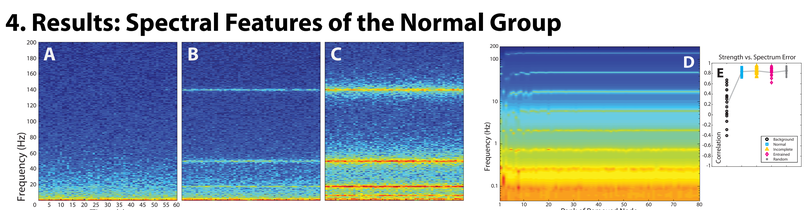
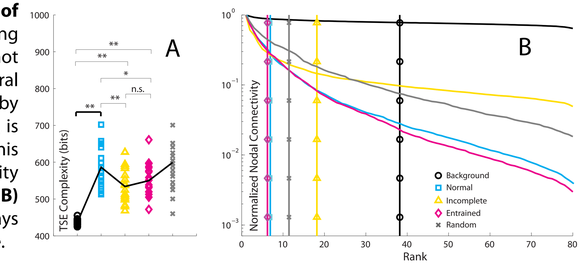



**Figure 4: Nodal Contributions to Brain Rhythms. (A)** Spectrograms from weakly-connected nodes, **(B)** from moderately-connected nodes, and **(C)** strongly-connected nodes. Note the difference in frequency components. **(D)** Power spectrum after the removal of an individual node of given rank. **(E)** Correlation of node relevance to error between the unperturbed and the perturbed spectra from (D).

## 5. Results: Neural Complexity

**Figure 5: Neural complexity of Virtual Brains. (A)** Excluding the Random group, which is not physiologically relevant, neural complexity, as defined by Tononi, Sporns and Edelman, is highest for the Normal case. This suggests that neural complexity is a measure of brain fitness. **(B)** The Normal group also displays the most hierachical structure.




## 6. Results: Structural Motifs

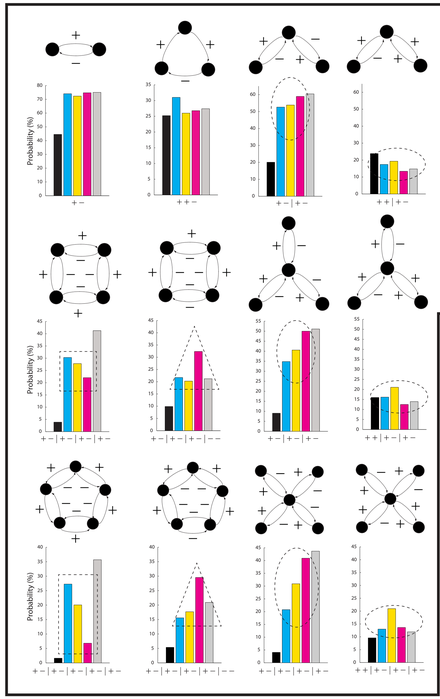



**Figure 6: Virtual Brains from different groups have different structural motifs.** The Normal group is characterized by cyclic graphs with balanced feedforward excitation and feedback inhibition, as well as by radial motifs in which the symmetry between excitation and inhibition is broken. Deviations from these structural patterns may be indicative of a pathological condition, as suggested by the results from the Incomplete and Entrained groups.

## 7. Conclusions

- The power spectrum of neural recordings conveys significant information about the functional connectivity of the brain.
- The presence of brain rhythms is indicative of a hierarchical network structure with high complexity, in which certain motifs with reciprocal connections are more probable than others.
- Alterations of the multi-oscillatory activity lead to a reduction of neural complexity, changes in the hierarchical structure, and in the probability of finding certain motifs.

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## References

G. K. Steinke and R. F. Galán (2011). *PLoS Computational Biology*, 7(10): e1002207.

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