Epileptic-seizure-related Synchronization Phenomena

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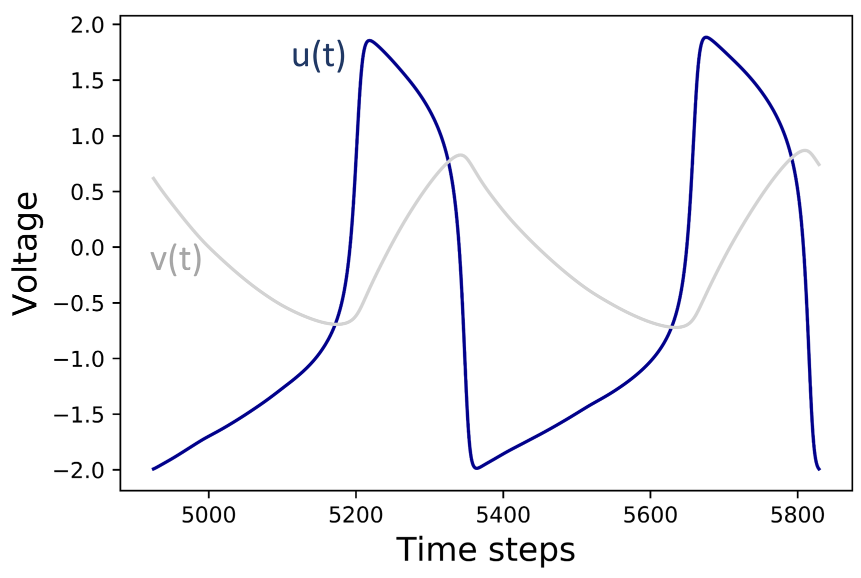
Epilepsy

„An epileptic seizure is a transient occurrence of signs and/or symptoms due to abnormal excessive or **synchronous** neuronal activity in the brain.“[1]

FitzHugh-Nagumo Model

$$\varepsilon \frac{du_k}{dt} = u_k - \frac{v_k^3}{3} - v_k + \sigma \sum_{j=1}^{N} \boldsymbol{G_{kj}} \left[b_{uu}(u_j - u_k) + b_{uv}(v_j - v_k)\right]$$

$$\frac{dv_k}{dt} = u_k + a + \sigma \sum_{j=1}^{N} \boldsymbol{G_{kj}} \left[b_{uu}(u_j - u_k) + b_{uv}(v_j - v_k)\right]$$

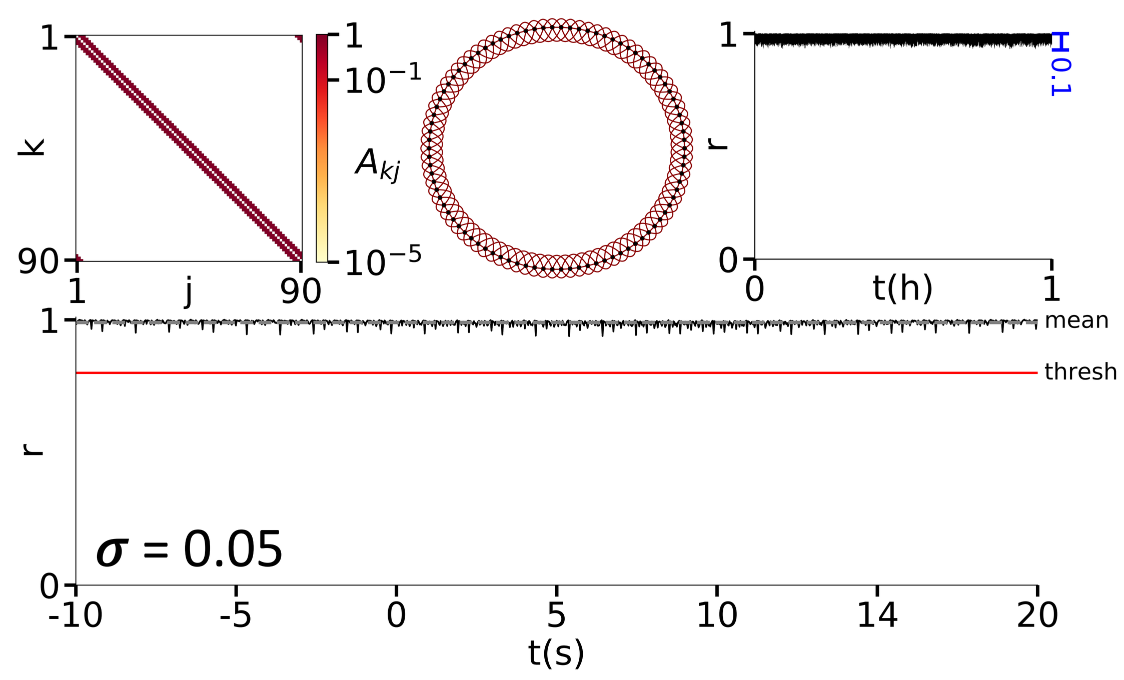


u: activator variable
v: inhibitor variable
$\boldsymbol{\varepsilon}$ = 0.05 - timescale separation
a = 0.5 - threshold parameter
|**a**| < 1 → oscillatory regime
$\boldsymbol{G_{kj}}$ - adjacency matrix
N=90

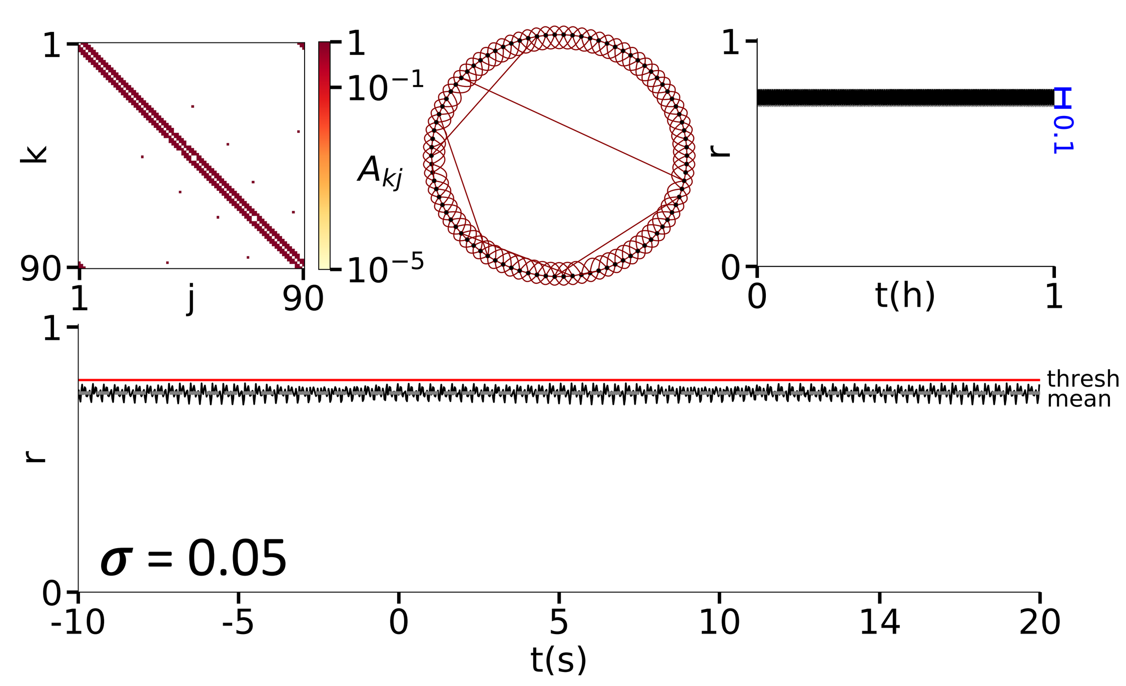
Rotational Coupling Scheme[2]: $\begin{pmatrix} b_{uu} & b_{uv} \\ b_{vu} & b_{vv} \end{pmatrix} = \begin{pmatrix} \cos\phi & \sin\phi \\ -\sin\phi & \cos\phi \end{pmatrix}, \quad \phi = \frac{\pi}{2} - 0.1$

Artificial Network Structure and Simulation Dynamics

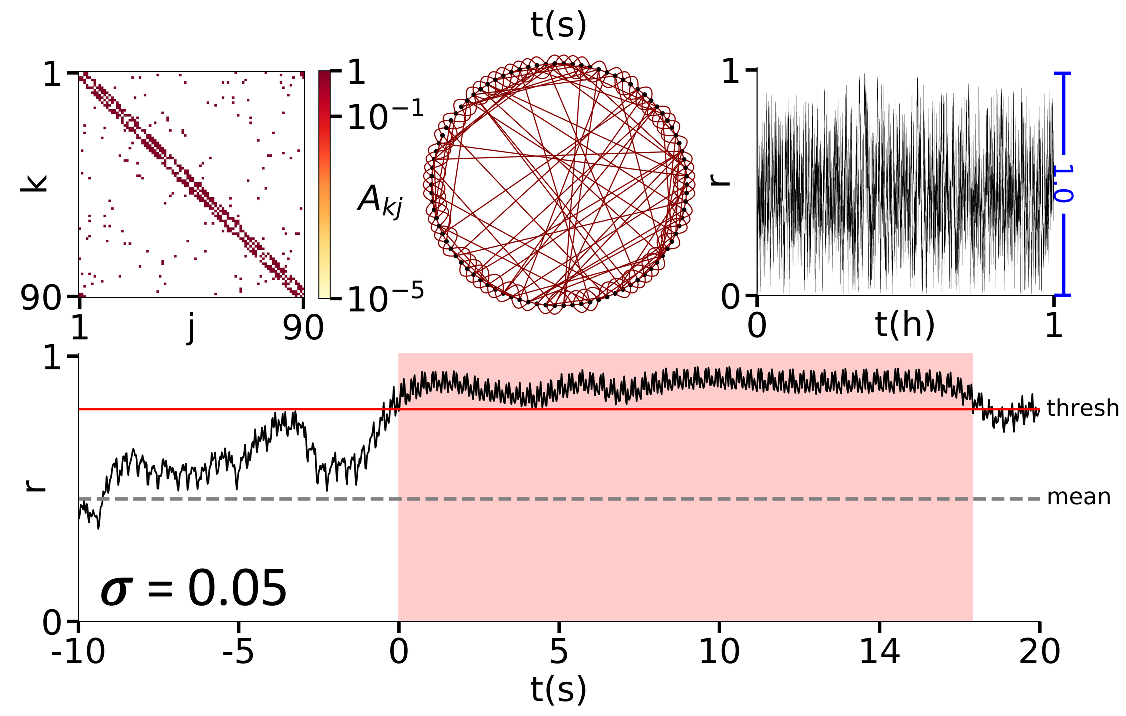
Nonlocally Coupled Ring,
p=0,
high clustering,
long paths,
full synchronization



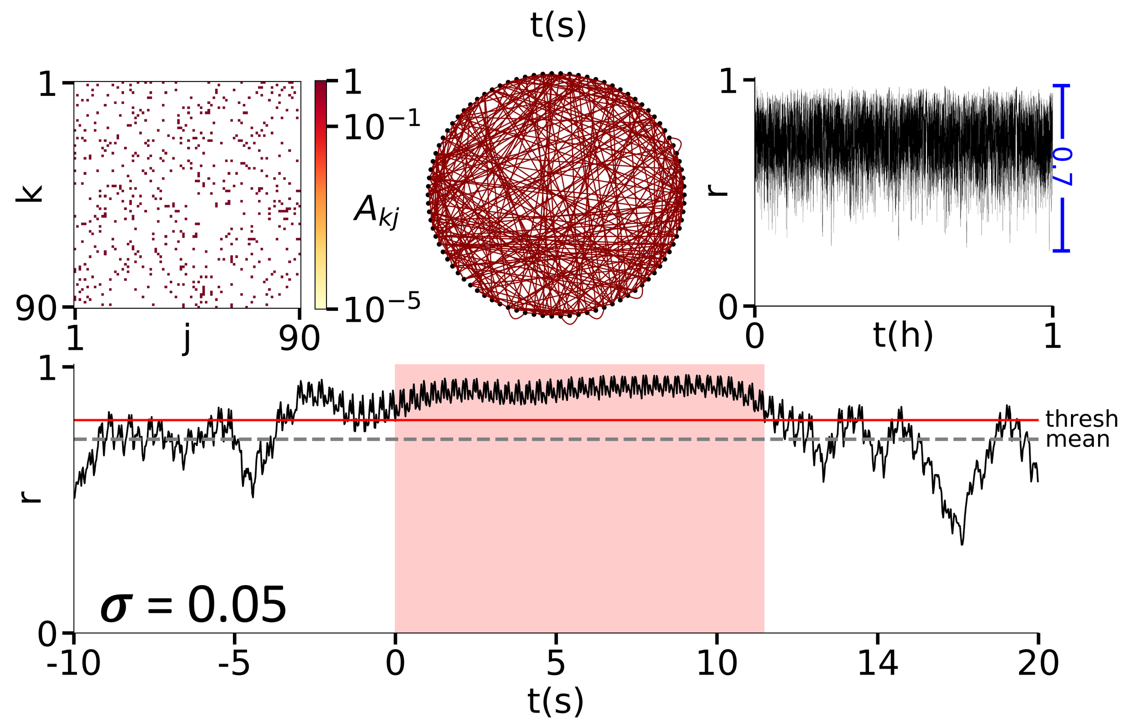
Small World,
p=0.006,
high clustering,
short paths,
constant synchronization



p=0.206
medium clustering,
short paths,
occurrence of seizures,
realisitic brain modeling

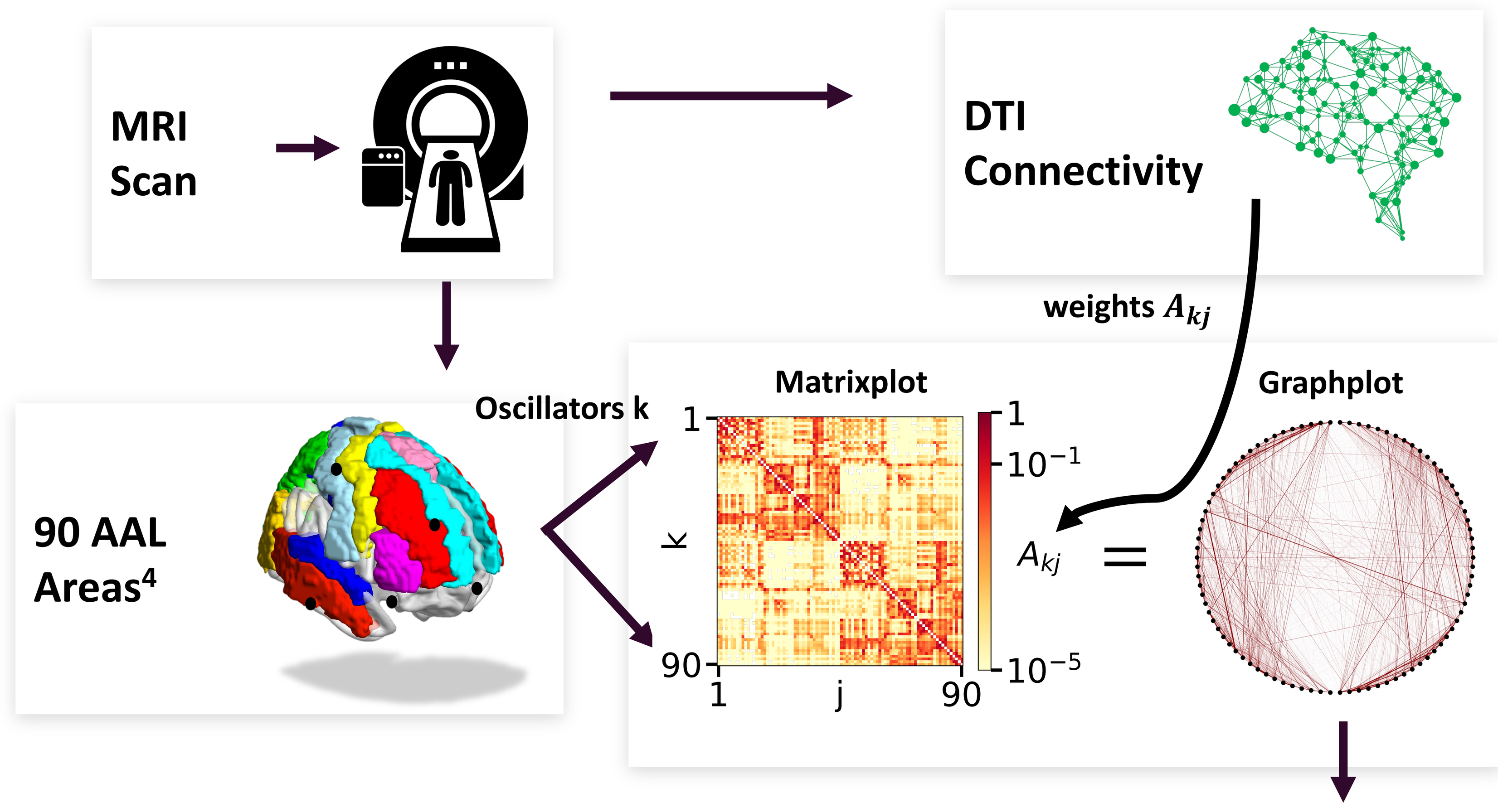


Random network,
p=1,
little clustering,
short paths,
noisy fluctuations of synchronization



Simulation Dynamics of Empirical Network Structure

Empirical complex network $\boldsymbol{G_{kj}}$:

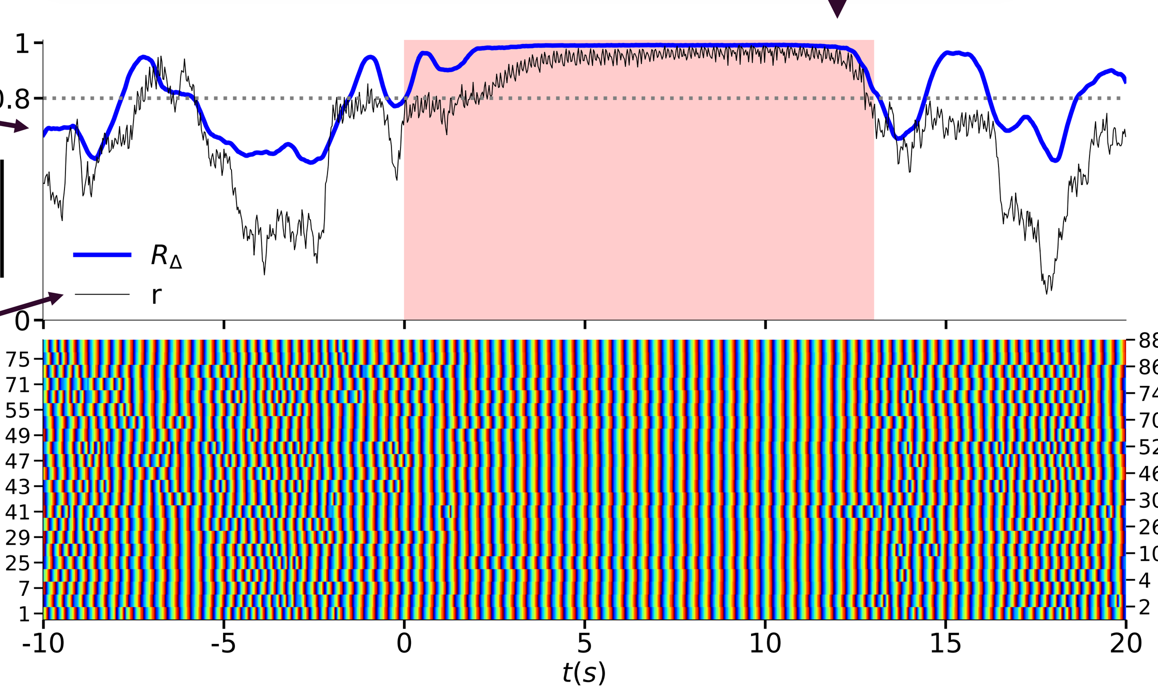


Global Phase Coherence

$$R_\Delta = \frac{1}{N(N-1)/2} \sum_{\substack{i,j=1, \\ i>j}}^{N} \left| \frac{1}{T} \sum_{t=1}^{T} e^{i\Delta\phi_{ij}(t)} \right|$$

Global Kuramoto Order Parameter

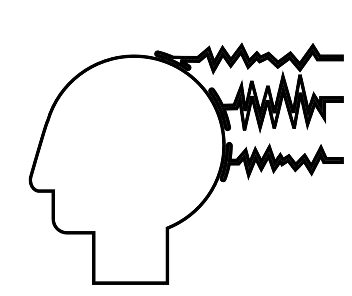
$$r = \left| \frac{1}{N} \sum_{k=1}^{N} e^{i\phi_k} \right|$$

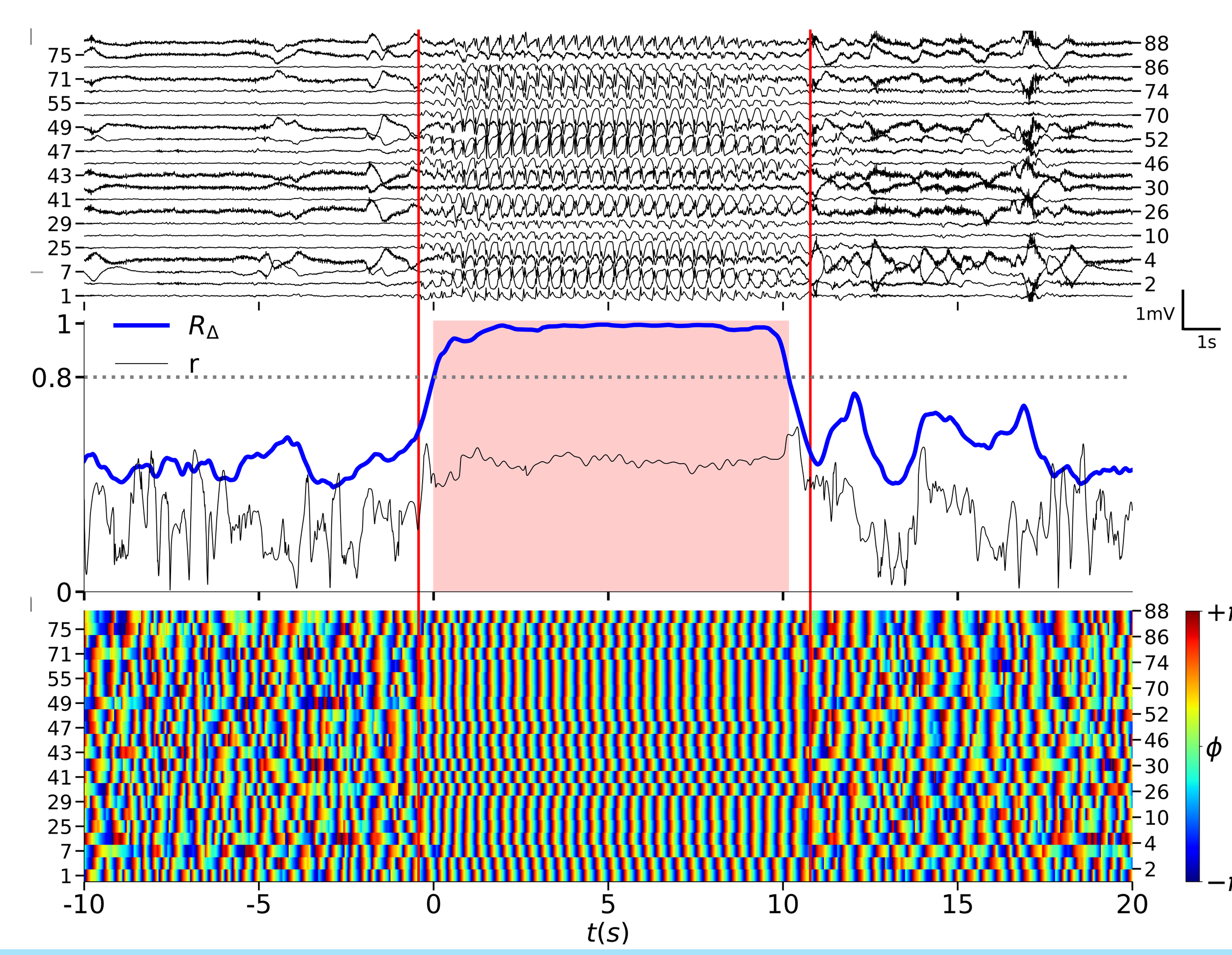


Computer simulation

Real Seizure Dynamics of Subject with Absence Epilepsy

Electroencephalography (EEG) measurement





Empirical data

Conclusion

A network of empirically coupled FitzHugh-Nagumo oscillators mimics synchronization phenomena observed in epileptic seizures.

Small-world networks with small rewiring probability, short path lengths, and high clustering, do not enable realistic brain modeling. Instead, realistic seizure dynamics can be observed in a window of intermediate rewiring probability around p≈0.206. This challenges the classical view of the human brain as a small-world network.

References

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