Epileptic seizure prediction from eigen-wavelet multivariate self-similarity analysis of multi-channel EEG signals

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Goal
Detection of preictal states from scale-free analysis of multi-channel scalp EEG recordings

Method
Eigen-wavelet estimation of multivariate self-similarity parameter vector $\underline{H} = (H_1, \ldots, H_M)$

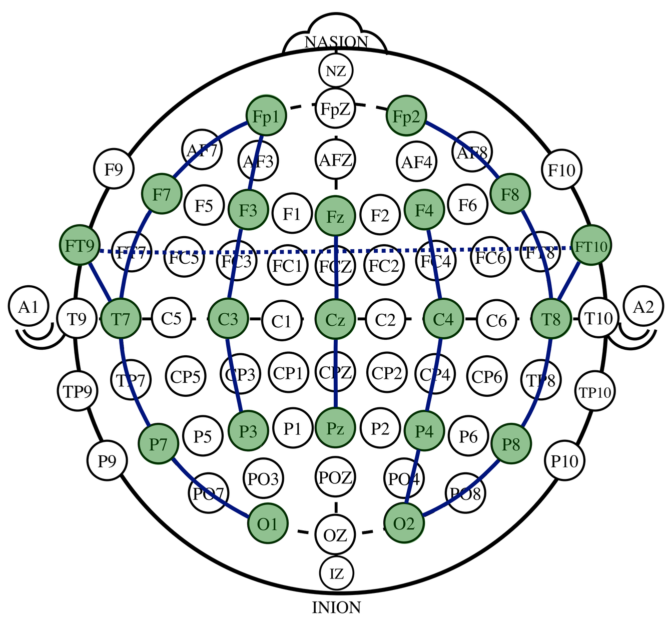
Results
Improved classification performance compared to univariate and classical multivariate analyses

Goal and data

Epileptic seizure prediction (binary classification)

- preictal state: period occuring few minutes before an epileptic seizure
- interictal state: period far in time from an epileptic seizure

Multi-channel EEG data



Used pairs of electrodes

Description

- CHB-MIT Scalp EEG database: https://physionet.org/content/chbmit/
- 23 pediatric subjects
- 19 channels sampled at 256Hz

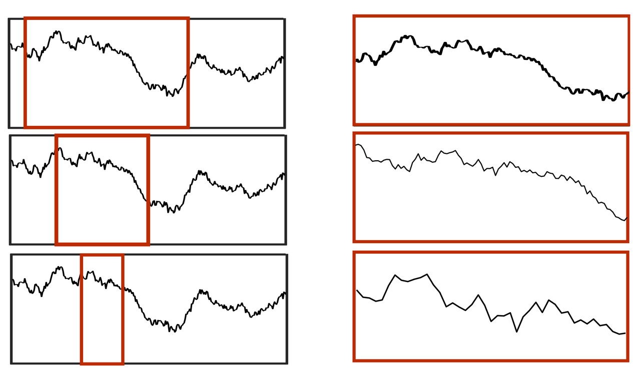
Analysis

- 2-minute windows
- subjects with at least 110 interictal and 10 preictal windows
  $\Rightarrow$ 8 subjects

Multivariate self-similarity

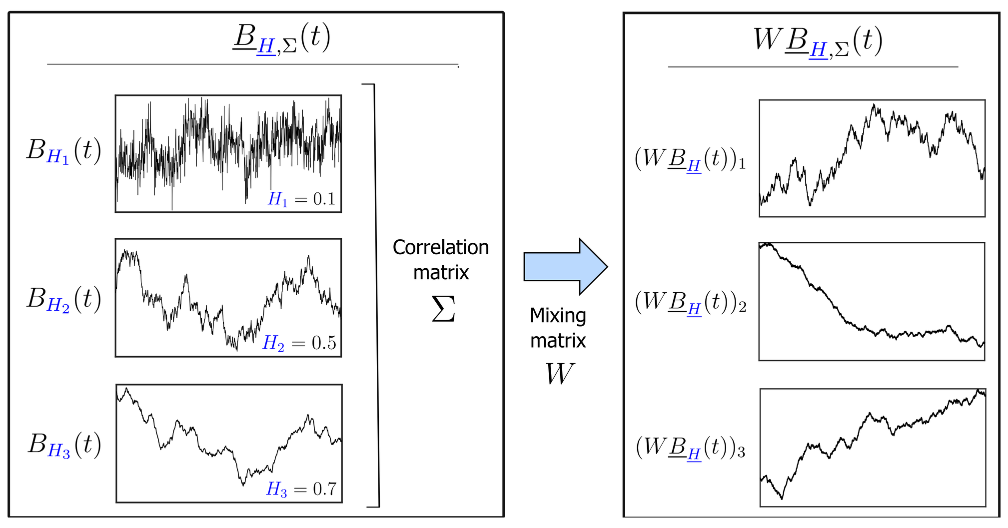
Model [Didier and Pipiras, 2011]

Univariate self-similarity



$B_{H_m}(t)$ characterized by $0 < H_m < 1$

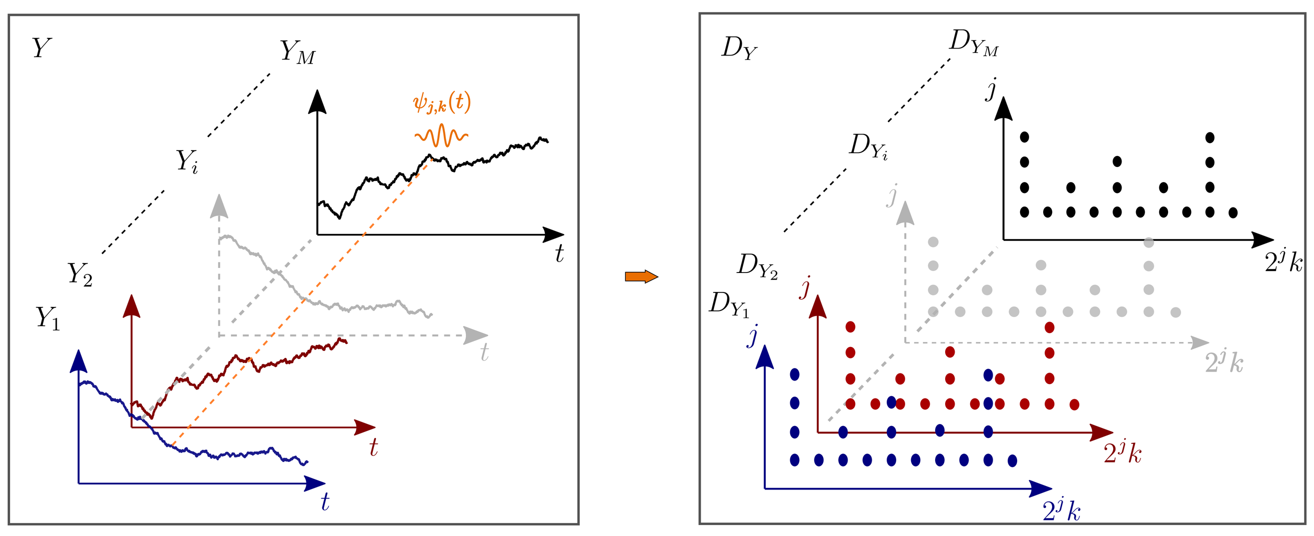
Multivariate self-similarity



Multivariate self-similarity exponents: $\underline{H} = (H_1, \ldots, H_M)$

Estimation

1. Multivariate wavelet transform of $Y = W\underline{B}_{\underline{H},\Sigma}$



with $D_{Y_m}(2^j, k) = \langle Y_m(t) | \psi_{j,k}(t) \rangle$, $\psi_{j,k}(t) = 2^{-j/2}\psi_0(2^{-j}t - k)$

2. Wavelet spectrum: $S(2^j) = \frac{1}{n_j}\sum_{k=1}^{n_j} D(2^j,k)D(2^j,k)^T$

↳ Linear regressions [Wendt et al., 2017]:

Univariate estimation

$$\hat{H}^U_m = \frac{1}{2}\sum_{j=j_1}^{j_2} \omega_j \log_2 S_{m,m}(2^j) - \frac{1}{2}$$

Classical multivariate estimation

$$\hat{H}_{m,m'} = \frac{1}{2}\sum_{j=j_1}^{j_2} \omega_j \log_2 |S_{m,m'}(2^j)| - \frac{1}{2}$$

3. Eigenvalues of $S(2^j)$: $\lambda_1(2^j), \ldots, \lambda_M(2^j)$ [Abry and Didier, 2018]

↳ asymptotic power law: $\lambda_m(2^j) \underset{j\to+\infty}{\sim} \xi_m 2^{j(2H_m+1)}$

4. Multivariate estimation: $\hat{H}^M_m = \frac{1}{2}\sum_{j=j_1}^{j_2}\omega_j \log_2 \lambda_m(2^j) - \frac{1}{2}$

↳ bias correction of $\hat{H}^M_m$ proposed in [Lucas et al., 2021]: $\lambda_m(2^j) \to \bar{\lambda}_m(2^j)$

[Didier and Pipiras, 2011] Didier, G., and Pipiras, V. (2011). Integral representations and properties of operator fractional Brownian motions. Bernoulli, 1-33.

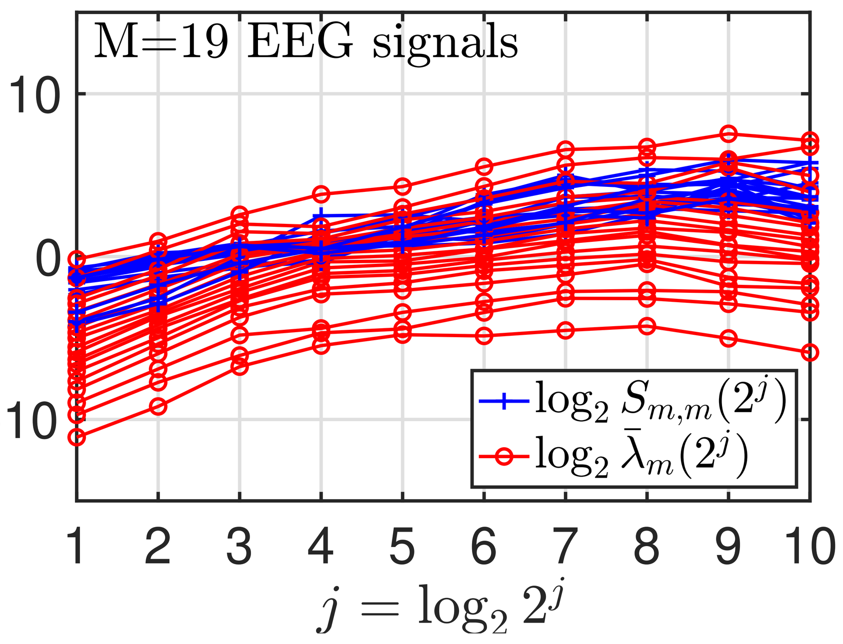
[Wendt et al., 2017] Wendt, H., Didier, G., Combrexelle, S., and Abry, P. (2017). Multivariate Hadamard self-similarity: testing fractal connectivity. Physica D: Nonlinear Phenomena, 356, 1-36.

[Abry and Didier, 2018] Abry, P., and Didier, G. (2018). Wavelet eigenvalue regression for n-variate operator fractional Brownian motion. Journal of Multivariate Analysis, 168, 75-104.

Detection of preictal states

Wavelet analysis scales: $2^{j_1} = 2^1 - 2^{j_2} = 2^4$ (frequencies: 10 – 85Hz)

Single-window analysis (Subject 5)



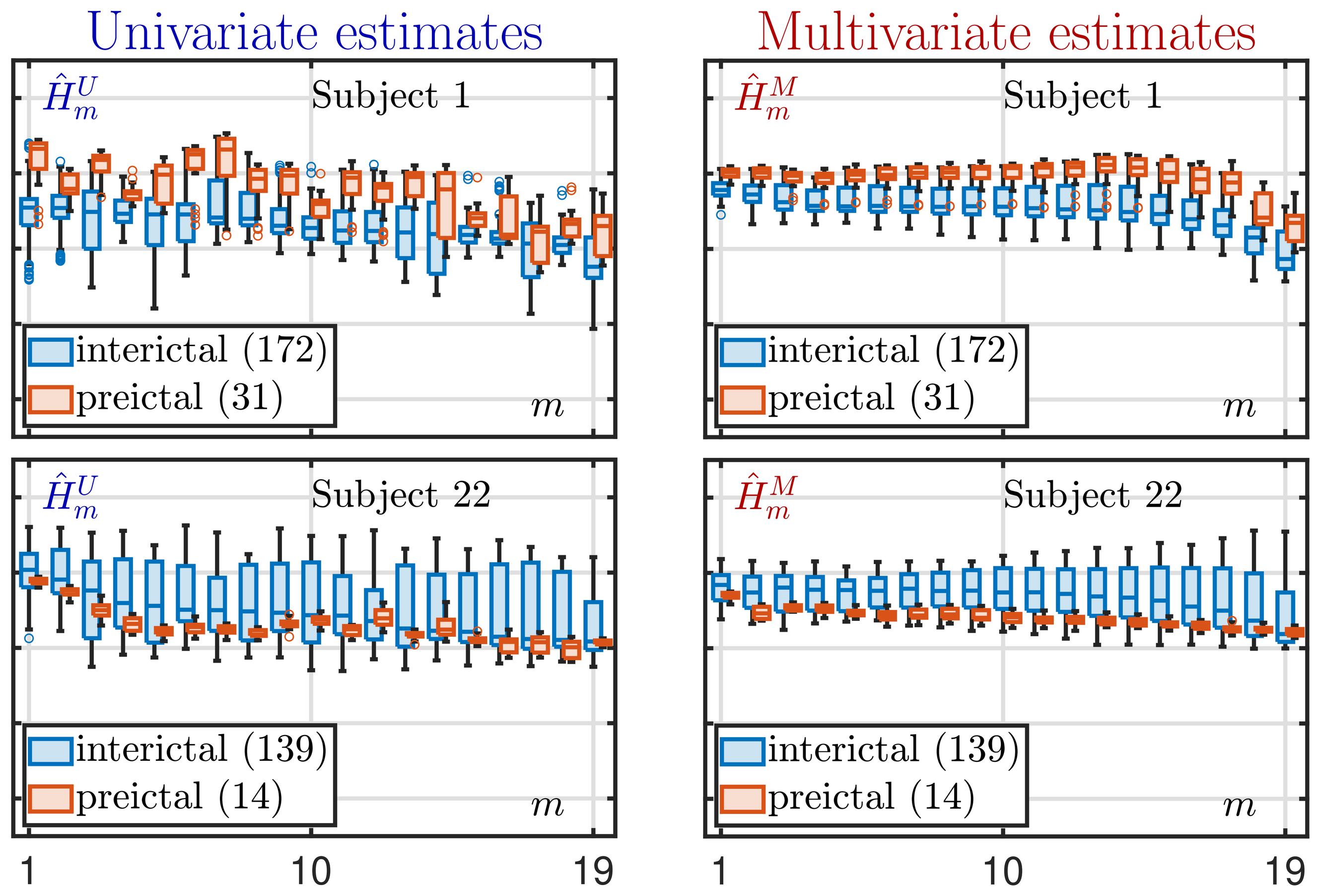
Univariate estimation vs. Multivariate estimation

→ power law behavior across analysis scales

Distributions of self-similarity parameter estimates

- Per-subject analysis
- Estimates across interictal windows and preictal windows

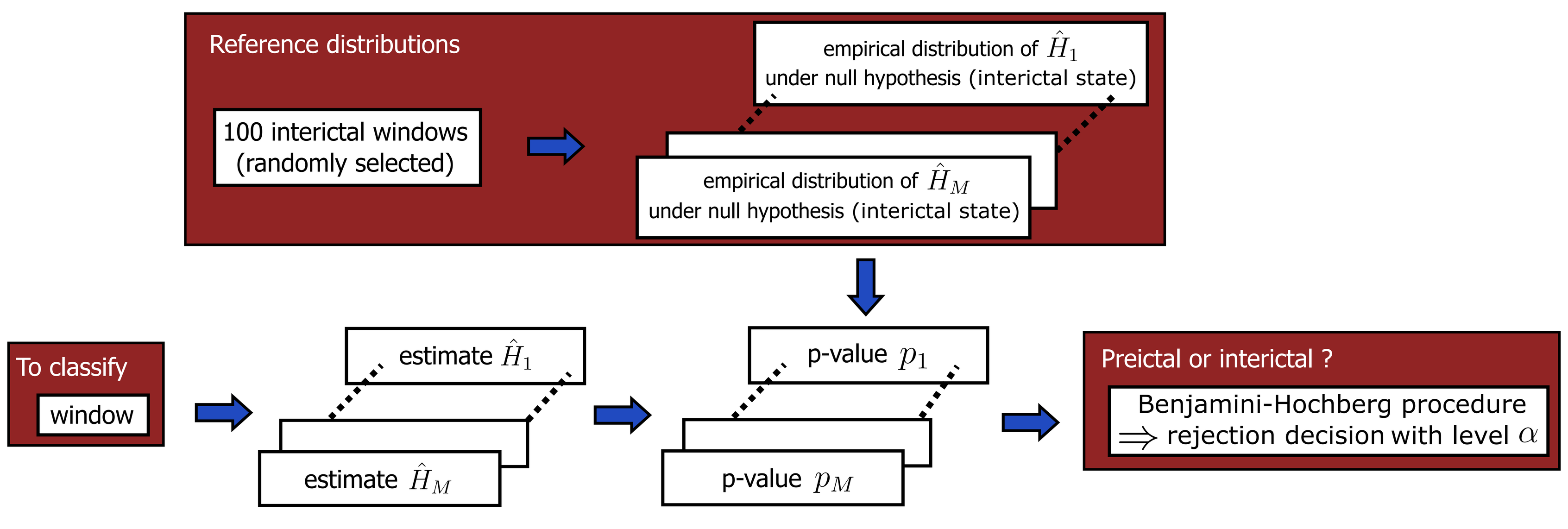
Univariate estimates / Multivariate estimates



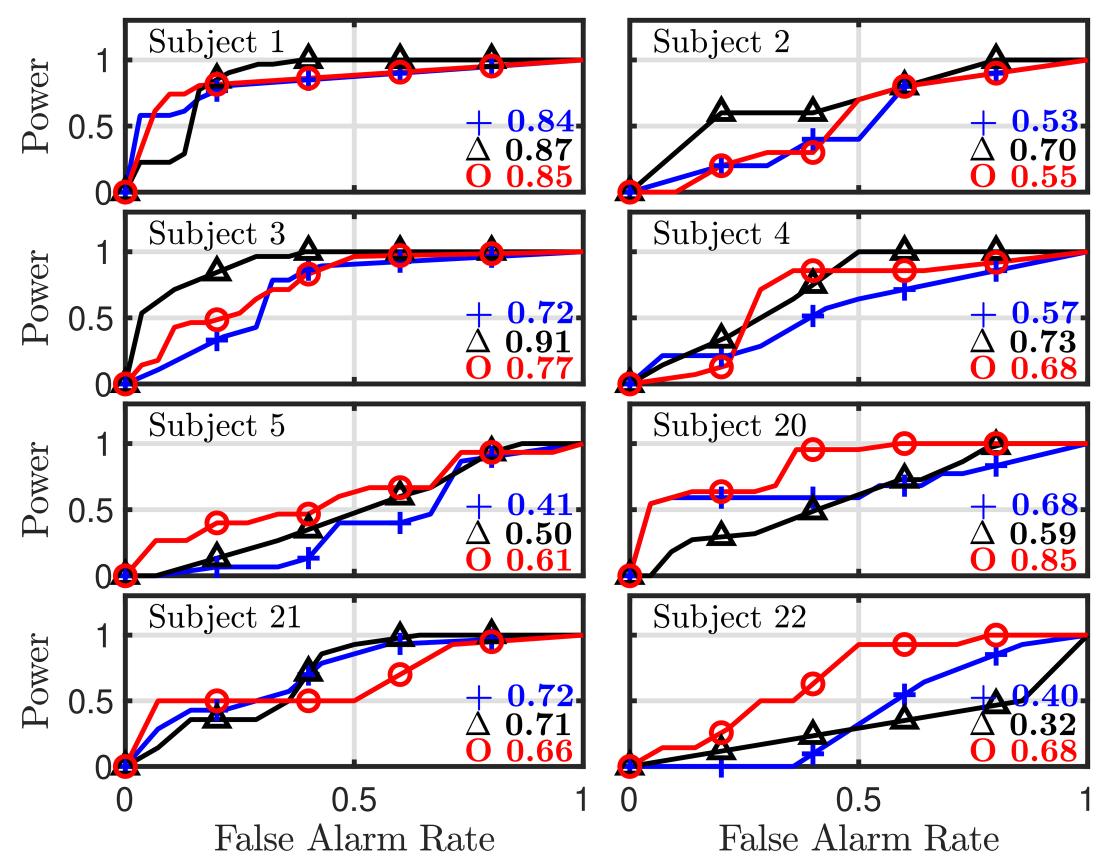
→ difference between preictal and interictal estimate distributions

→ difference between interictal estimate distributions of different subjects

Test procedure



ROC curves



+ M univariate estimates $\hat{H}^U_m$

Δ $M(M+1)/2$ classical multivariate estimates $\hat{H}_{m,m'}$

o M multivariate estimates $\hat{H}^M_m$

→ $\hat{H}^M_m$ outperforms $\hat{H}^U_m$

→ $\hat{H}^M_m$ close to $\hat{H}_{m,m'}$ but sometimes significantly better

[Lucas et al., 2021] Lucas, C. G., Abry, P., Wendt, H., and Didier, G. (2021, August). Bootstrap for testing the equality of selfsimilarity exponents across multivariate time series. In 2021 29th European Signal Processing Conference (EUSIPCO) (pp. 1960-1964). IEEE.