Fractal and multifractal organization of neuroimaging signals in cognitive tasks and in disease

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Aims

- Differences between individuals/groups (healthy/diseased) for clinical diagnosis/biomarkers/prediction
- Differences in information processing
- …detection aided by analysis of temporal patterns in neural signals

Evidence for criticality

- *1/f power spectra* (fMRI, EEG, MEG)

  Zarahn E, Aguirre GK, D'Esposito M. Empirical analyses of BOLD fMRI statistics I. Spatially unsmoothed data collected under null hypothesis conditions. NeuroImage 1997; 5: 179–97.

  Linkenkaer-Hansen K et al. Long-Range Temporal Correlations and Scaling Behavior in Human Brain Oscillations. J Neurosci 21(2001) 1370

- Scaling size of neural activity (field potentials *in vivo/vitro*, fMRI)

  Beggs, J. M. & Plenz, D. Neuronal avalanches in neocortical circuits. J. Neurosci. 23 (2003) 11167

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- Maximal susceptibility (fMRI)

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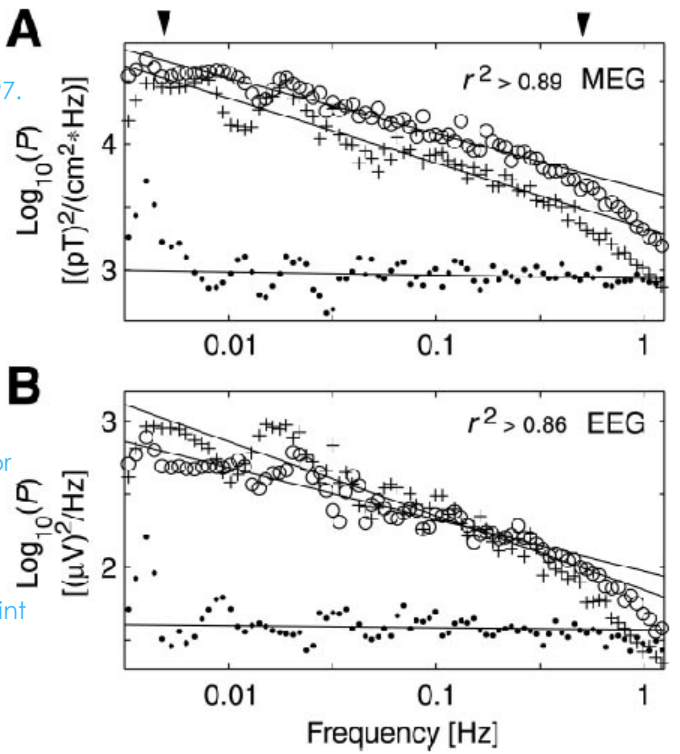

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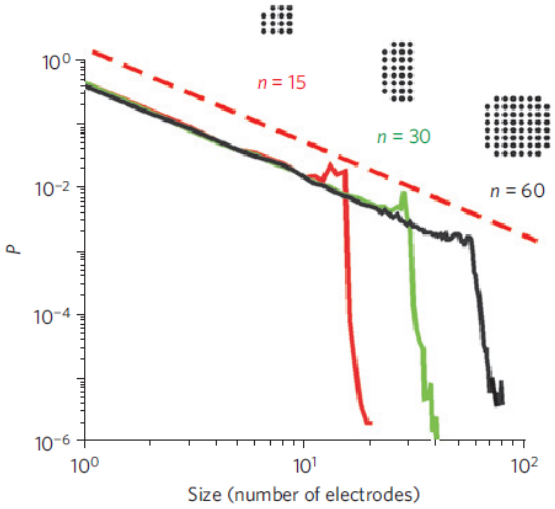

Figure 1 | Neuronal avalanches are complex. Size distribution of neuronal avalanches in mature cortical cultured networks follows a power law with an exponent close to 3/2 (dashed line) and exhibits finite-size scaling. The

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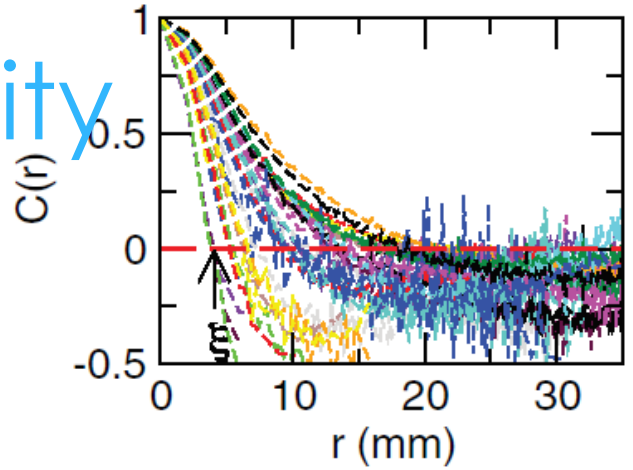

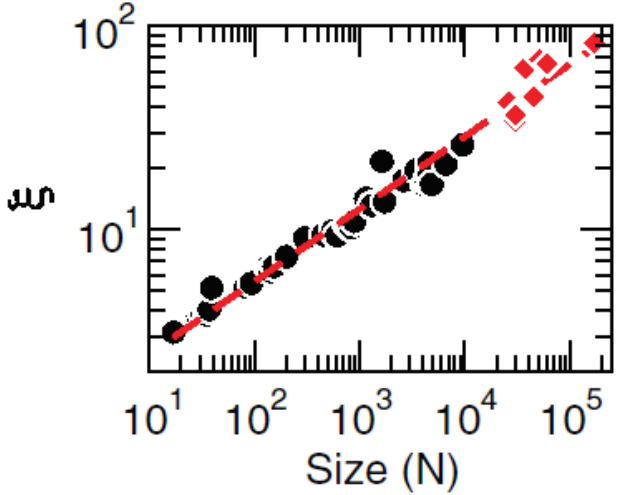

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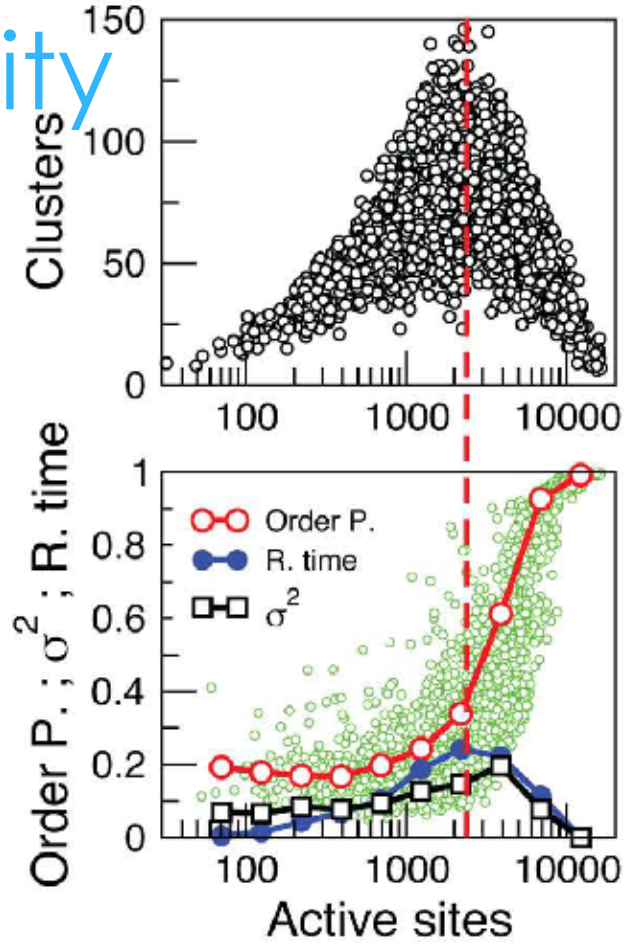

Non-trivial dynamics

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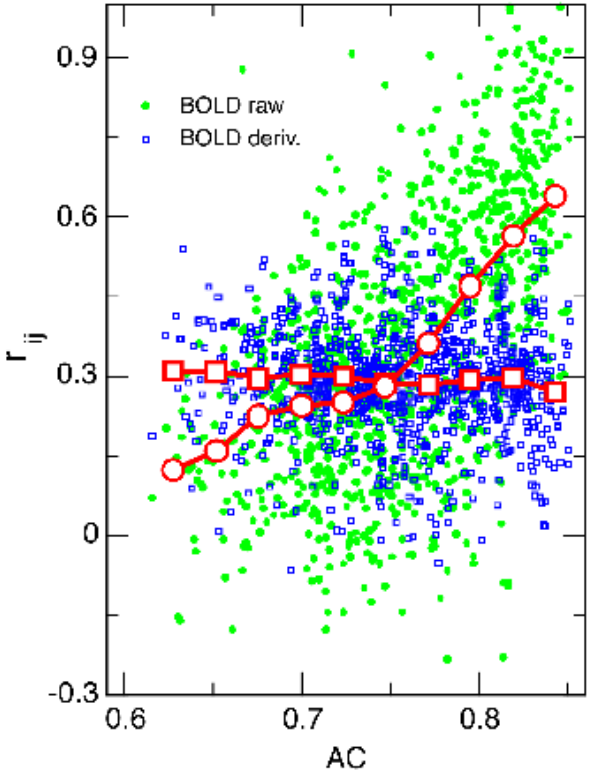


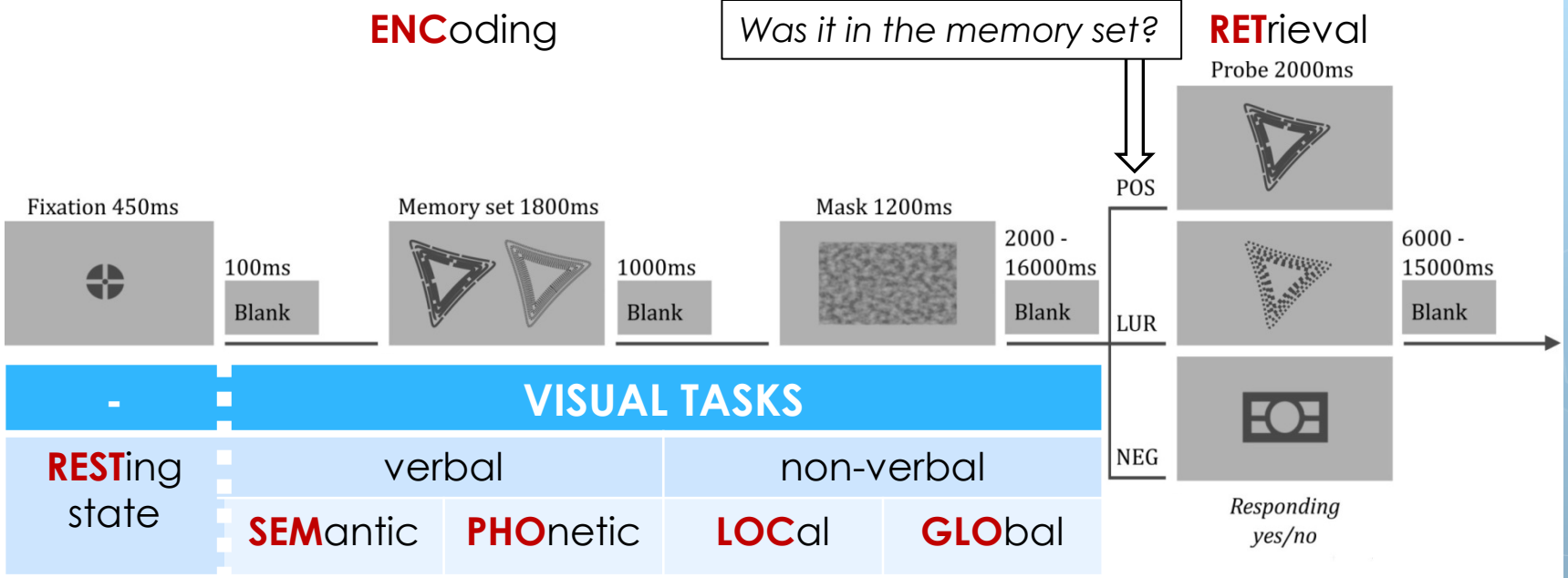
JK Ochab, W Tarnowski, MA Nowak and DR Chialvo, *On the pros and cons of using temporal derivatives to assess brain functional connectivity, NeuroImage 184 (2019) 577-585.*

fMRI (functional magnetic resonance imaging)

Data: Working memory task

Technique: Hurst + detrended cross-correlations

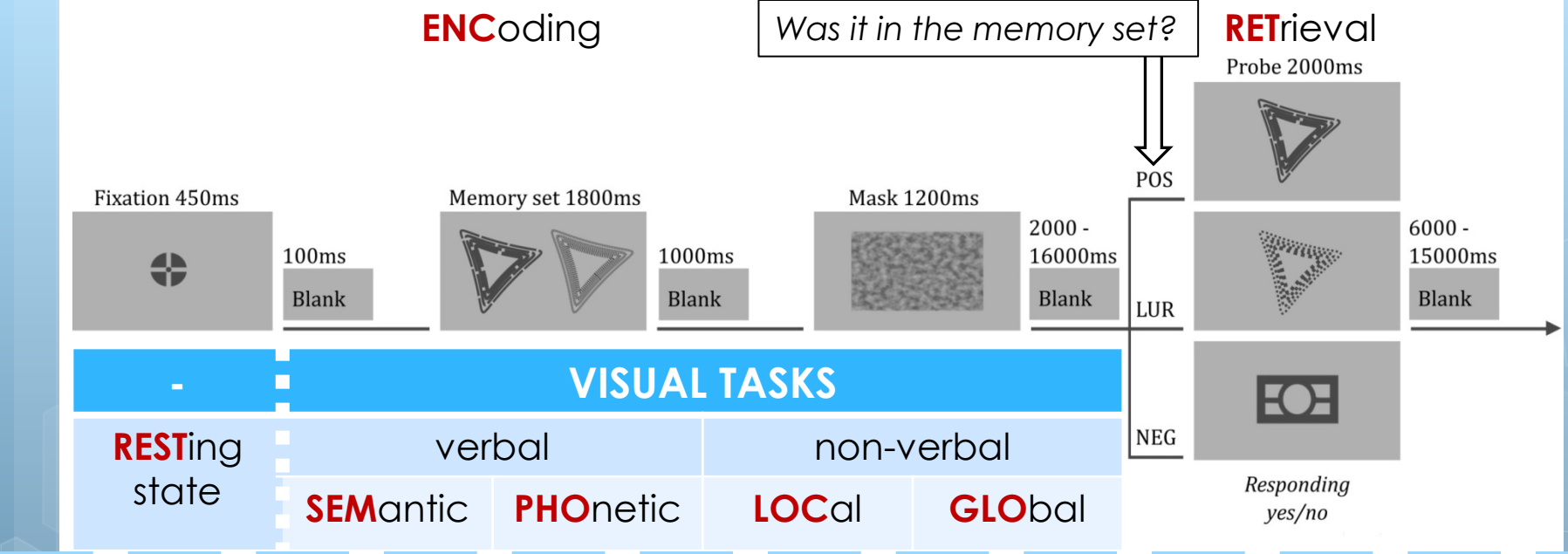
Ochab JK, Wątorek M, Ceglarek A, Fafrowicz M, Lewandowska K, Marek T, et al. Scientific Reports. 2022;12(1):17866.

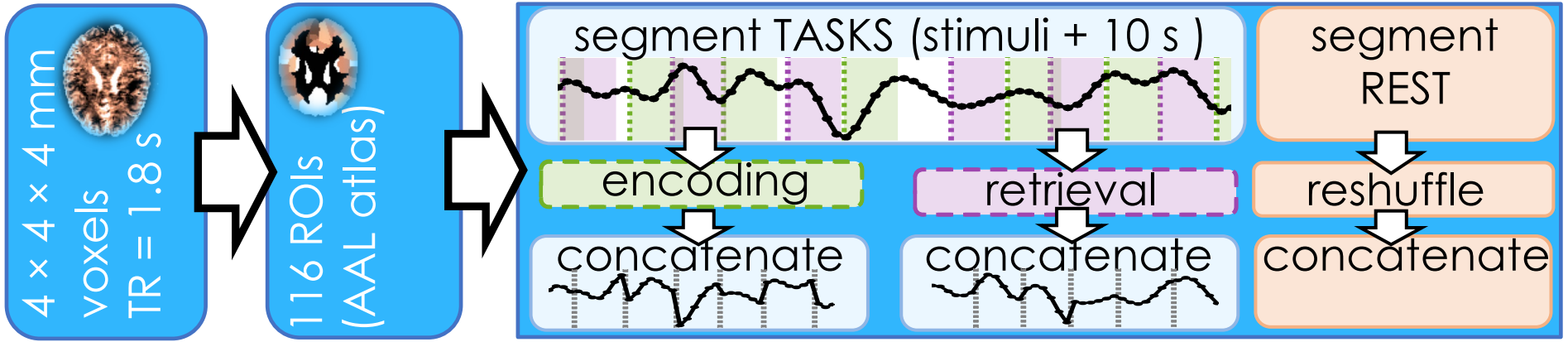


- 54 subjects (32 f., age: 24.17±3.56) selected with Pittsburgh Sleep Quality Index, Epworth Sleepiness Scale and genetic testing for the polymorphism of clock gene PER3, and divided into 26 morning-oriented and 28 evening-oriented types
- 2 sessions of modified DRM paradigm task: morning and evening

Lewandowska et al. Would you say "yes" in the evening? Time-of-day effect on response bias in four types of working memory recognition tasks. Chronobiol. Int. 35, 80–89 (2018).

J Deese (1959). Journal of Experimental Psychology, 58(1):17–22
HL Roediger and KB McDermott (1995). Journal of Experimental Psychology: Learning, Memory, and Cognition, 21(4):803–814
AS Atkins and PA Reuter-Lorenz (2011). NeuroImage, 56(3):1726–1734


ENCoding
Was it in the memory set?
RETrieval
Probe 2000ms
Fixation 450ms
100ms
Blank
Memory set 1800ms
1000ms
Blank
Mask 1200ms
2000 - 16000ms
Blank
POS
LUR
NEG
6000 - 15000ms
Blank
Responding yes/no
-
VISUAL TASKS
RESTing state
verbal
non-verbal
SEMantic
PHOnetic
LOCal
GLOBal


4 x 4 x 4 mm voxels TR = 1.8 s
116 ROIs (AAL atlas)
segment TASKS (stimuli + 10 s)
encoding
retrieval
concatenate
concatenate
segment REST
reshuffle
concatenate

Detrended fluctuation analysis

Take a time series

$$X(j) = \sum_{i=1}^{j} [x_i - \langle x \rangle]$$

detrend and sum MSE

$$F^2(\nu, s) = \frac{1}{s} \sum_{k=1}^{s} \left[X((\nu - 1)s + k) - P_\nu(k) \right]^2$$

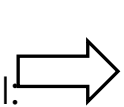
average fluctuation in segments

$$F(s) = \left\{ \frac{1}{2N_s} \sum_{\nu=1}^{2N_s} F^2(\nu, s) \right\}^{1/2}$$

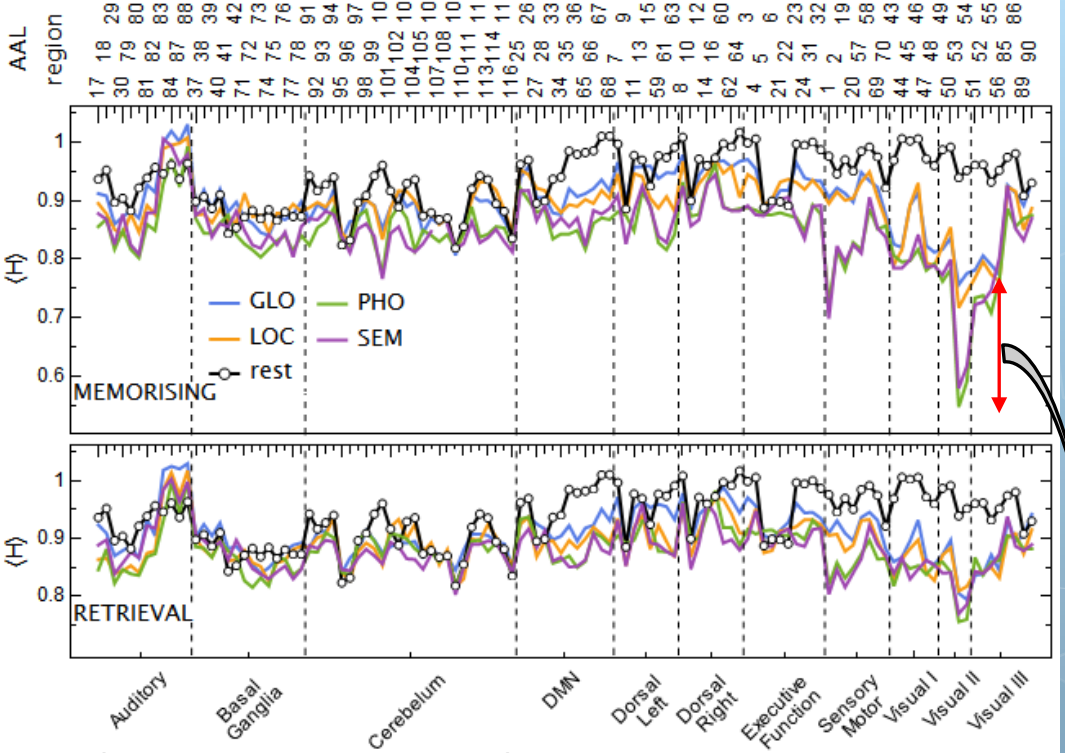
get Hurst exponent

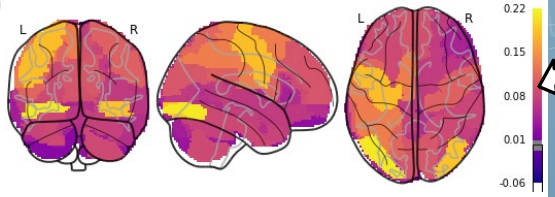
$$F(s) \sim s^H$$

short-range correlated:
H = 0.5
long-range monofractal:
0<H<0.5 (antipersistent)
0.5<H<1 (persistent)



persistent (temporally correlated) behaviour differences in specific areas between conditions





C-K Peng et al. (1994). Physical review E, 49(2):1685
P Oświęcimka at al. (2006). Physical Review E 74, 016103

Detrended cross-correlation

Take 2 time series

$$X(j) = \sum_{i=1}^{j} [x_i - \langle x \rangle] \quad Y(j) = \sum_{i=1}^{j} [y_i - \langle y \rangle]$$

detrend and sum MSE

$$F^2_{XY}(\nu, s) = \frac{1}{s} \sum_{k=1}^{s} [X((\nu-1)s + k) - P_{X,\nu}(k)] \times [Y((\nu-1)s + k) - P_{Y,\nu}(k)]$$

average fluctuation in segments

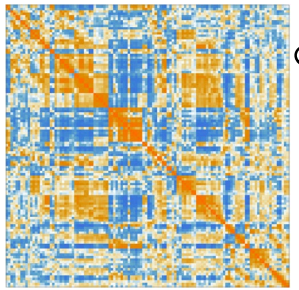
$$F^q_{XY}(s) = \frac{1}{2N_s} \sum_{\nu=1}^{2N_s} \mathrm{sgn}(F^2_{XY}(\nu, s)) \left[F^2_{XY}(\nu, s)\right]^{q/2}$$

correlation matrix

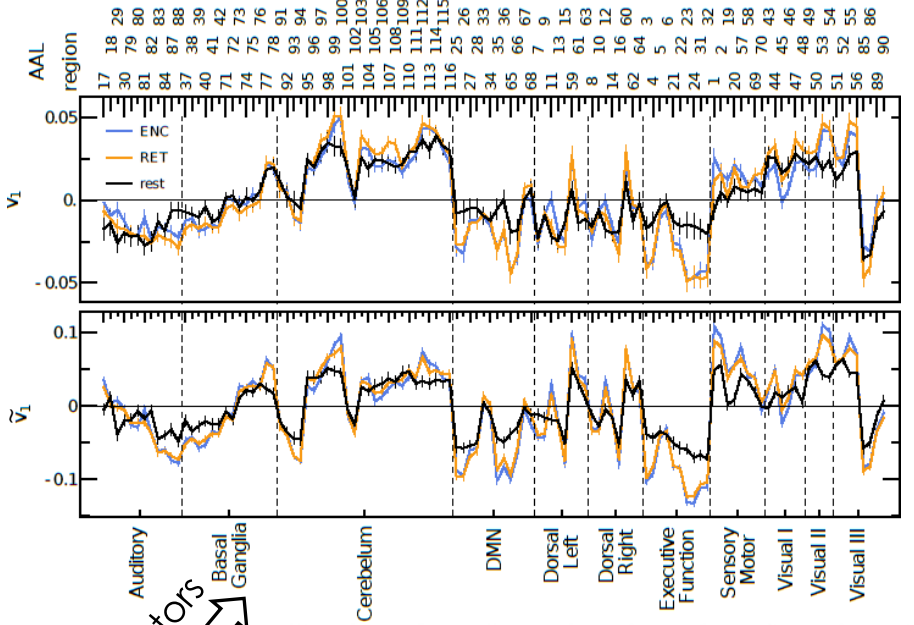
$$\rho(q, s) = \frac{F^q_{xy}(s)}{\sqrt{F^q_{xx}(s) F^q_{yy}(s)}}$$

Time scale dependence

Fluctuation size dependence



eigenvectors



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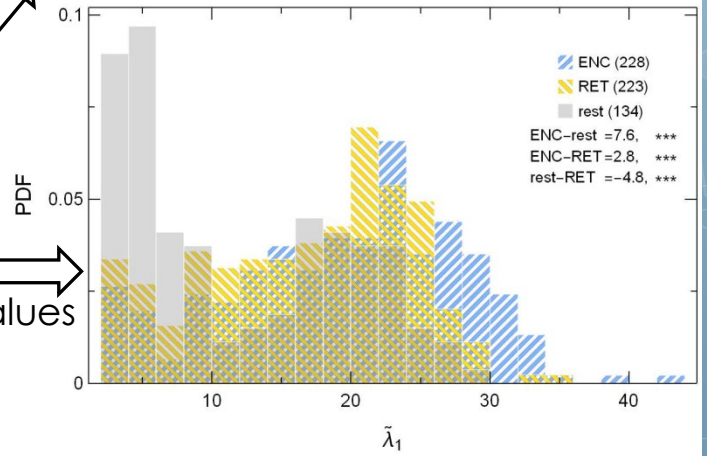


P Oświęcimka et al. (2014). Physical Review E, 89(2):023305

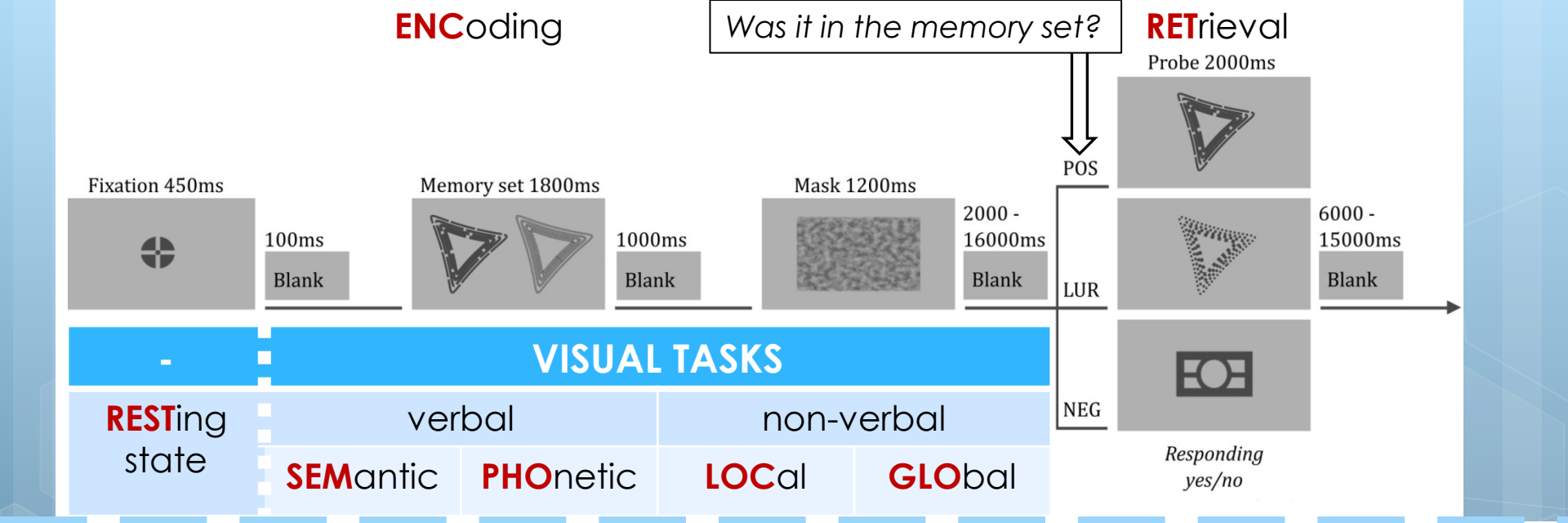
J Kwapień et al. (2015). Physical Review E, 92(5):052815

fMRI (functional magnetic resonance imaging)

Data: Working memory task

Technique: Machine Learning

Tutajewski M, Sieradzki I, Ochab JK, et al. *Classification of ROI-based fMRI data in short-term memory tasks using discriminant analysis and neural networks*. (submitted).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Was it in the memory set?
RETrieval
Probe 2000ms
Fixation 450ms
100ms
Blank
Memory set 1800ms
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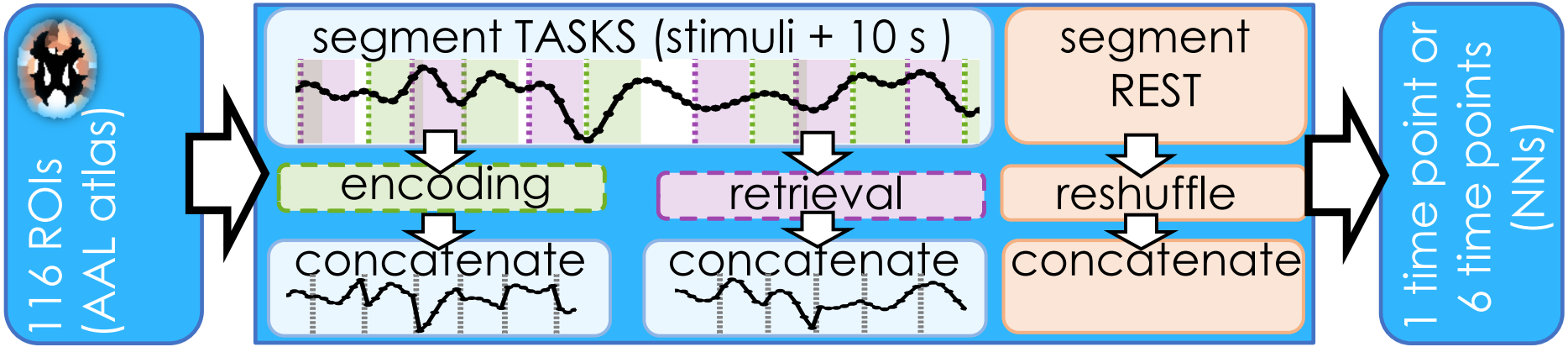
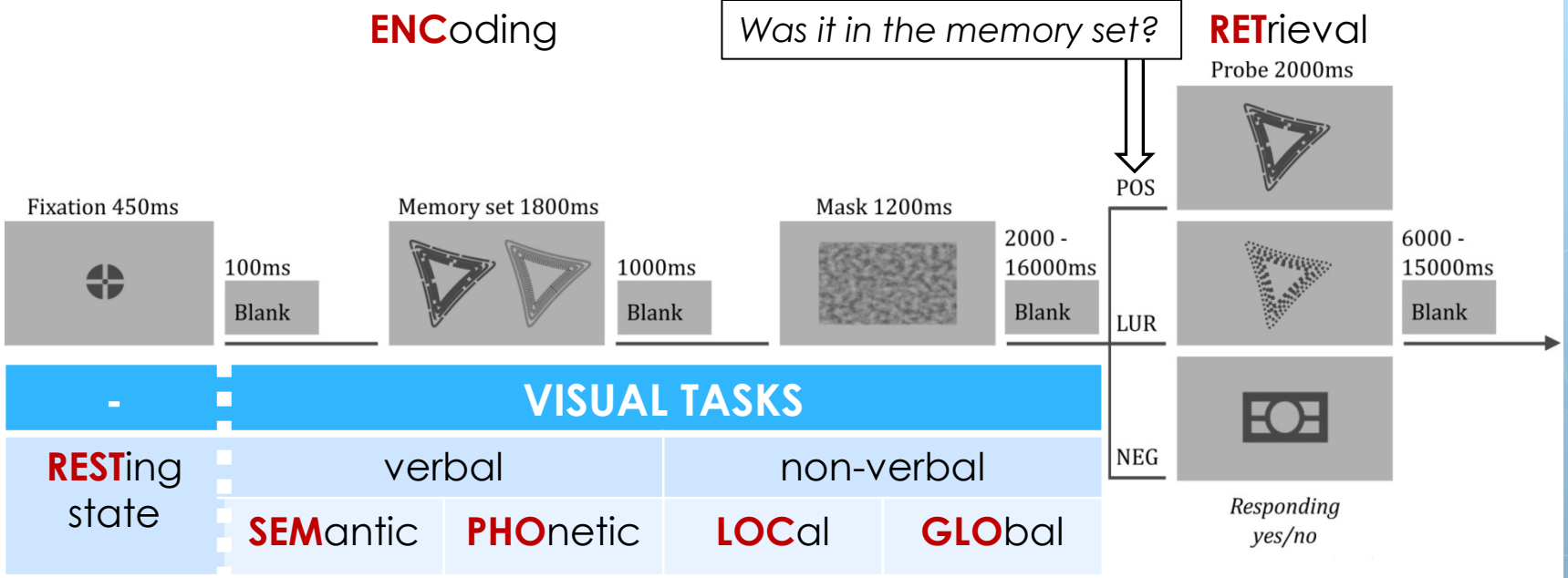
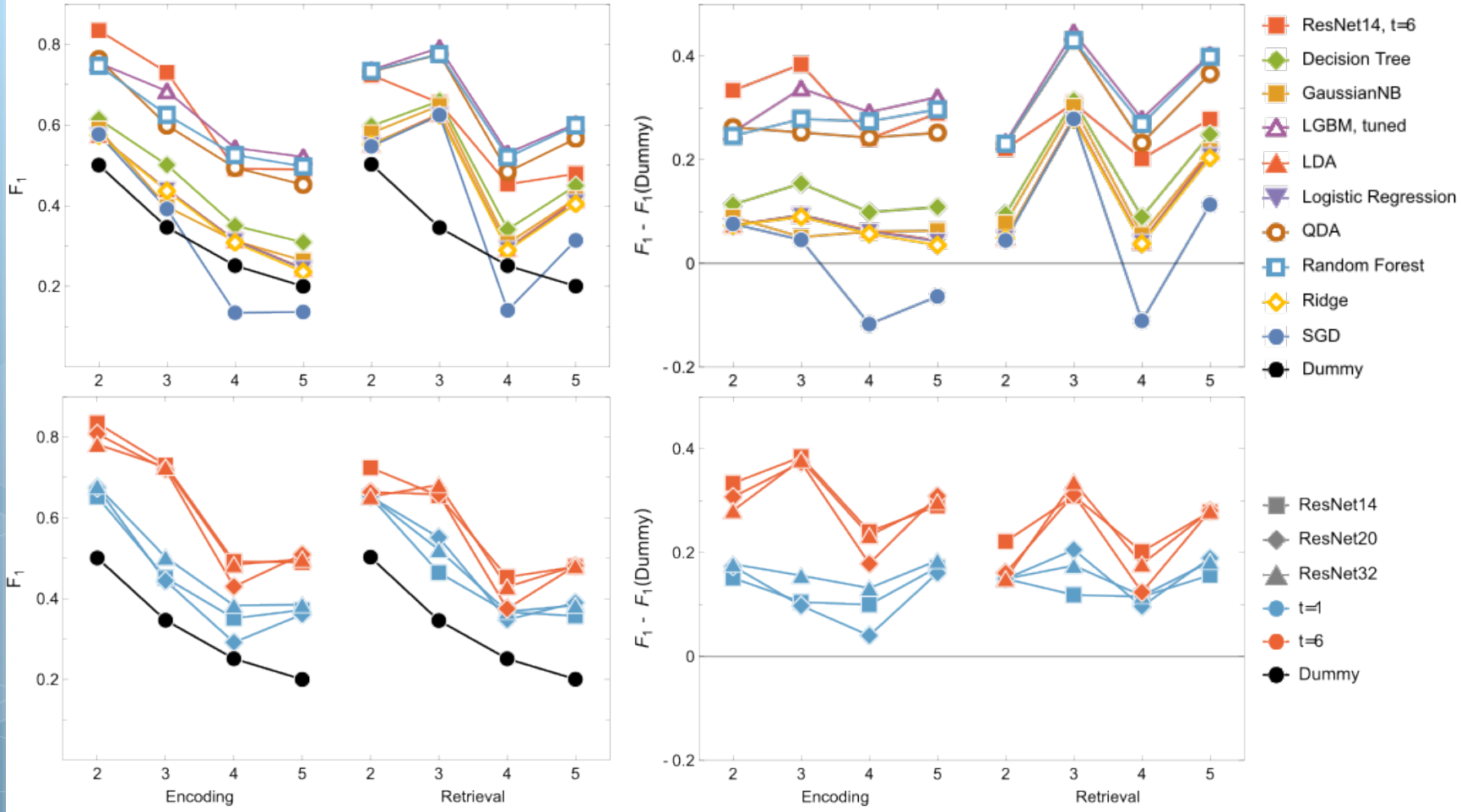
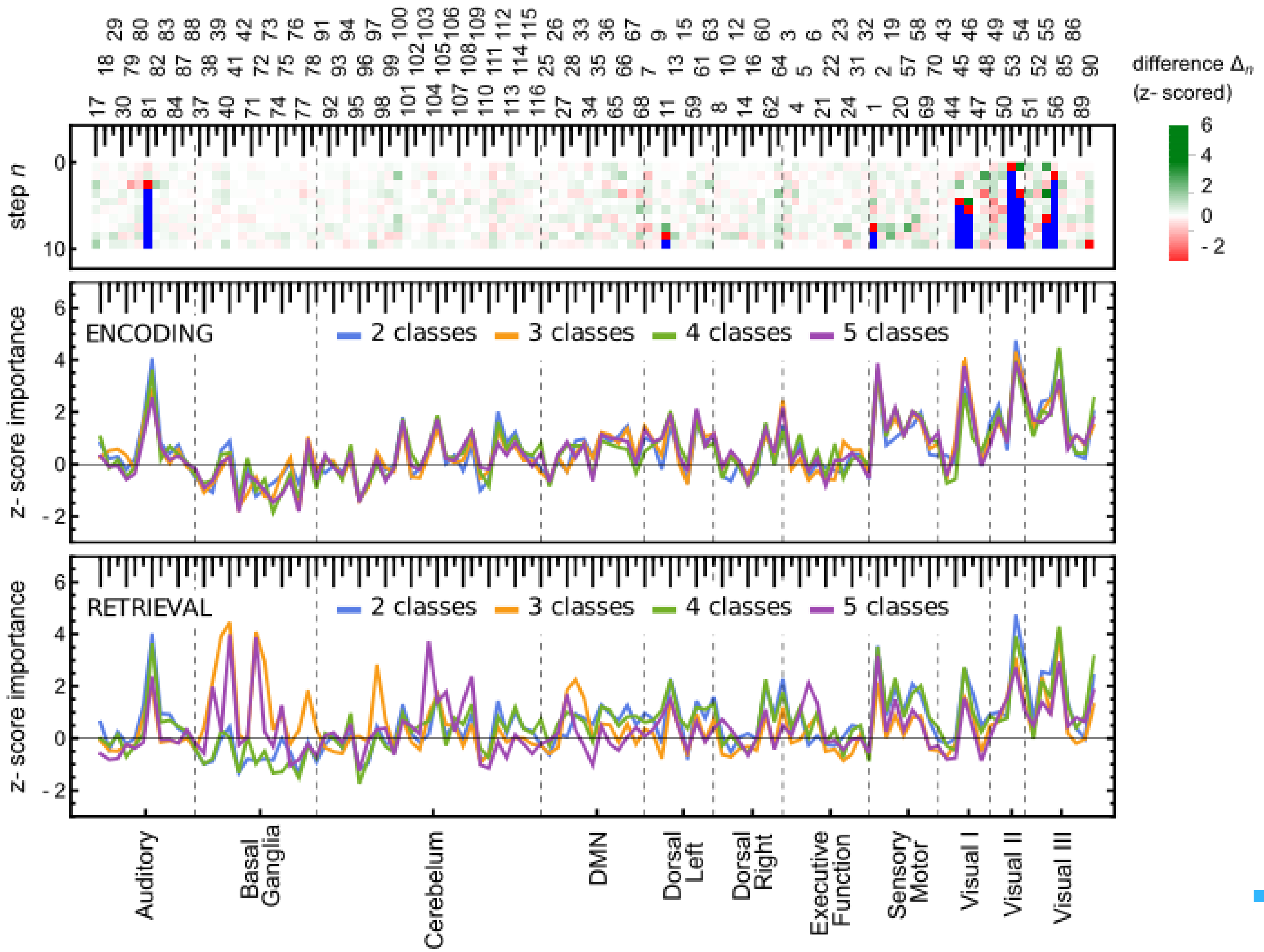
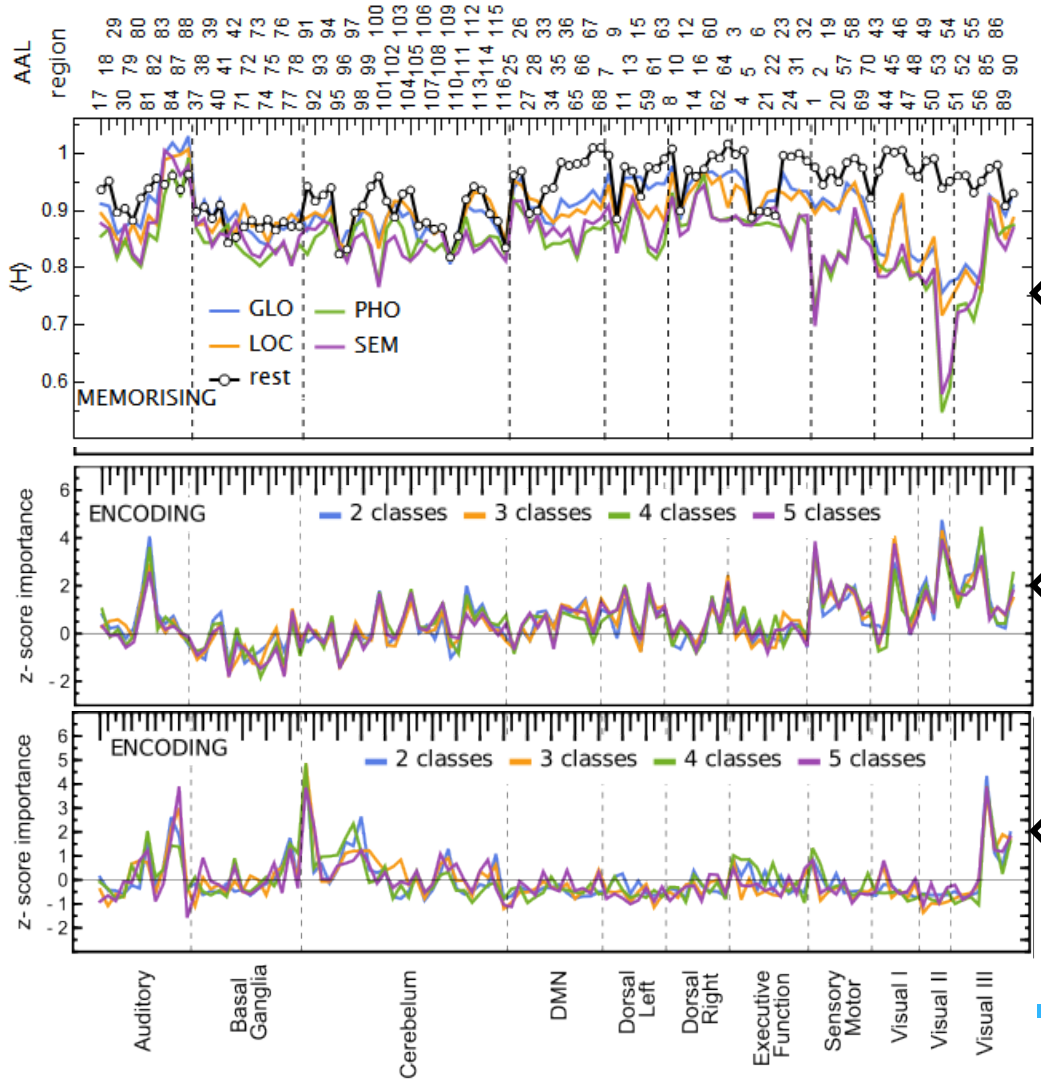

116 ROIs (AAL atlas)
segment TASKS (stimuli + 10 s)
encoding
retrieval
concatenate
concatenate
segment REST
reshuffle
concatenate
1 time point or 6 time points (NNs)



Experiment name	Class 1	Class 2	Class 3	Class 4	Class 5
ENC2	GLO, LOC	SEM, PHO			
ENC3	GLO, LOC	SEM, PHO	REST		
ENC4	GLO	LOC	SEM	PHO	
ENC5	GLO	LOC	SEM	PHO	REST
RET2	GLO, LOC	SEM, PHO			
RET3	GLO, LOC	SEM, PHO	REST		
RET4	GLO	LOC	SEM	PHO	
RET5	GLO	LOC	SEM	PHO	REST


F1
F1 - F1(Dummy)
Encoding
Retrieval
ResNet14, t=6
Decision Tree
GaussianNB
LGBM, tuned
LDA
Logistic Regression
QDA
Random Forest
Ridge
SGD
Dummy
ResNet14
ResNet20
ResNet32
t=1
t=6
Dummy


difference Δ_n (z-scored)
step n
ENCODING
RETRIEVAL
2 classes
3 classes
4 classes
5 classes
z-score importance
Auditory
Basal Ganglia
Cerebelum
DMN
Dorsal Left
Dorsal Right
Executive Function
Sensory Motor
Visual I
Visual II
Visual III



Hurst

LGBM

ResNet

EEG (electroencephalography)

Data: Multiple-sclerosis

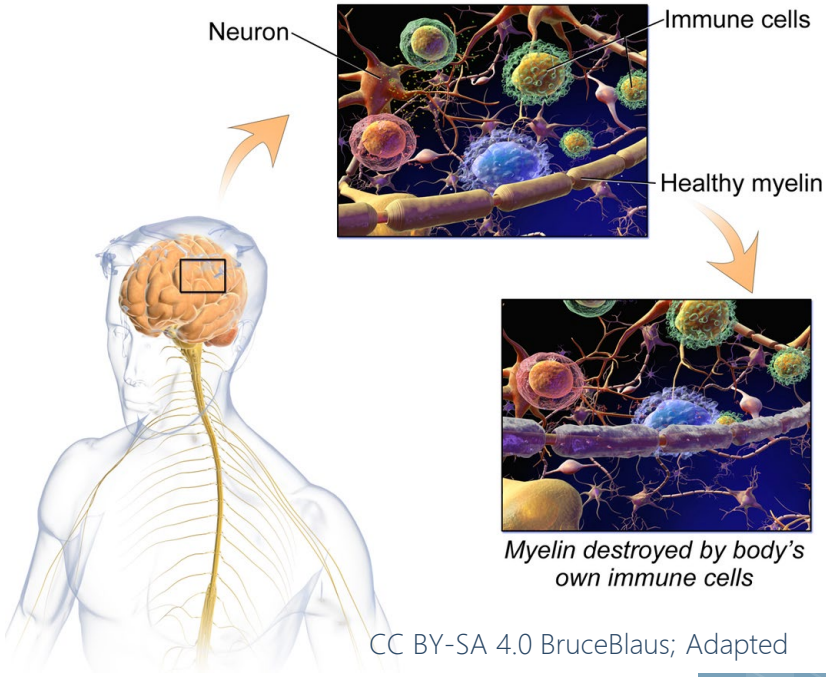
Technique: Multifractality

Wątorek M et al., „Multifractal organization of EEG signals in Multiple Sclerosis" (in review). 2023.

Multiple sclerosis

Multiple sclerosis (MS) is a chronic immune-mediated disease, the most common nontraumatic disorder of the central nervous system. Symptoms, depending on the lesion areas, include: fatigue, optic neuritis, depression, heat sensitivity, dizziness, numbness, loss of balance and cognitive dysfunction.

> 2.8 million people with MS worldwide!*



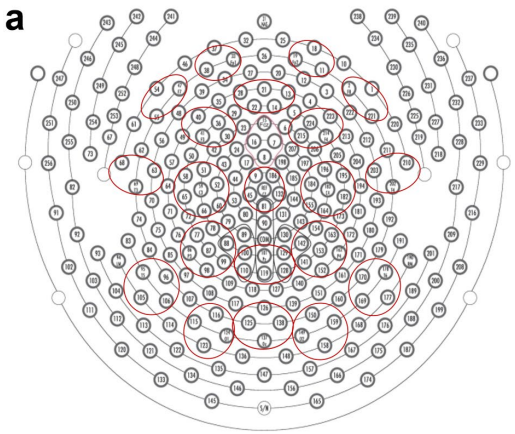
* C.Walton et al., Mult. Scler. 26(14), 1816 (2020)

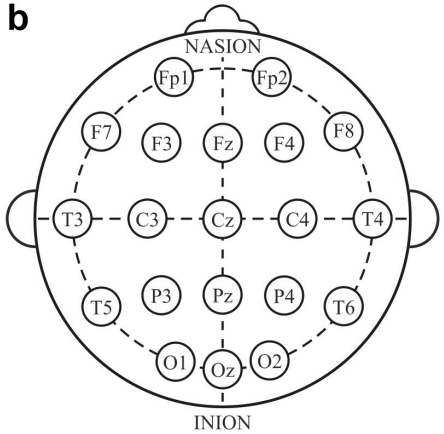
Experiment

- 38 MS patients
  (age: 34.3±2.97, 19 females)
  from Jagiellonian University's
  Multiple Sclerosis Clinic and
  27 healthy controls
  (age: 35.6±2.79, 16 females)
- prior to the study, all the patients were diagnosed with early onset relapsing remitting multiple sclerosis (RRMS) with **Expanded Disability Status Scale** (EDSS) score from 0 to 3.5 points (mean: 1.2±0.84)
- **Aims:** correlates of disease duration, EDSS, farmacotherapy

Data

- dense array EEG (256 electrodes) averaged to 20 channels
- 1000 Hz sampling rate





Multifractal DFA

q-dependent fluctuation function

$$F_q(s) = \left\{ \frac{1}{2N_s} \sum_{\nu=1}^{2N_s} [F^2(\nu, s)]^{q/2} \right\}^{1/q}$$

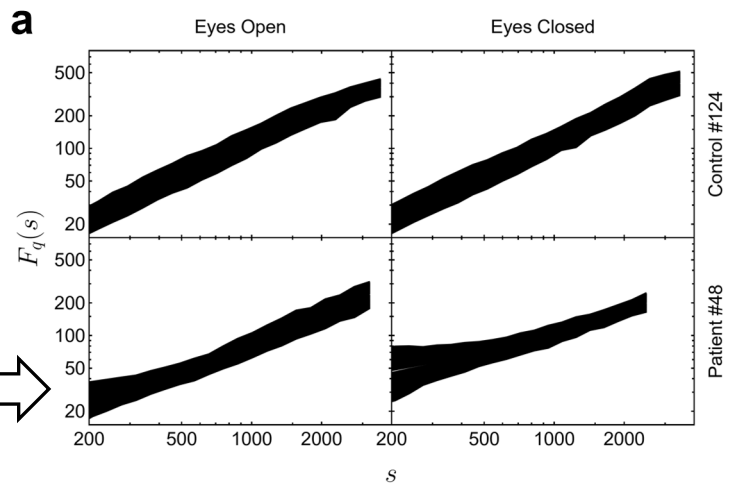
a family of generalised Hurst exponents *h(q)*:

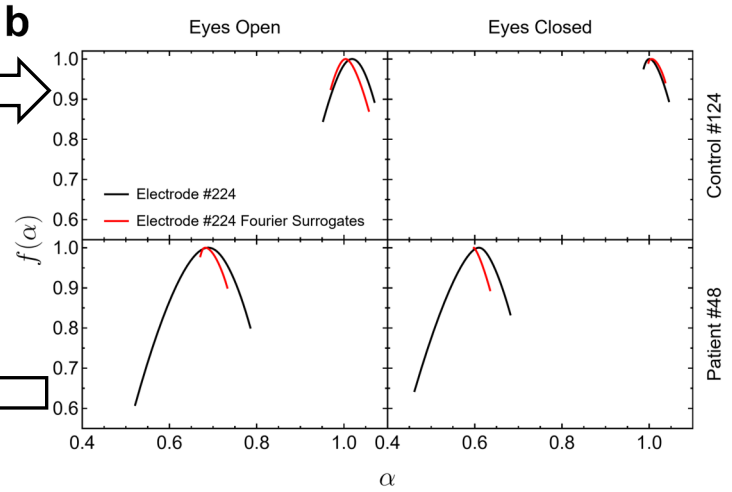
$$F_q(s) \sim s^{h}(q)$$

leading to a multifractal/ singularity spectrum of Hölder exponents *f(a)* given by

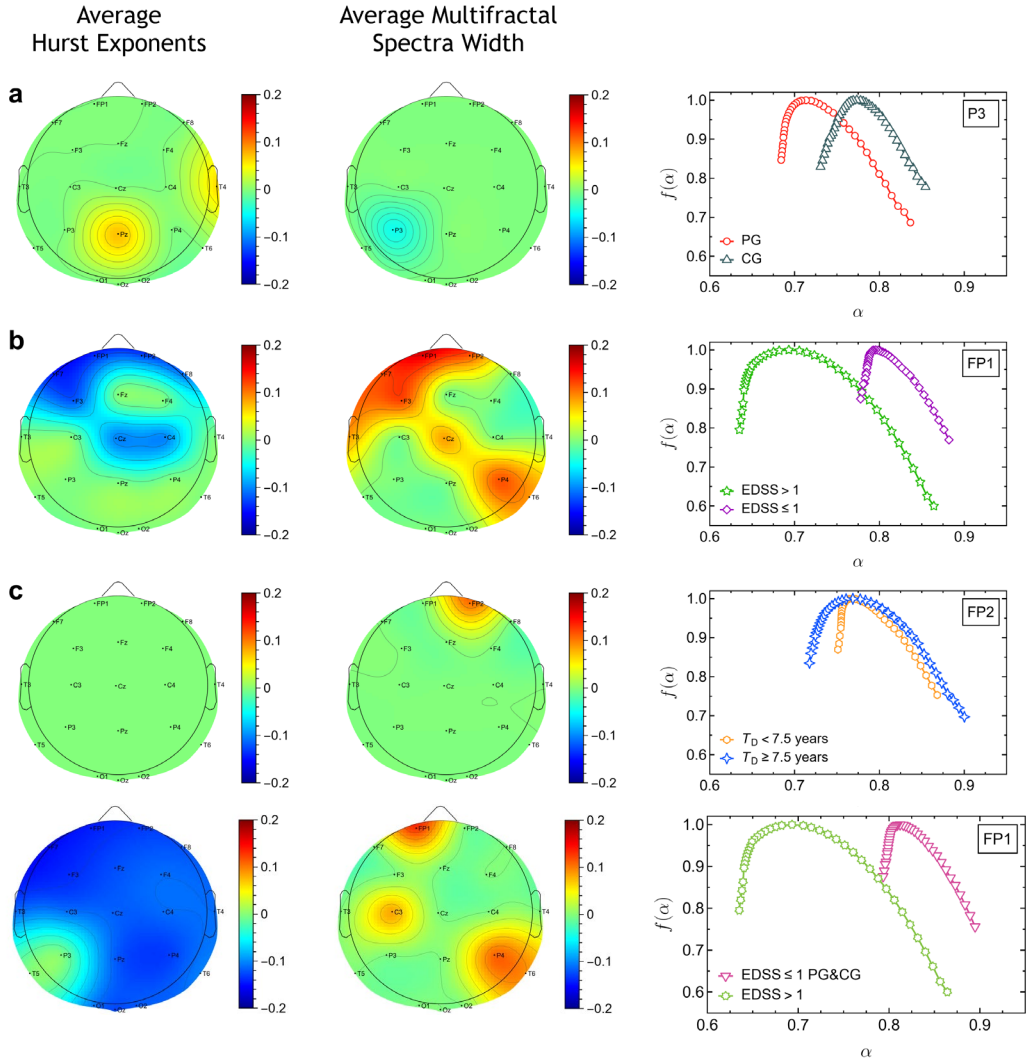
$$\alpha = h(q) + qh'(q)$$
$$f(\alpha) = q(\alpha - h(q)) + 1$$

f(a) – a fractal dimension of a subset of the time series with singularities of magnitude *a*

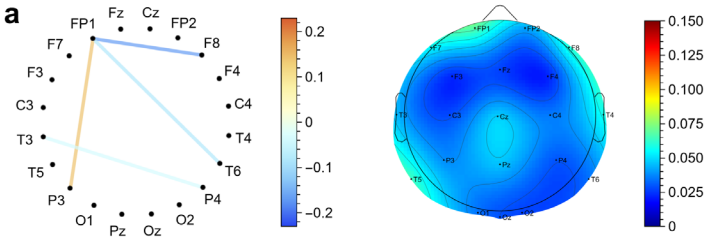




Spectrum located at:
a = 0.5 (weak linear autocorr.)
a<0.5 (negative autocorrelation)
a>0.5 (positive autocorrelation)



- Control group and patients
- Patients with EDSS > 1 and patients with EDSS ≤ 1
- Patients with the disease duration ≥ 7.5 and < 7.5 years
- Patients with EDSS > 1 and the combined group of patients with EDSS ≤ 1 and controls.

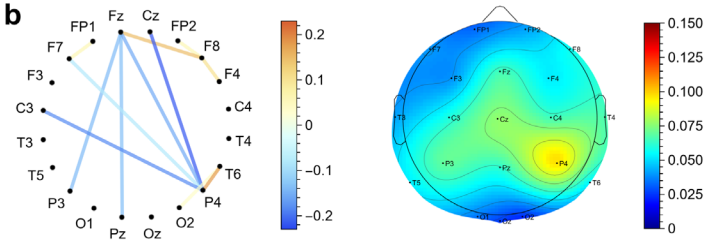


- Control group and patients

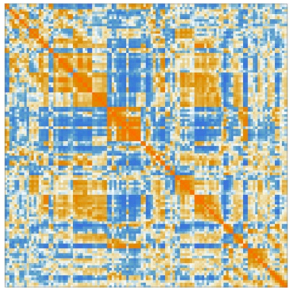
$$\rho(q,s) = \frac{F^q_{xy}(s)}{\sqrt{F^q_{xx}(s)F^q_{yy}(s)}}$$

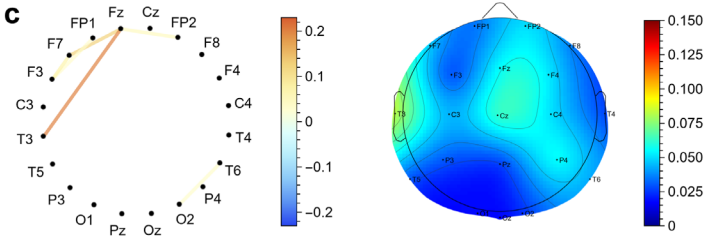
Time scale dependence

Fluctuation size dependence

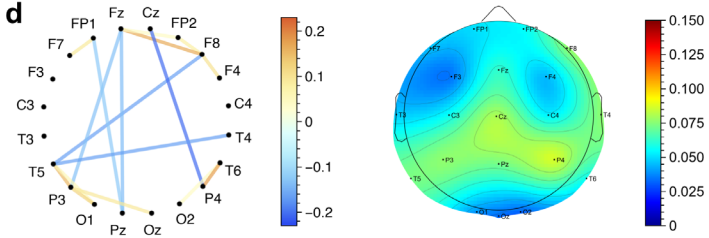


- Patients with EDSS > 1 and patients with EDSS≤1





- Patients with the disease duration ≥ 7.5 and < 7.5 years



- Patients with EDSS > 1 and the combined group of patients with EDSS ≤ 1 and controls.

Conclusions

Hurst exponents of fMRI signals and their detrended cross-correlations:

- are sensitive to the type of task the brain is processing
- are different for people with and without cognitive dysfunction (plus some local differences in multifractal spectra)

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