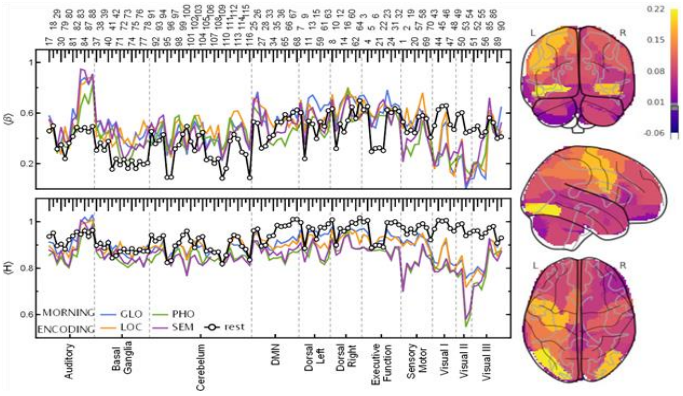
Fractal and multifractal organisation of neuroimaging signals in cognitive tasks and in disease

Anna Ceglarek[1], Magda Gawłowska[1], **Jeremi Ochab[1]**, Paweł Oświęcimka[1,2], Wojciech Tomczyk[1], Marcin Wątorek[1,3]

[1]Jagiellonian University, Kraków, Poland, [2]Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland, [3]Cracow University of Technology, Kraków, Poland

In this contribution, we present A) a detrended fluctuation analysis of functional magnetic resonance imaging (fMRI) data from a working memory experiment and B) a multifractal analysis of the electroencephalography (EEG) data obtained from patients with multiple sclerosis (MS). fMRI and EEG signals are notoriously challenging to analyse due to their very low temporal and spatial resolution, respectively, and a non-trivial auto-correlation and cross-correlation structure. In A), we applied fractal analysis to investigate how a person is memorising and retrieving information in four types of experimental tasks: two visual-verbal (based on lists of semantically or phonetically associated words) and two non-verbal (pictures of similar objects). The regional brain activity was quantified with the Hurst exponent (see Fig. 1) and Detrended Cross-Correlation Analysis (DCCA) [1,2]. We clearly observe 1/f signature in most brain areas, a reduction of persistent behaviour in tasks relative to the spontaneous brain activity and regional dependence of exponents depending on the tasks and the stage of the experiment (memorising the stimuli or information retrieval). We uncover such regionally coordinated changes also by analysing eigensystems of detrended correlation matrices (which turn out to be more sensitive than Pearson correlations). In B), we compared the complexity of the EEG time series, paying particular attention to analysing the correlations between the degree of multifractality, disease duration, and level of disease progression quantified by the Expanded Disability Status Scale (EDSS). We used Multifractal Detrended Fluctuation Analysis [3], a generalisation of the DFA which is a robust tool for multilevel characterisation of time series (e.g., see [4]) and specifically other types of brain signals [5]. Based on the generalised Hurst exponents, we obtained the multifractal/singularity spectrum of the Hölder exponents [6], f(α). To quantify the coupling between the brain regions we again used the DCCA. Our results reveal a significant correspondence between the complexity of the time series and the stage of multiple sclerosis progression. Namely, we identified brain regions whose EEG signals were characterised by a well-developed multifractality (the estimated multifractal spectra take the shape of asymmetrical parabolas with larger widths Δα) and lower persistence of the time series (spectra localised above but closer to α=0.5) for patients with a higher level of disability, whereas for the control group and patients with low-level EDSS they were characterised by monofractality and higher persistence. The link between multifractality and disease duration has not been observed. Our conclusions are supported by the cross-correlations analysis.



References

[1] P. Oświęcimka, S. Drożdż, M. Forczek, S. Jadach, J. Kwapień, Phys. Rev. E. 89(2), 023305 (2014).
[2] J. Kwapień, P. Oświęcimka, S. Drożdż, Phys. Rev. E. 92(5), 052815 (2015).
[3] J.W. Kantelhardt, S.A. Zschiegner, E. Koscielny-Bund, S. Havlin, A. Bunde, H.E. Stanley, Physica A 316(1), 87-114 (2002).
[4] P. Oświęcimka, S. Drożdż, M. Frasca, R. Gbarowsk, N. Yoshimur, et al., Nonlinear Dyn., 100(2), 1689-704 (2020).
[5] J.K. Ochab, M. Wątorek, A. Ceglarek, M. Fafrowicz, K. Lewandowska, T. Marek, et al., Sci. Rep. 12(1) ,17866 (2022).
[6] T.C. Halsey, M.H. Jensen, L.P. Kadanof, I. Procaccia, B.I. Shraima, Phys. Rev. A. 33(2), 1141 (1986).