Seeking for a fingerprint: analysis of point processes in actigraphy recordings

Ewa Gudowska-Nowak

Plus ratio quam vis

M. Kac Center Complex Systems Research Center, M. Smoluchowski Institute of Physics
and Malopolska Center of Biotechnology
Jagiellonian University in Kraków, Poland

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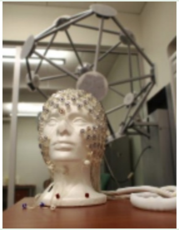
Motivation: Self-similarity and anomalous diffusion in cognitive science

Ubiquity of power-law scaling (in general, non-Gaussian fluctuations!) and other manifestations of fractal and self-similar patterns (both in time/space) have been detected at all levels of neural organization...

- dynamics of channel gating in neuronal membranes
- neurons discharge patterns (trains of neuron spikes)
- temporal structure and long-range correlations in EEG signals
- "brain criticality" - detection of neural avalanches in fMRI dynamics
- measures of temporal organization ?, universality ?
- markers of pathophysiology of neurobehavioral diseases ?

Scale invariance in human motor activity



Collaboration/Funding

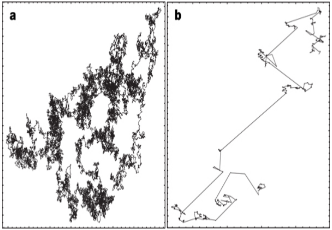
- *Mark Kac Center for Complex Systems Research, Malopolska Center of Biotechnology, Jagiellonian University, Kraków*, M.A. Nowak, E. Gudowska-Nowak, K. Oleś, J.K. Ochab, J. Szwed
- *Department of Cognitive Neuroscience and Neuroergonomics JU, Kraków*, T. Marek, M. Fąfrowicz, A. Domagalik, H. Ogińska
- *CONICET, Buenos Aires, Argentina*, D.R. Chialvo
- *Institute for Medical Psychology, Albrechts University, Kiel*, E. Tagliazucchi

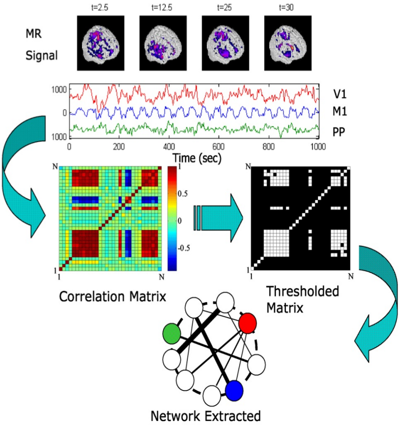
Criticality in neural systems...

P. Bak *Life laws* Nature **391** 652 (1998)
D. Chialvo *Complex emergent neural dynamics* Nature Physics **6** 744 (2010)

E. Niebur, D. Plenz, H.G. Schuster *Criticality in neural systems* Wiley (2013) ISBN 978-3-527-41104-7

$$\langle x^2(t) \rangle \propto t^{\gamma}$$

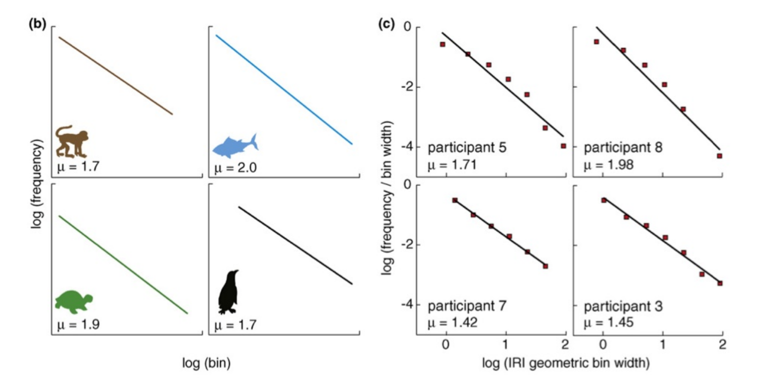




Spontaneous fluctuations of fMRI data show anomalous behavior of the variance and divergence of the correlation length

$$p(x) \propto x^{-(1+\alpha)}, \alpha < 2$$

Reaction time and word finding, Lévy strategies



C. T. Kello et al., Trends in Cognitive Sciences, **14** 232 (2010)

Scale invariance

Patterns of animal foraging or human communication in social networks exhibit complex self-similar properties reproducible over multiple time scales

A. Proekt et al., PNAS, **109** 10564 (2012)

Table 1. Timing of many diverse behaviors is scale-invariant

Examples of scale-free dynamics	Scaling exponent (β + 1)
Time intervals between e-mail communications (2)	~1
Time it took Einstein and Darwin to reply to letters (3)	~3/2
Times that a human stays within a small area based on currency dispersal (4)	~1.6
Times that a human stays within a small area based on phone records (5)	~1.8
Times between movie ratings on Netflix (6)	~1.5–2.7
Times between car movements in Florence (7)	~0.97
Times between print job submissions (8)	~1.76
Times between hospitalizations for exacerbations of schizophrenia (9)	~1.21
Times that a healthy human stays at rest (10)	~1.9
Times that a depressed human stays at rest (10)	~1.7
Waiting times during foraging of spider monkeys (11)	~1.7
Lengths of step sizes (or times between changes in direction) during foraging of marine predators (12, 13)	1.4–3
Times between turns of a fruitfly in a featureless environment (14)	1–2
Times between turns of a fruitfly tracking an odor (15)	~1.3
Times that a mouse rests (16)	1.97
Times that a rat rests (17)	1.7

Scale-invariant distribution of time intervals characterizing the dynamics of many behaviors follow a power law—the probability of occurrence of a time interval (t) is $p(t) \sim t^{-(\beta+1)}$.

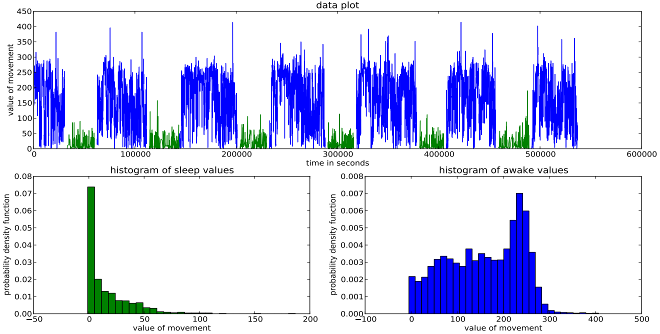
Example: actigraphy studies of spontaneous behavior

Ochab J., Tyburczyk J., Beldzik E., Chialvo D.R., Domagalik A., Fafrowicz M., Gudowska-Nowak E., Marek T., Nowak M.A., Oginska H., Szwed J. *Scale free fluctuations in behavioral performance: delineating changes in spontaneous behavior of humans with induced sleep deficiency* PLoS One **9** e107542 (2014)

- Actigraphy measurements were performed on healthy individuals over one week of their normal life [rested wakefulness (RW)] and one week of partial sleep deprivation (SD)
- The circadian cycle of both groups differs substantially: while RW individuals have relatively long nights and short days, members of the SD group are characterized by a reversed pattern of longer days and shorter nights, which clearly influences their activity/rest patterns.
- To overcome this problem normalization of the days and nights of both groups to the same length has been performed, followed by a statistical analysis.
- Bouts of activity/rest obey different distributions of duration

Accelerometer recordings

spontaneous locomotor activity of healthy individuals has been recorded a) during a week of regular sleep and b) and a week of chronic partial sleep deprivation

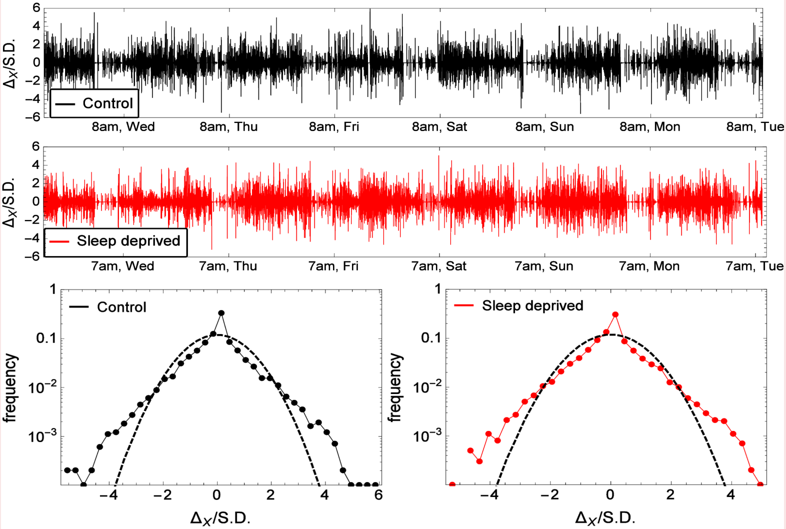


transformed signal components...

$$\dot{X}(t) + \int_{-\infty}^{t} \Lambda(\tau) X(\tau) = Y(t) + A \sin \Omega t + \xi(t)$$

Actigraphy studies

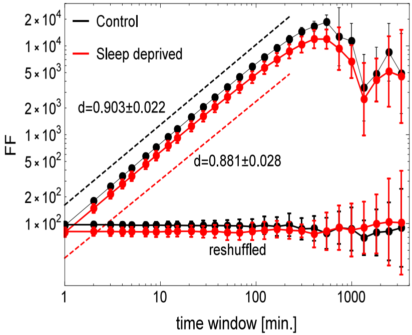
Non-Gaussian process

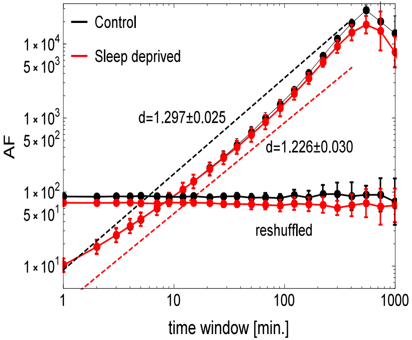


Character of the event counts: point process

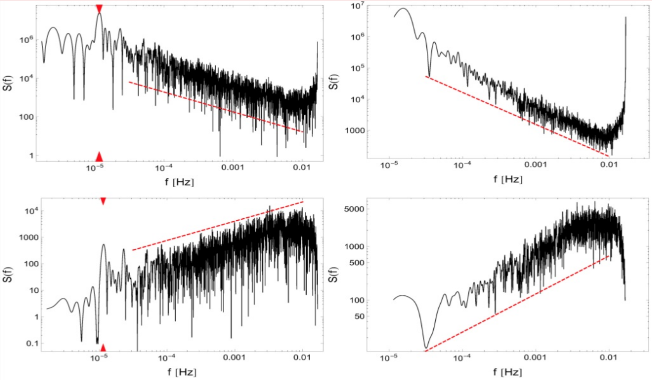
Measures of events clustering in time

$$FF = \frac{\langle N_k^2 \rangle - \langle N_k \rangle^2}{\langle N_k \rangle} \qquad AA = \frac{\langle (N_{k+1} - N_k)^2 \rangle}{2 \langle N_k \rangle}$$





Temporal universality of signal $I(t)$ for a typical subject



Spectral densities evaluated (left panel) for one-week experimental time series and (right panel) for 24 hr periods averaged over the week. $1/f^{\eta}$ slopes (dashed lines) with $\eta = 1.03 \pm 0.02$ (left panel) and $\eta = 1.09 \pm 0.02$ (right panel), respectively. Lower panels: similar spectral analysis for the time series of increments - $\eta' = -0.73 \pm 0.02$ (left panel) and $\eta = -0.71 \pm 0.02$ (right panel).

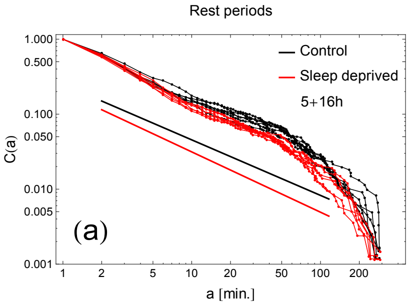
Character of the event counts: dwell time distribution

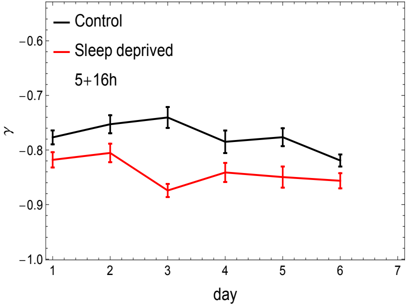
Dynamics of spontaneous fluctuations between activity and rest

$$C(a) = Pr\,(T \geq a) = \int_a^{\infty} p(t)dt = 1 - \int_{-\infty}^{a} p(t)dt = 1 - F(a)$$

$$Pr\,(t \leq T \leq t + dt | T \geq t) = \Lambda(t)dt$$

$$\Lambda(t)dt = -\frac{Pr(T \geq +dt) - Pr(T \geq t)}{Pr(T \geq t)} = -\frac{dPr(T \geq t)}{Pr(T \geq t)} = -\frac{dC(t)}{C(t)}$$





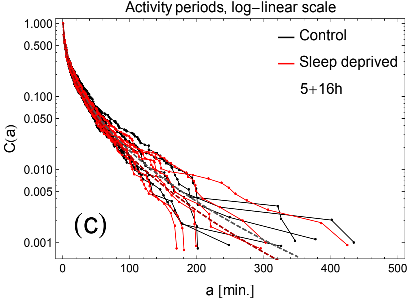
Character of the event counts: duration of activity states

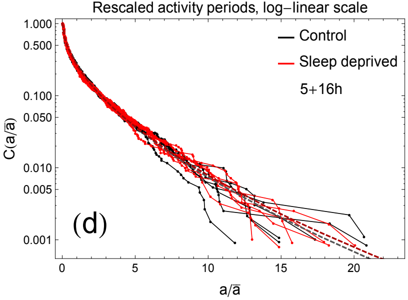
Dynamics of spontaneous fluctuations between activity and rest

$$C(a) = Pr\,(T \geq a) = \int_a^{\infty} p(t)dt = 1 - \int_{-\infty}^{a} p(t)dt = 1 - F(a)$$

$$C(a) \sim \exp\left(-Da^{\beta}\right)$$

$$\overline{\beta} = 0.49 \pm 0.03 \quad \overline{D} = 0.31 \pm 0.04$$





Summary of studies

Robustness of the results

- no clear difference between RW and SD individuals for the activity periods
- profiles of the rest periods cumulative distributions significantly different
- higher coefficient $\overline{\gamma} = 0.85 \pm 0.03$ for SD group - more short periods of rest than in the RW group (fewer longer inactivity time intervals than in the control group)
- findings contrast with the results for the rest-time distributions of depressed humans, where lower scaling exponentss γ (and heavier tails) in the cumulative distributions were observed

Nakamura T., Takumi T., Takano A., Aoyagi N, Yoshiuchi K, et al. *Of mice and men - universality and breakdown of behavioral organization* PloS One **3** e2050 (2008).
Nakamura T, Kiyono K, Yoshiuchi K, Nakahara R, Struzik Z, et al. *Universal scaling law in human behavioral organization* Phys. Rev. Lett. **99** 138103 (2007).

Character of the event counts: a model?

Dynamics of spontaneous fluctuations between activity and rest

$\frac{dC(t)}{dt} = -\Lambda(t)C(t)$

$$C(t) = e^{-\lambda t} \quad p(t) = \lambda e^{-\lambda t}$$

for a Poisson point process

Survival function under randomization of the rate $\Lambda(t)$

$$Pr(T \geq t|\Lambda = \lambda) = C(t|\Lambda \equiv \lambda) = e^{-\lambda t}$$
$$C(t) = \langle e^{-\lambda t} \rangle = \int_0^\infty e^{-\lambda t} dF_\Lambda(\lambda)$$
$$\text{effective } \Lambda(t) = -\frac{d}{dt} \log \int_0^\infty e^{-\lambda t} dF_\Lambda(\lambda)$$

Survival function under randomization of the rate $\Lambda(t)$

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$$\text{effective } \Lambda(t) = -\frac{d}{dt} \log \int_0^\infty e^{-\lambda t} dF_\Lambda(\lambda)$$

Examples

- Gudowska-Nowak E., Psonka-Antończyk K., Weron K., Taucher-Scholz G. *Distribution of DNA fragment sizes after irradiation with ions* Eur. Phys. J. E **30** 317 (2009)
- Dybiec B., Gudowska-Nowak E. *Subordinated diffusion and CTRW asymptotics* Chaos **20** 043129 (2010)
- Ochab J., Tyburczyk J., Beldzik E., Chialvo D.R., Domagalik A., Fafrowicz M., Gudowska-Nowak E., Marek T., Nowak M.A., Oginska H., Szwed J. *Scale free fluctuations in behavioral performance: delineating changes in spontaneous behavior of humans with induced sleep deficiency* PLoS One **9** e107542 (2014)
- Chialvo D.R., Gonzalez-Torrado A.M., Gudowska-Nowak E., Ochab J.K., Nowak M.A., Tagliazucchi E. *How we move is universal: scaling in the average shape of human activity* arXiv:1506.06717v1

Summary

- Higher values of derived exponents for sleep-deprived subjects signal less heavy tails of waiting time PDFs in an immobile state than in an analogous distribution in the control group and can be associated with restlessness/inquietude and increased variability (burstiness) of activity in recorded time series.
- Such alteration of locomotor behavior can be a representative sign of disorders related to sleep-deficiency and possibly, a valuable diagnostic fingerprint discriminating between healthy and depressed/disordered individuals.
- What is the underlying mechanism generating "criticality"? Correlations between "brain criticality" and perceptual and behavioral processes?

Work in progress

Interrelation between measures of scaling laws in actigraphy and EEG recordings