Unraveling Neural Complexity: Exploring the Separation of Oscillations and 1/f Noise in Neuroscience

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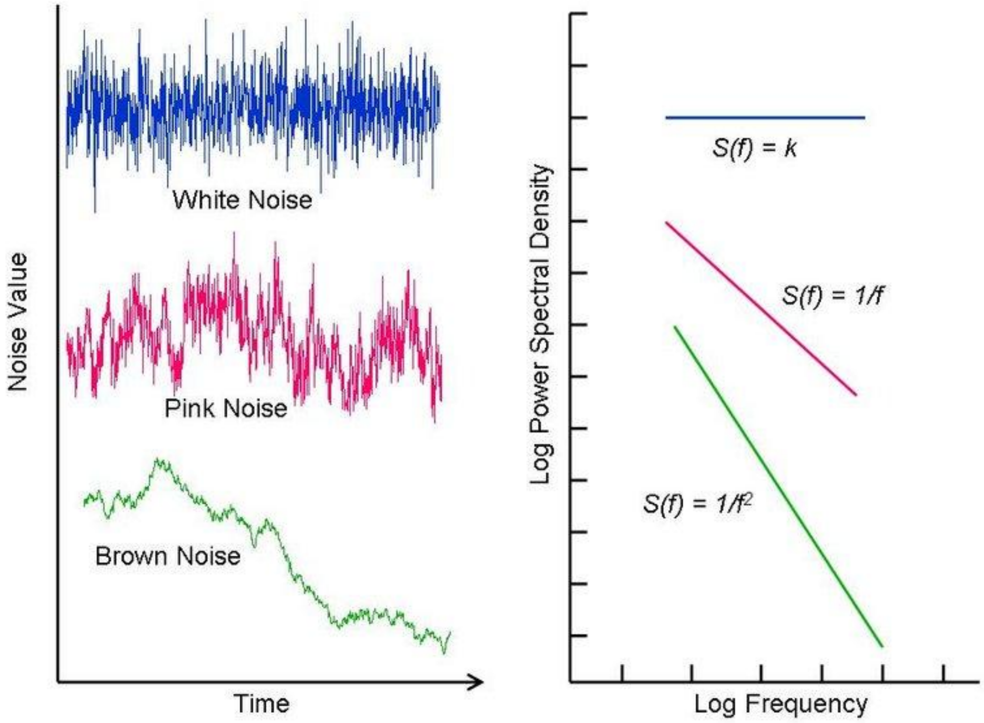
Outline

- Definition & History
- Examples in Neuroscience
- Hypotheses in Neuroscience
- How do we model aperiodic activity
- Tools and frameworks - IRASA vs. FOOOF
- Interactive demonstration with GUI
- Limitations and challenges of current methods
- Example with Sleep EEG data
- Tips & Recommendations

Definition & History

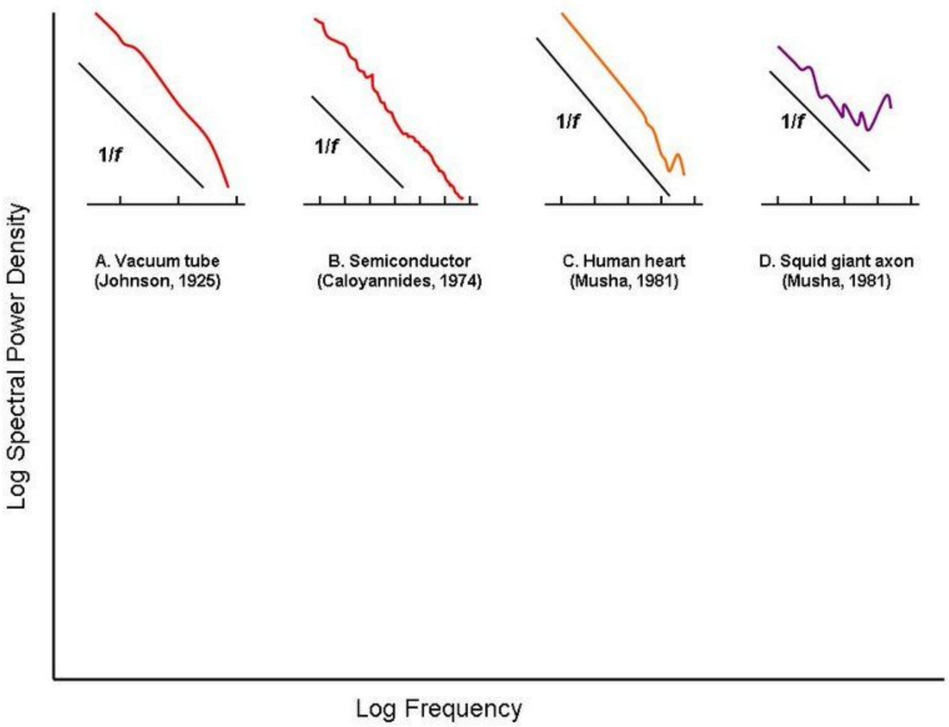
- Power spectral density (PSD) is inversely proportional to frequency, as the frequency increase, the PSD decays linearly in log-log space.



http://www.scholarpedia.org/article/1/f_noise

Definition & History

- 1/f noise was first observed discovered by Johnson [1] in 1925 in data from an experiment designed to test theory of shot noise in vacuum tubes.



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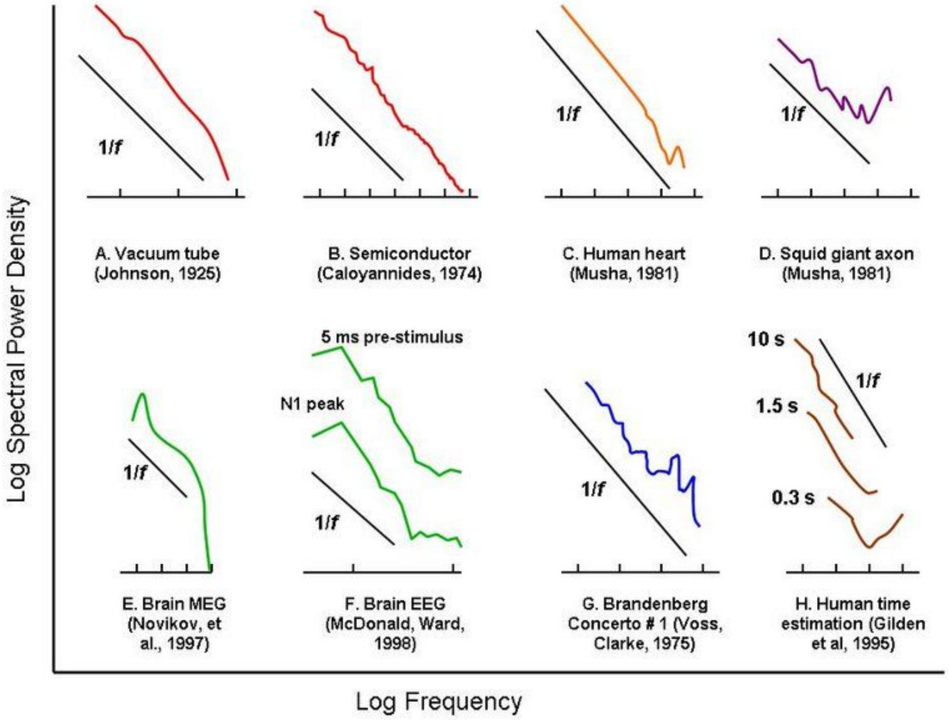
Definition & History

- 1/f noise was first observed discovered by Johnson [1] in 1925 in data from an experiment designed to test theory of shot noise in vacuum tubes.
- Subsequently observed in semiconductors [2], human heart rhythm [3], squid axons [3], M/EEG [4, 5], musical pieces [6], time perception [7], among others.
- Primacy of neural oscillations [8]



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Examples in Neuroscience

- Aperiodic exponent (β) for human voltage spectra: Mean = -3.1 (IQR: -4 to -2.5) for freqs >20 Hz [9]

β	Ref	Year	Recording modality	Frequency	Experimental condition
−0.08	[53]	2019	Scalp EEG (n=5)	20-40 Hz	Anesthesia (Ketamine)
−1.12	[19]	2022	Scalp EEG (n=16, control subjects)	1-40 Hz	Eyes closed
−1.3	[59]	2021	Scalp EEG (n=74, Tourette syndrome)	2-40 Hz	Behavioral experiments
−1.44	[59]	2021	Scalp EEG (n=74, control)	2-40 Hz	Behavioral experiments
−1.48	[19]	2022	Scalp EEG (n=18, stroke patients)	1-40 Hz	Stroke patients
−1.51	[18]	2019	Scalp EEG (n=78, control subjects)	4-50 Hz	Resting state
−1.67	[18]	2019	Scalp EEG (n=76, ADHD subjects)	4-50 Hz	Resting state
−1.84	[10]	2020	Scalp EEG (n=9)	30-45 Hz	Wakefulness
−1.86	[60]	2013	Scalp EEG (n=7, adults)	0.2-30 Hz	Sleep
−1.87	[10]	2020	Scalp EEG (n=14)	30-45 Hz	Resting state
−2.03	[53]	2019	Scalp EEG (n=5)	20-40 Hz	Wakefulness
−2.07	[60]	2013	Scalp EEG (n=15, newborns)	0.2-30 Hz	Sleep
−2.32	[61]	2000	Intracranial EEG (n=5)	0.5-150 Hz	Resting state
−2.33	[12]	2021	Scalp EEG (n=175, T5)	2-48 Hz	NREM sleep
−2.44	[31]	2010	Intracranial EEG (n=5)	1-100 Hz	Wakefulness
−2.48	[53]	2019	Scalp EEG (n=5)	20-40 Hz	Wakefulness
−2.71	[11]	2022	Scalp EEG (n=251)	2-48 Hz	NREM sleep
−2.73	[12]	2021	Scalp EEG (n=175, Fz)	2-48 Hz	NREM sleep
−2.75	[10]	2020	Intracranial EEG (n=12)	30-45 Hz	Wakefulness
−2.87	[31]	2010	Intracranial EEG (n=5)	1-100 Hz	Slow wave sleep
−2.99	[10]	2020	Intracranial EEG (n=10)	30-45 Hz	Wakefulness
−3.1	[10]	2020	Scalp EEG (n=9)	30-45 Hz	Anesthesia
−3.13	[53]	2019	Scalp EEG (n=5)	20-40 Hz	Wakefulness
−3.46	[10]	2020	Scalp EEG (n=14)	30-45 Hz	N3 Sleep
−3.59	[53]	2019	Scalp EEG (n=5)	20-40 Hz	Anesthesia (Xenon)
−3.67	[10]	2020	Scalp EEG (n=14)	30-45 Hz	N2 Sleep
−3.69	[10]	2020	Intracranial EEG (n=10)	30-45 Hz	N3 Sleep
−4	[27]	2009	Intracranial EEG (n=20)	80-500 Hz	Behavioral experiments
−4.15	[10]	2020	Intracranial EEG (n=10)	30-45 Hz	REM sleep
−4.34	[10]	2020	Intracranial EEG (n=12)	30-45 Hz	Anesthesia
−4.36	[53]	2019	Scalp EEG (n=5)	20-40 Hz	Anesthesia (Propofol)
−4.73	[10]	2020	Scalp EEG (n=14)	30-45 Hz	REM sleep

Examples in Neuroscience

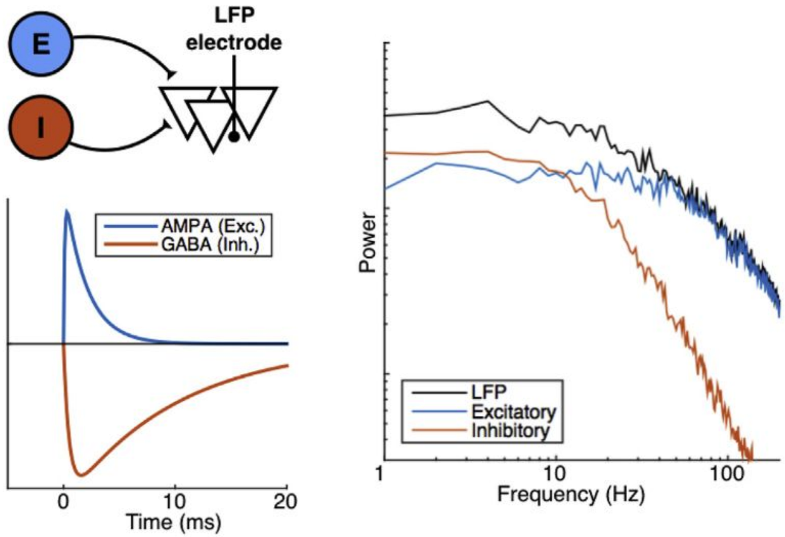
*Derived from [8]

Study (year)	Domain Examined	Key Finding
He (2014), Kello et al. (2010)	Aperiodic component	Introduction and interest in the aperiodic component of 1/f.
Ouyang et al. (2020), Podvalny et al. (2015), Waschke et al. (2021)	Task	Changes in the 1/f exponent with tasks.
Bódizs et al. (2021), Dave et al. (2018), Waschke et al. (2017), Cellier et al. (2021), He et al. (2019), Schaworonkow & Voytek (2021), Voytek et al. (2015)	Age	1/f exponent changes with age.
Muthukumaraswamy & Liley (2018), Stock et al. (2020), Timmermann et al. (2019)	Psychoactive drug administration	1/f changes with drug administration.
Molina et al. (2020), Robertson et al. (2019), Veerakumar et al. (2019), van Heumen et al. (2021), Ostlund et al. (2021), Karalunas et al. (2022)	Disease	1/f exponent correlation with diseases.
Halgren et al. (2021)	Cortical Depth	1/f decreases with cortical depth.
Gao et al. (2017)	Computational modeling	1/f exponent β as estimator of excitation–inhibition balance.
Lendner et al. (2020), Miskovic et al. (2019), Colombo et al. (2019), Muthukumaraswamy & Liley (2018), Waschke et al. (2021), Zhou et al. (2021)	Consciousness States	Differences in 1/f exponent in NREM sleep, anesthesia vs. awake states.

Hypotheses in Neuroscience

What could it mean?

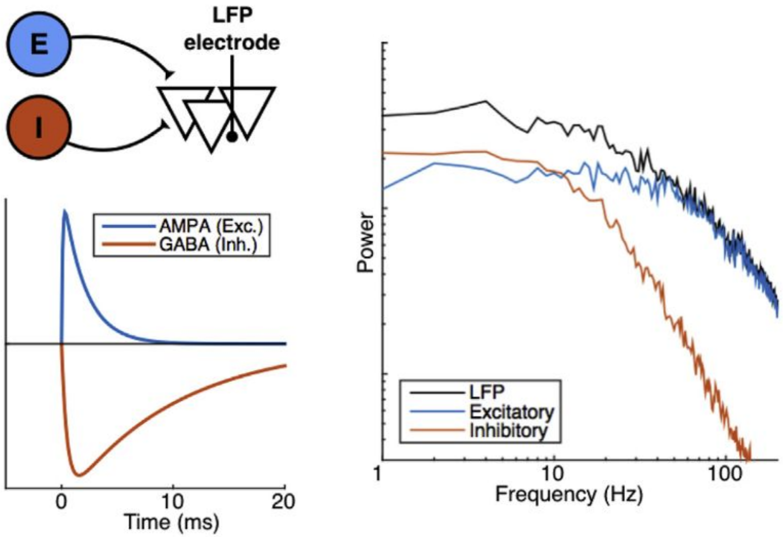
- Neurophysiological interpretation
  - Several computational models indicate that desynchronized non-oscillatory brain activity correlates with population excitation-to-inhibition balance (E-I Ratio) [10-11]



Hypotheses in Neuroscience

What could it mean?

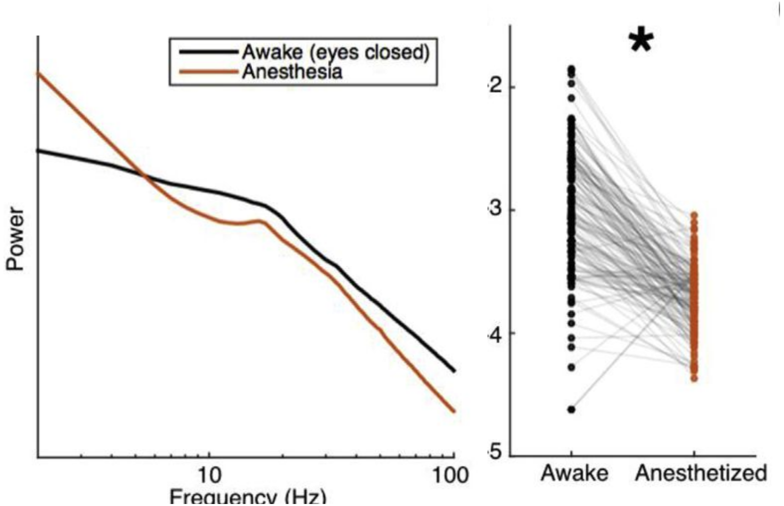
- Neurophysiological interpretation
  - Several computational models indicate that desynchronized non-oscillatory brain activity correlates with population excitation-to-inhibition balance (E-I Ratio) [10-11]
  - *Offset* reflects neuronal population spiking, whereas *exponent* relates to the integration of synaptic currents [14]



Hypotheses in Neuroscience

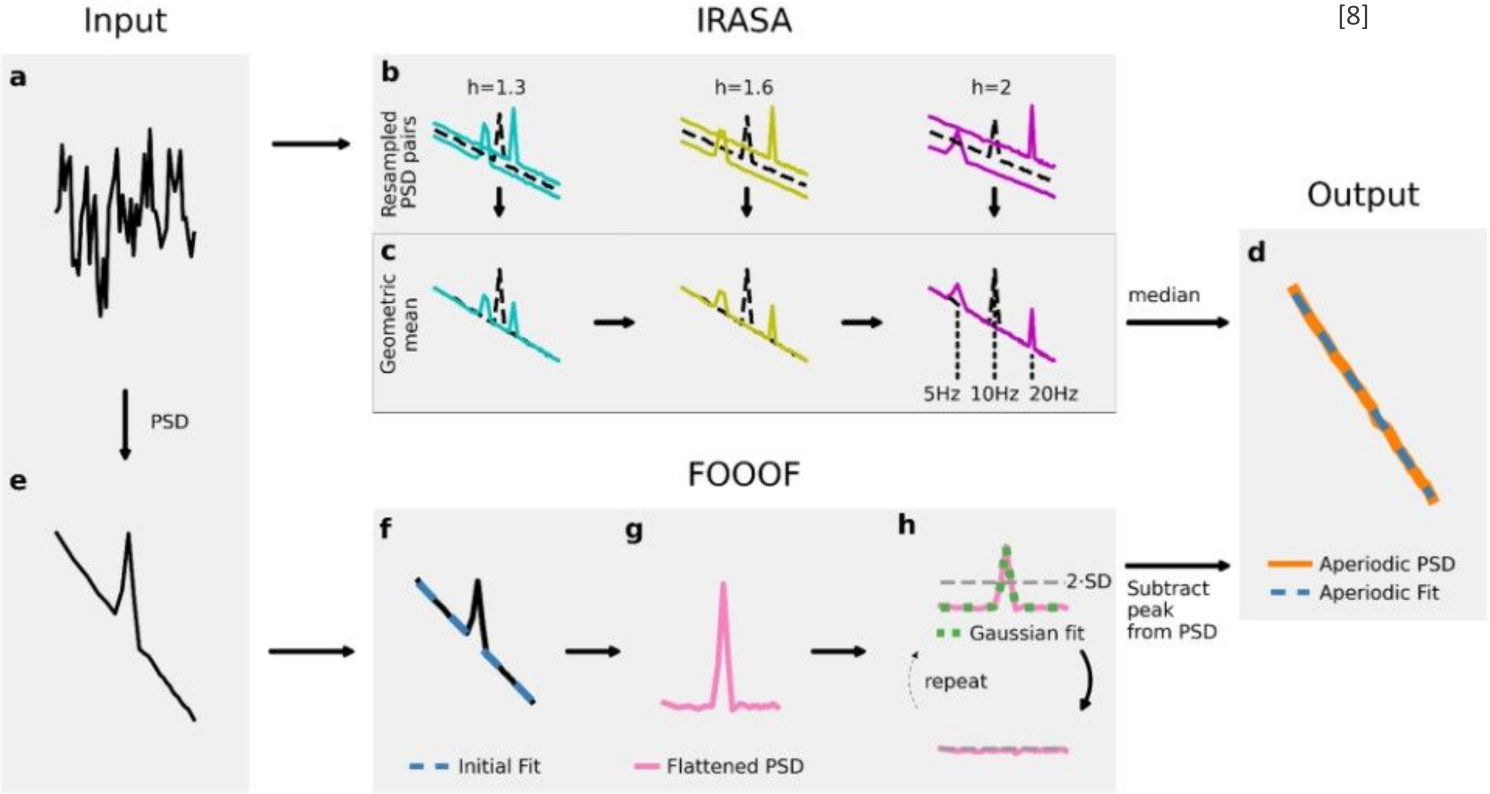
What could it mean?

- Neurophysiological interpretation
  - Several computational models indicate that desynchronized non-oscillatory brain activity correlates with population excitation-to-inhibition balance (E-I Ratio) [10-11]
  - Conscious states (increased excitation) vs unconscious states (increased inhibition) [8]
    - (i.e., larger 1/f exponents observed for NREM sleep and anesthesia compared to wakefulness)



How to model aperiodic activity

[8]

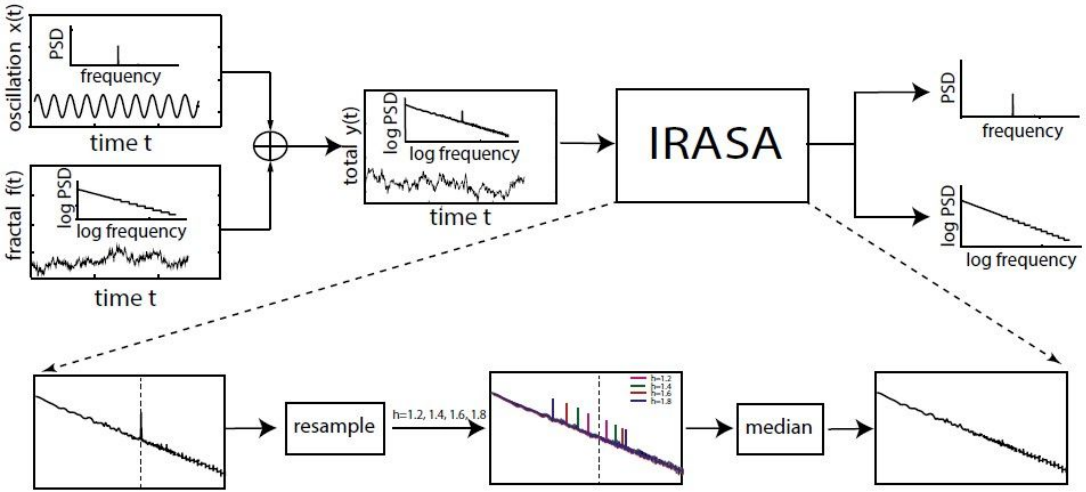


Tools and frameworks - IRASA

[12]

Step 1: Compute the original power spectral density (PSD).

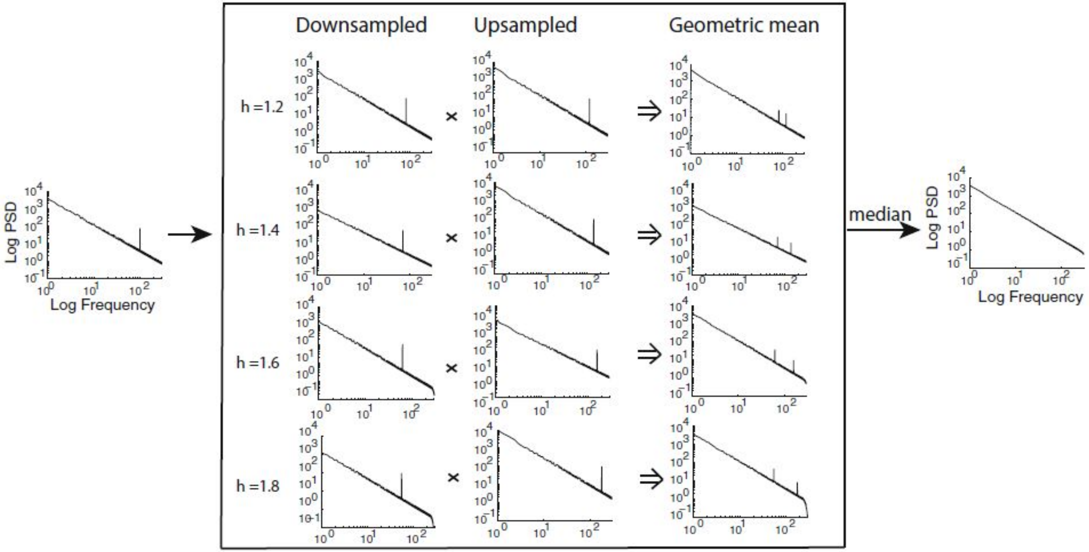
Step 2: Resample the EEG data by multiple non-integer factors and their reciprocals (h and $1/h$)



Tools and frameworks - IRASA

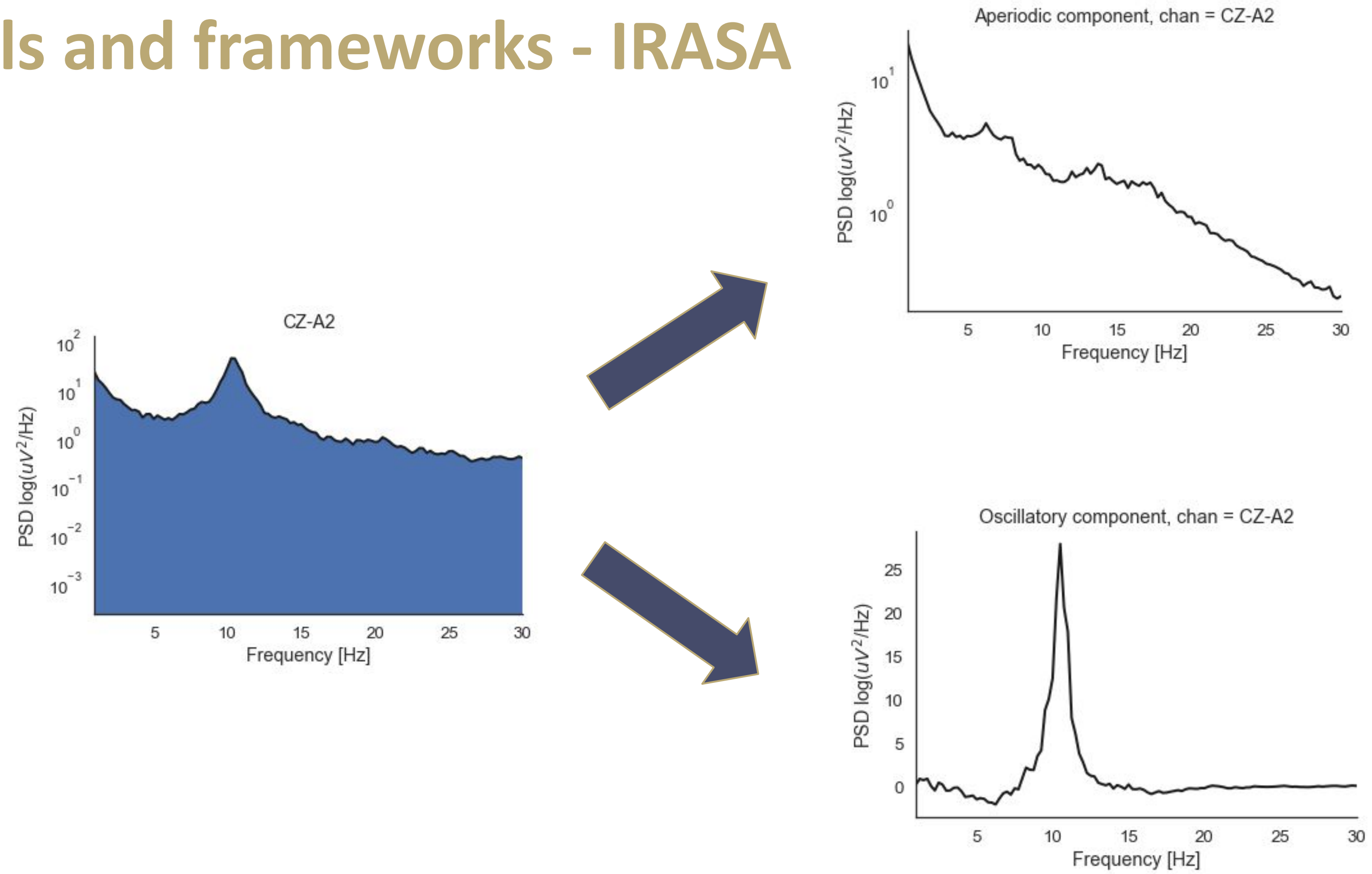
Step 3: For each resampled signal pair, compute the PSD and then determine their geometric mean; this process shifts oscillatory component power by a varying frequency offset while keeping the fractal component's power consistent.

Step 4: Extract the fractal component's power spectrum by finding the median PSD of the resampled signals, and subtract this from the original to estimate the oscillatory component's power spectrum.



[12]

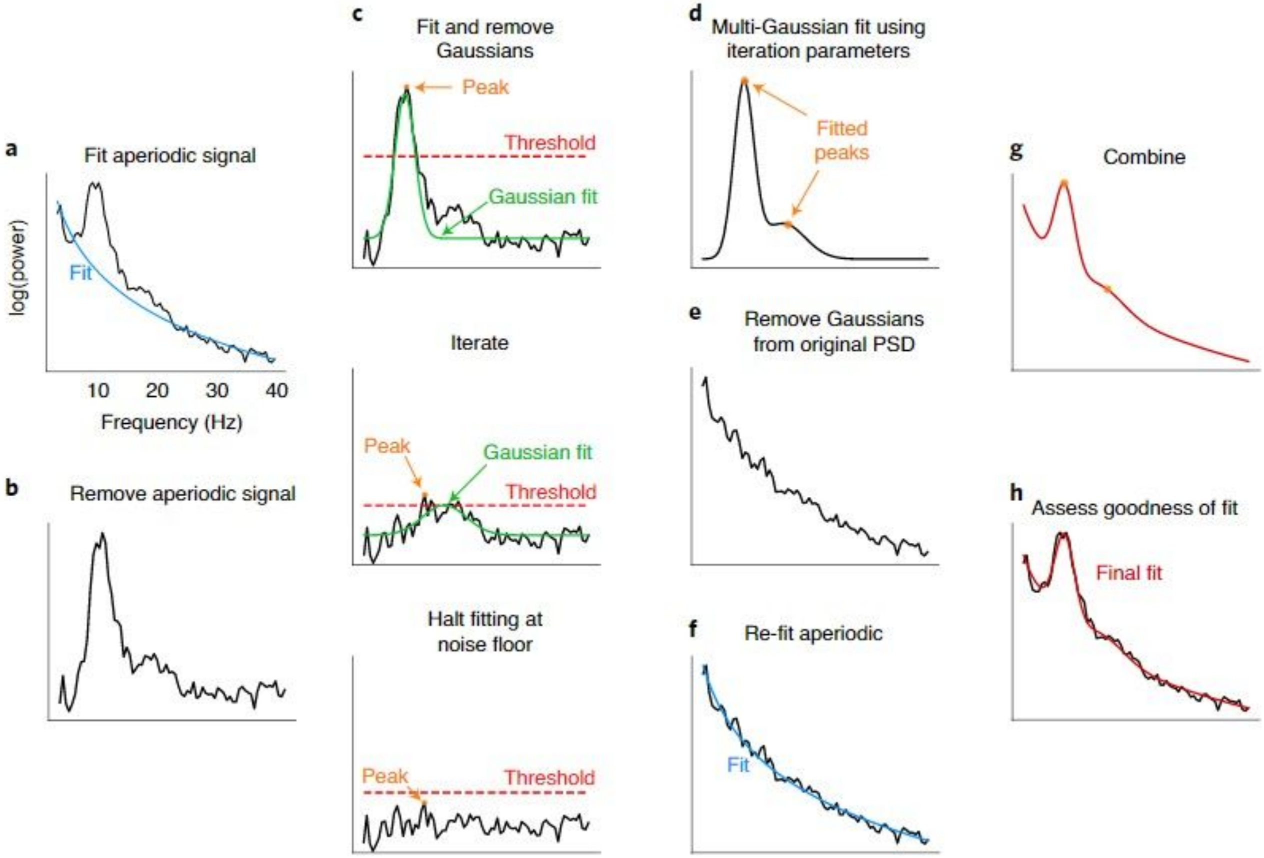
Tools and frameworks - IRASA



https://github.com/raphaelvallat/yasa/blob/master/notebooks/09_IRASA.ipynb

Tools and frameworks - FOOOF

[13]



Tools and frameworks - FOOOF

Resulting goodness of fit metrics (i.e., fit error & R^2)

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                                FOOOF - POWER SPECTRUM MODEL

                       The model was run on the frequency range 3 - 40 Hz
                                Frequency Resolution is 0.49 Hz

                           Aperiodic Parameters (offset, exponent):
                                      -21.3713, 1.1239

                                      2 peaks were found:
                              CF:  10.00, PW:  0.685, BW:  3.18
                              CF:  16.32, PW:  0.138, BW:  7.03

                                   Goodness of fit metrics:
                                  R^2 of model fit is 0.9909
                                  Error of the fit is 0.0332

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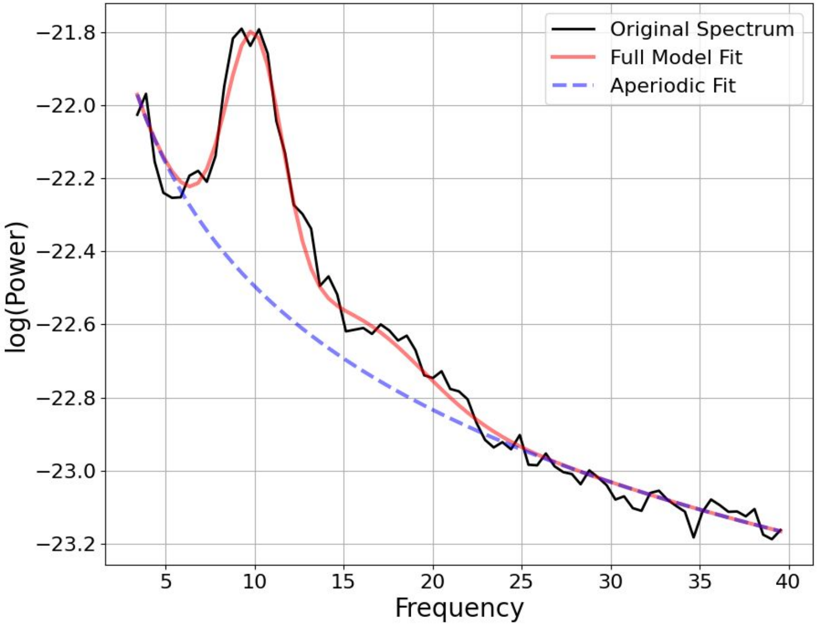
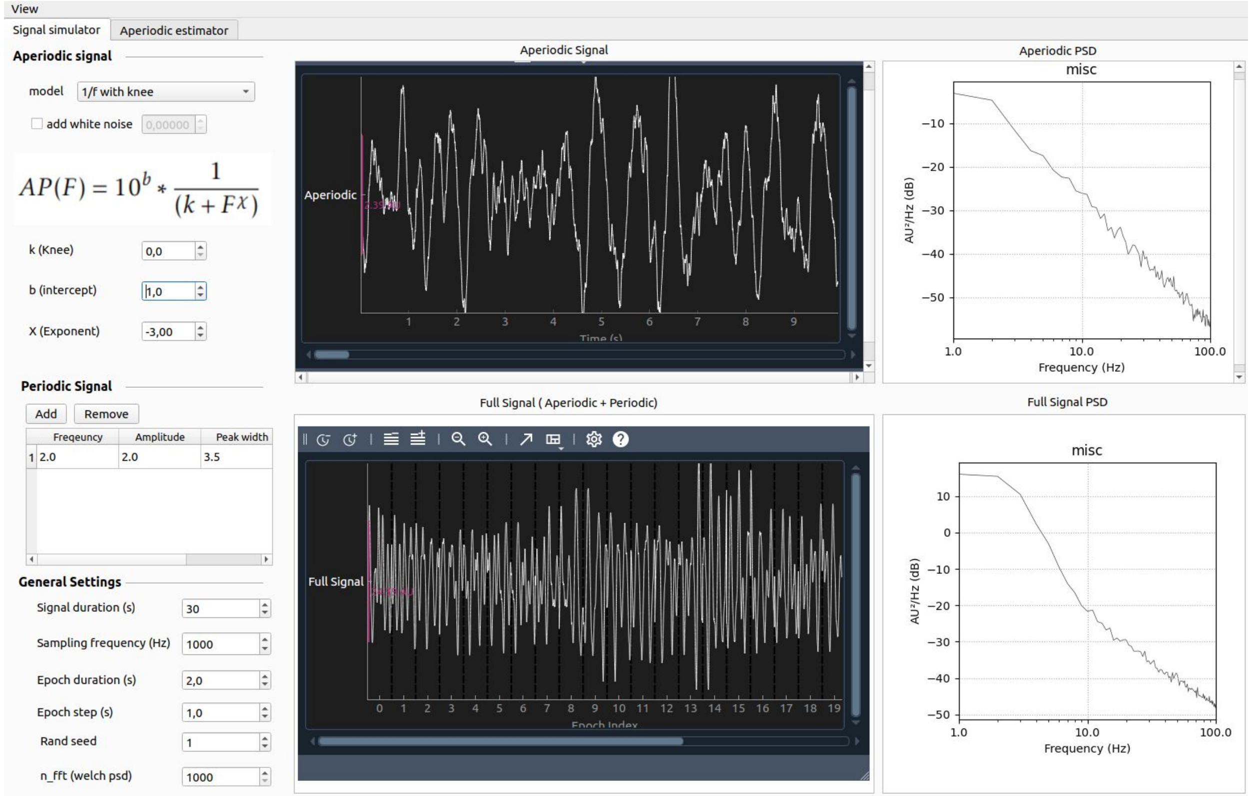


Full model fit of the power spectrum

https://fooof-tools.github.io/fooof/auto_tutorials/plot_03-FOOOFAlgorithm.html#sphx-glr-auto-tutorials-plot-03-fooofalgorithm-py

Interactive demonstration with GUI



Interactive demonstration with GUI

- All workshop materials are available at:
  - https://github.com/Farzin-Negahbani/NeNa_aperiodic_GUI
  - https://github.com/mvaliadis/2023_NENA_Aperiodic_Workshop

- To have the GUI repository:
  a. git clone git@github.com:Farzin-Negahbani/NeNa_aperiodic_GUI.git
  b. conda create -n aperiodic python=3.9.7
  c. conda activate aperiodic
     - pip install -r requirements.txt
     - python -m pip install -r requirements.txt

- To run the GUI:
  a. python gui.py

Demonstrations

1. Pick higher freq band for fitting when having low frequency oscillations.
    a. E.g. CF= 2 hz, amp= 2, width=3,   use 1-30 hz and 30-60 hz for fitting

2. Add gaussian noise and increase the noise level and observe the spectral plateau. Try changing fitting range to exclude the plateau.

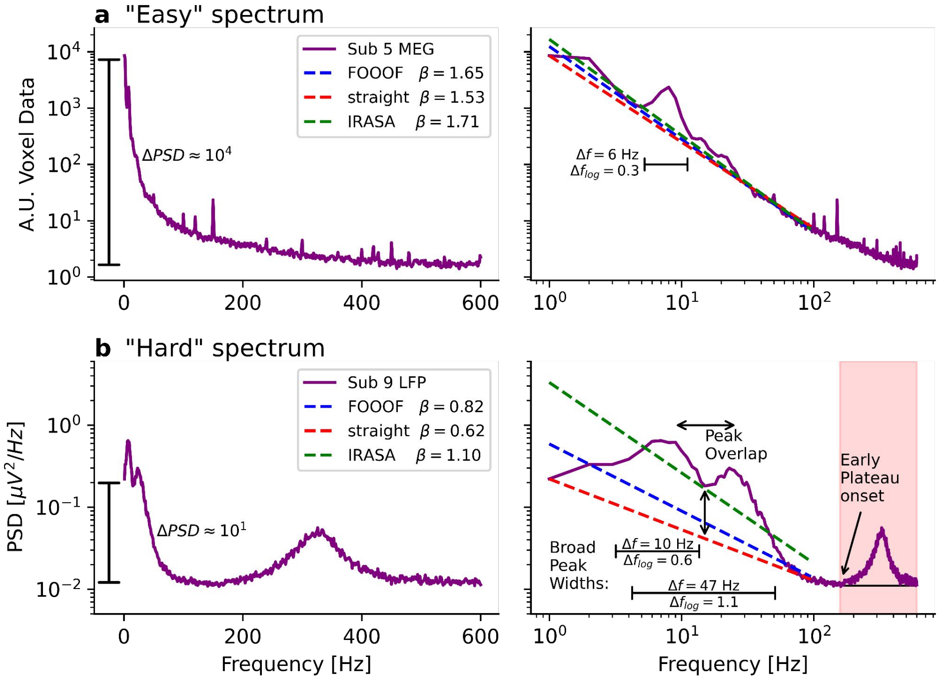
3. Change h_max parameter and observe change in fit of IRASA.

$$f_{\text{eval. min}} = f_{\text{fit min}} / h_{\text{max}}$$

$$f_{\text{eval. max}} = f_{\text{fit max}} \cdot h_{\text{max}}$$

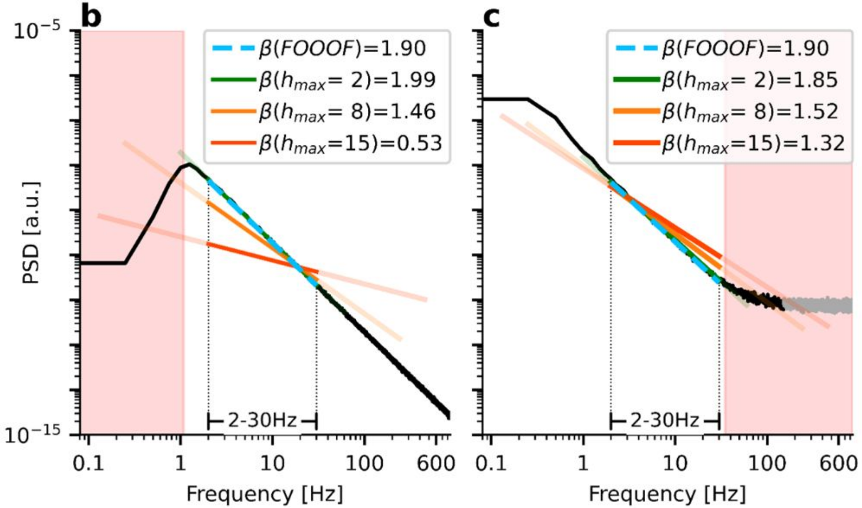
Limitations and challenges of current methods

- Main challenges of FOOOF [8]:
  - 1/f disruption from spectral plateaus
  - Avoiding oscillations that cross fitting range boundaries
  - Not sensitive to oscillatory peaks that are not clearly distinguishable



Limitations and challenges of current methods

- Main challenges of IRASA [8]:
  - Evaluated frequency range is larger than the fitting range
  - Broad peak widths require large resampling factors
  - Not sensitive to oscillatory peaks that are not clearly distinguishable
  - Computational speed

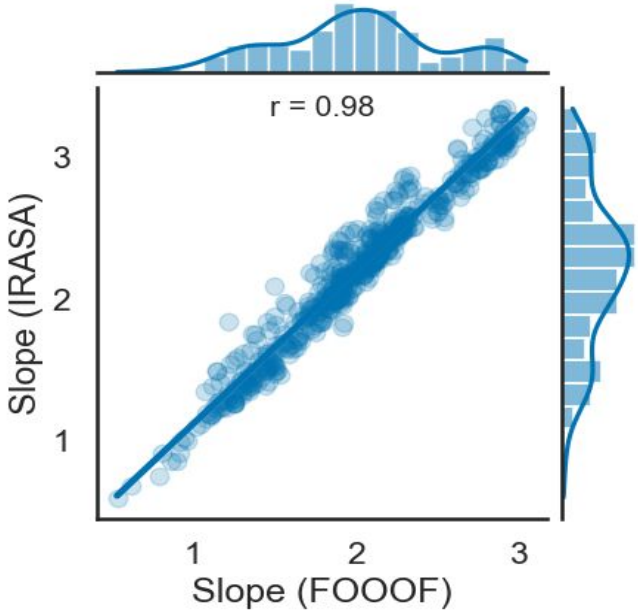


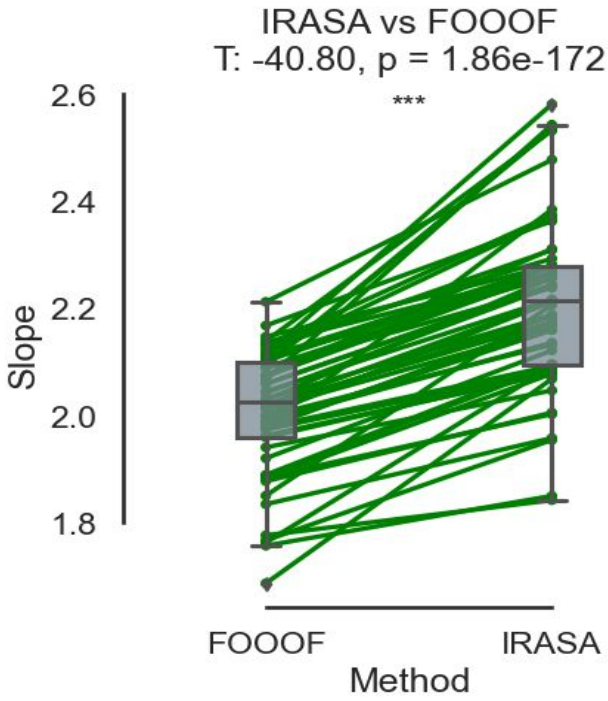
Example with Sleep EEG data

- Cleveland Family Study (Sleep EEG) Data (*n = 50*)
  - longitudinal study on the heritability and pathophysiology of sleep apnea across diverse families

Example with Sleep EEG data

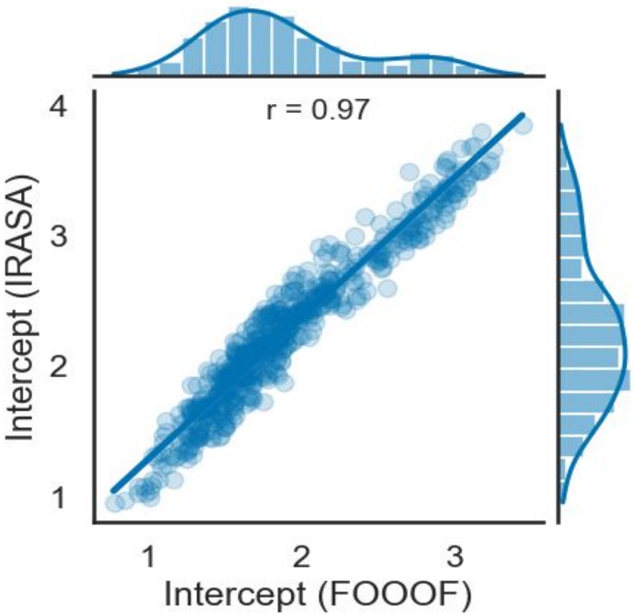
- Cleveland Family Study (Sleep EEG) Data (*n = 50*)
- IRASA vs. FOOOF (Slope)

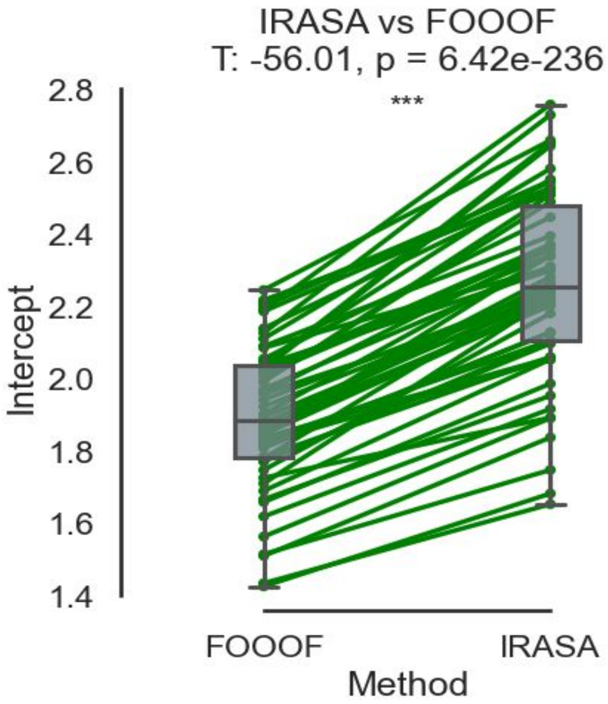




Example with Sleep EEG data

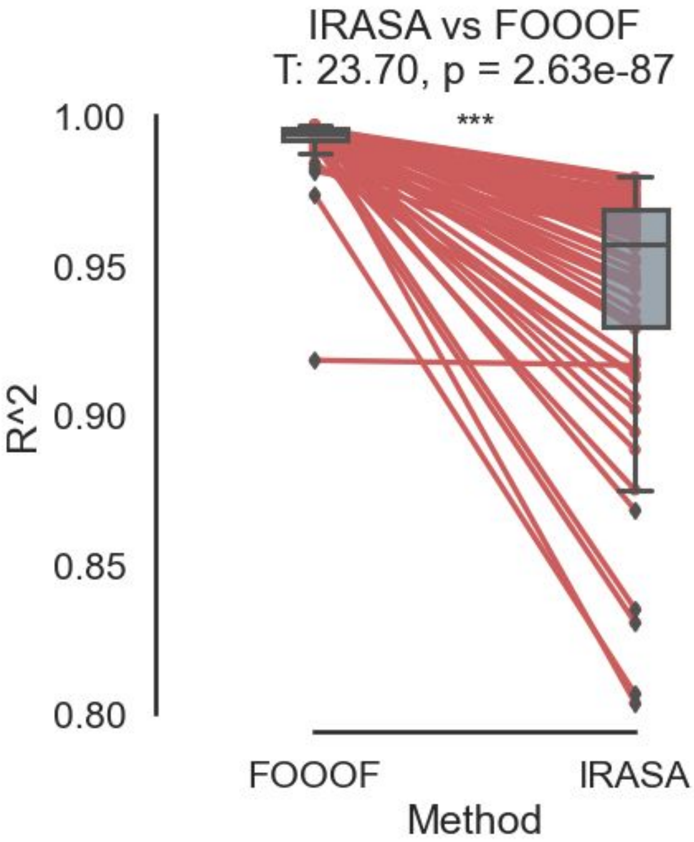
- Cleveland Family Study (Sleep EEG) Data (*n = 50*)
- IRASA vs. FOOOF (Intercept)





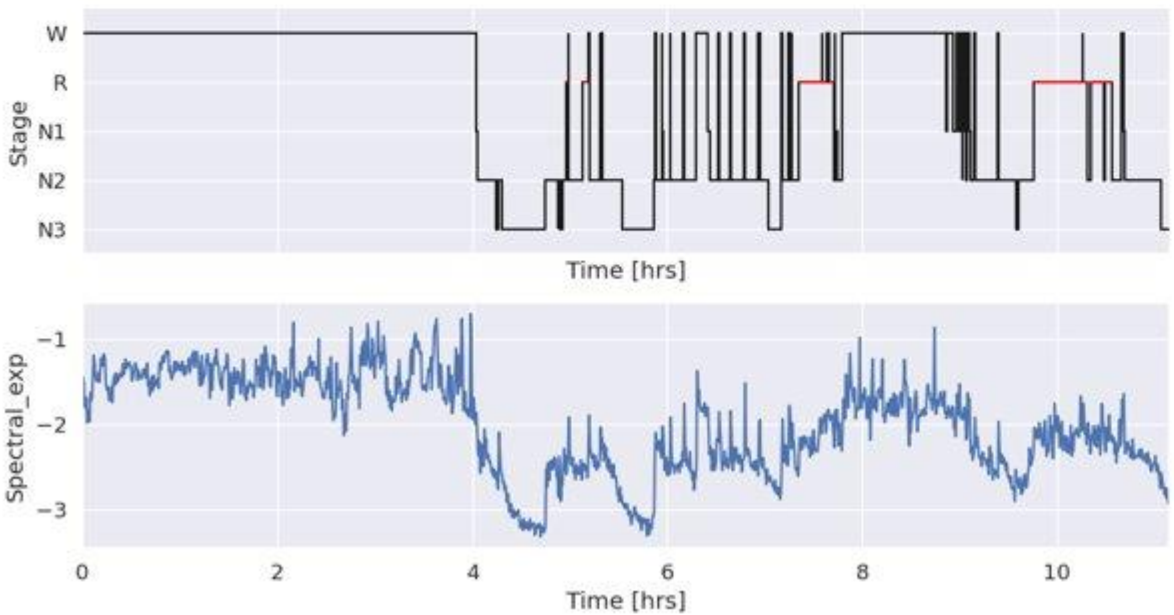
Example with Sleep EEG data

- Goodness of fit comparison
    - FOOOF > IRASA



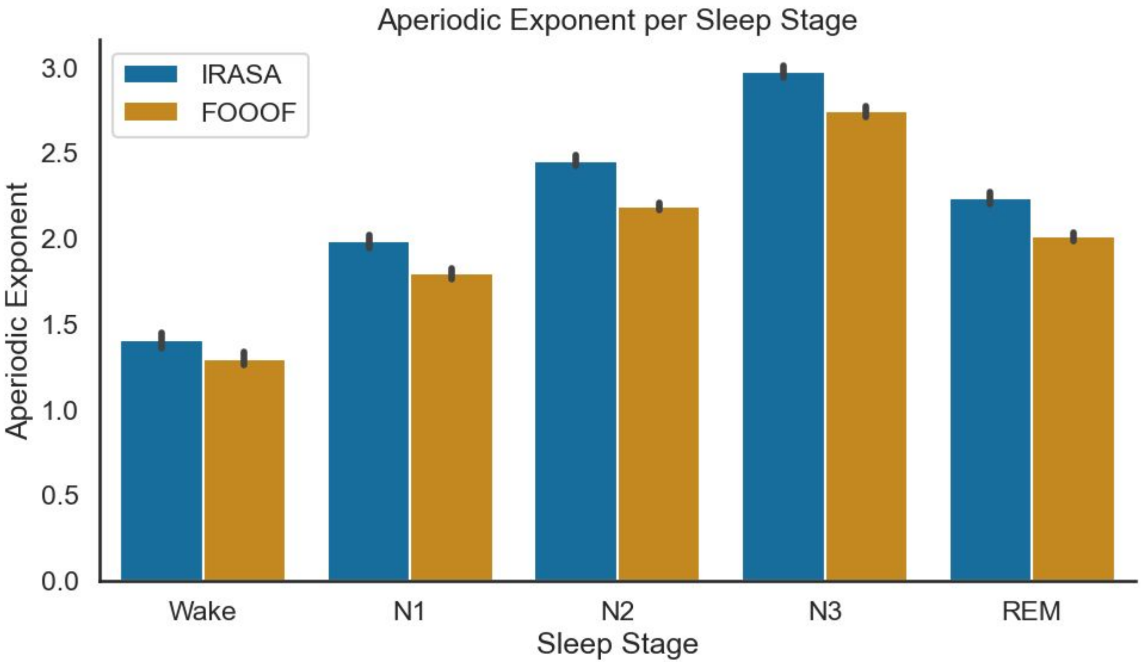
Example with Sleep EEG data

- Sleep Stage Differences (Example Subject with IRASA)



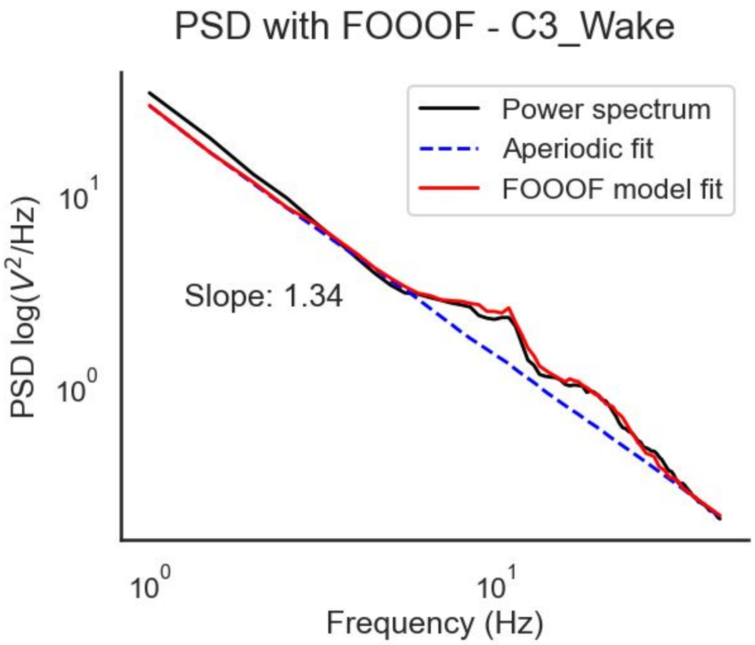
Example with Sleep EEG data

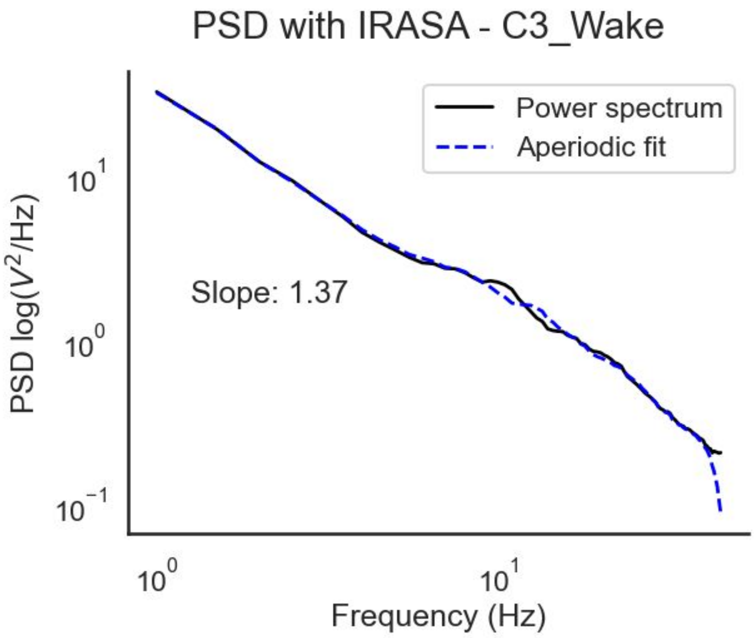
- Sleep Stage Differences (Group level):



Example with Sleep EEG data

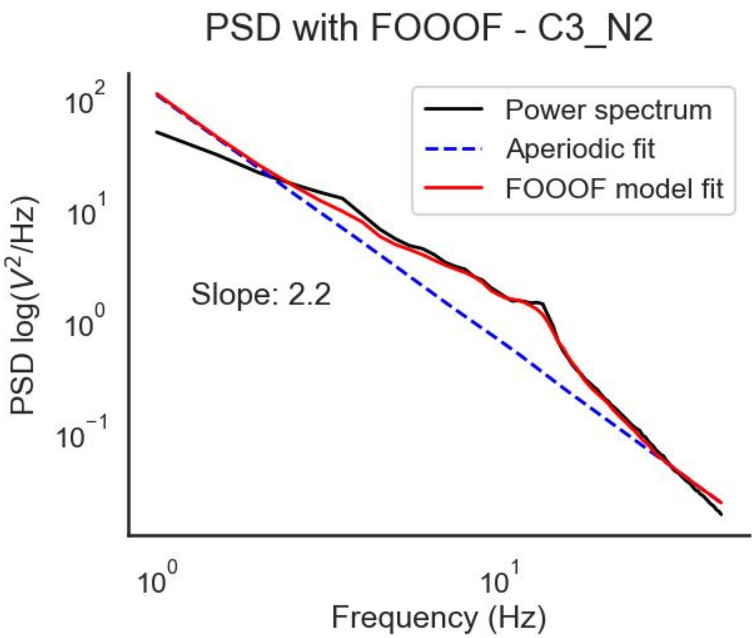
- Sleep Stage Comparison (Wake)

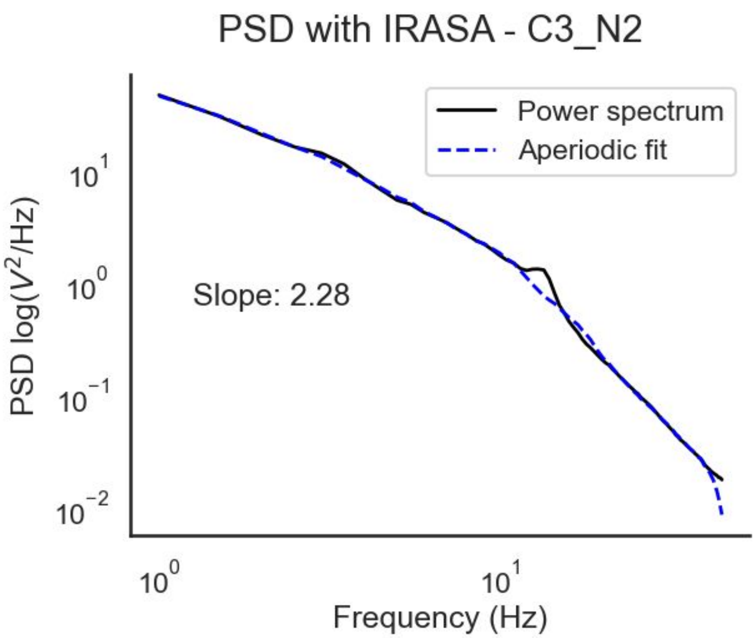




Example with Sleep EEG data

- Sleep Stage Comparison (NREM2)





Tips & Recommendations

- Spend time looking at your raw PSDs!
  - If there’s too many overlapping peaks, avoid fitting aperiodic component
  - Decide on maximal of number of peaks -> go low
  - You may need to model the knee!
- Use a fitting range at higher frequencies (e.g., 40–60 Hz) to avoid distortion from low-frequency oscillation

Tips & Recommendations

- Spend time looking at your raw PSDs!
  - If there's too many overlapping peaks, avoid fitting aperiodic component
  - Decide on maximal of number of peaks -> go low
  - You may need to model the knee!
- Use a fitting range at higher frequencies (e.g., 40–60 Hz) to avoid distortion from low-frequency oscillation
- Choose h_{max} as small as possible but large enough to obtain peak-free estimates of the aperiodic component

$$f_{\text{eval. min}} = f_{\text{fit min}} / h_{\text{max}}$$

$$f_{\text{eval. max}} = f_{\text{fit max}} \cdot h_{\text{max}}$$

References

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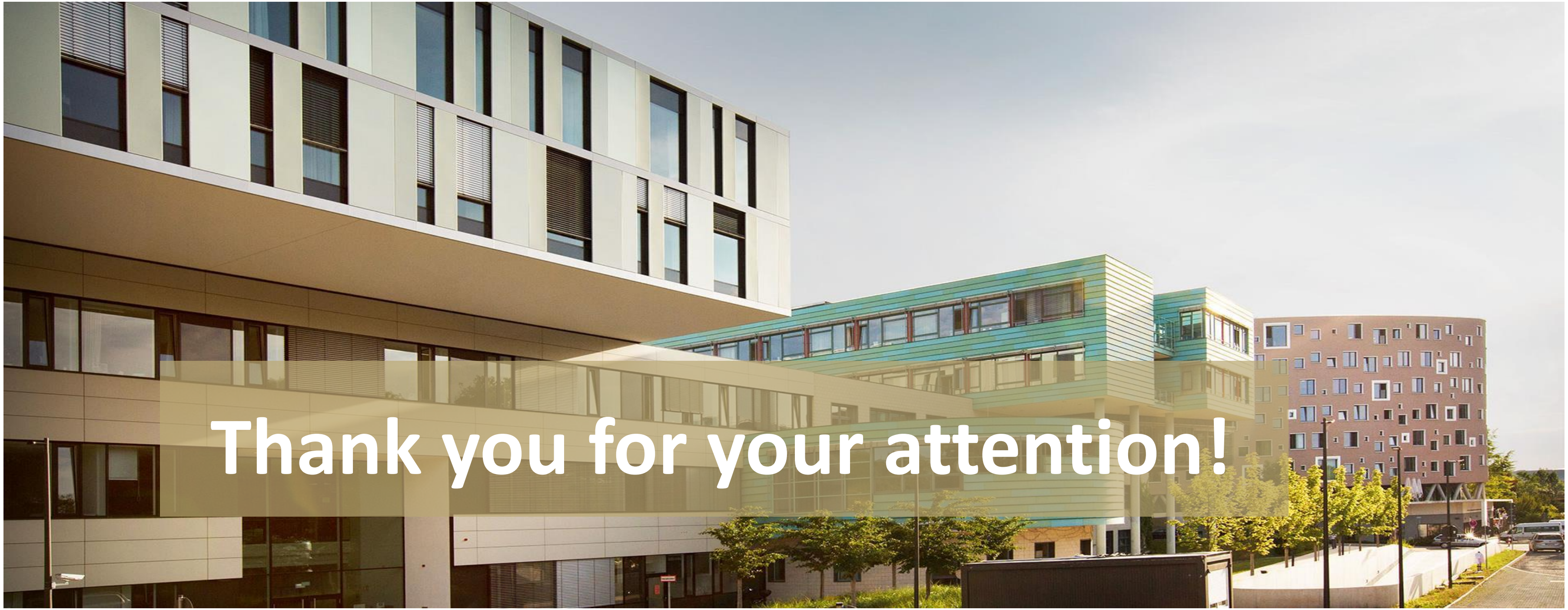

Thank you for your attention!

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