Dynamics of complex systems

Lecture 4: Long-range correlations and scaling

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change perspective

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- Spectral analysis (power spectral density analysis)
- Detrended Fluctuations Analysis (DFA)
- Applications

High variability

Low variability

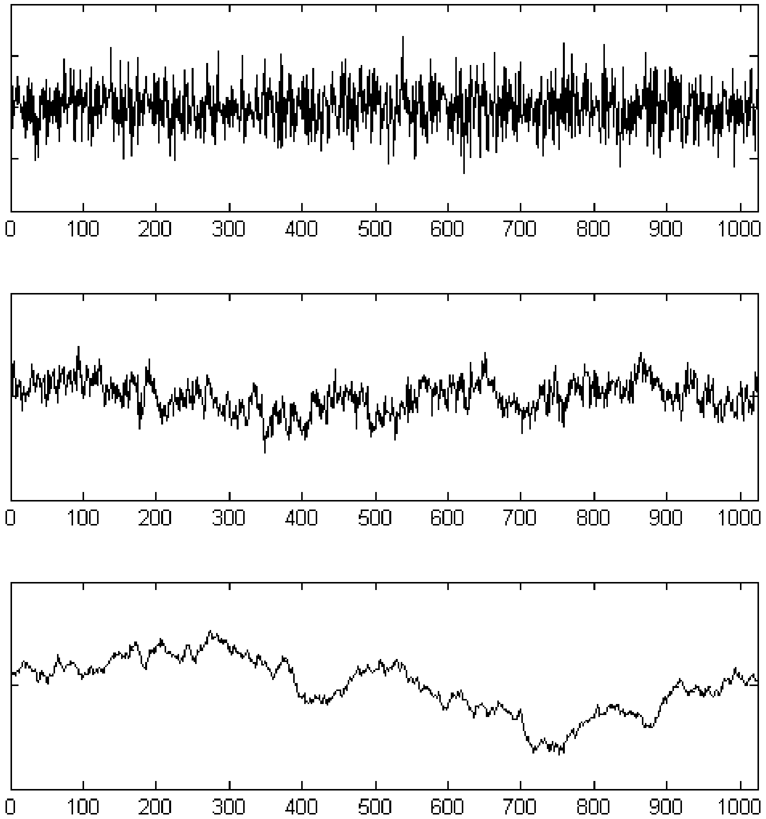
Different faces of variability

<u>Variability is noise</u>

- X = T + E

➔ Amount of variability

- Low ←→ High
- e.g., standard deviation



<u>Variability is structured</u>

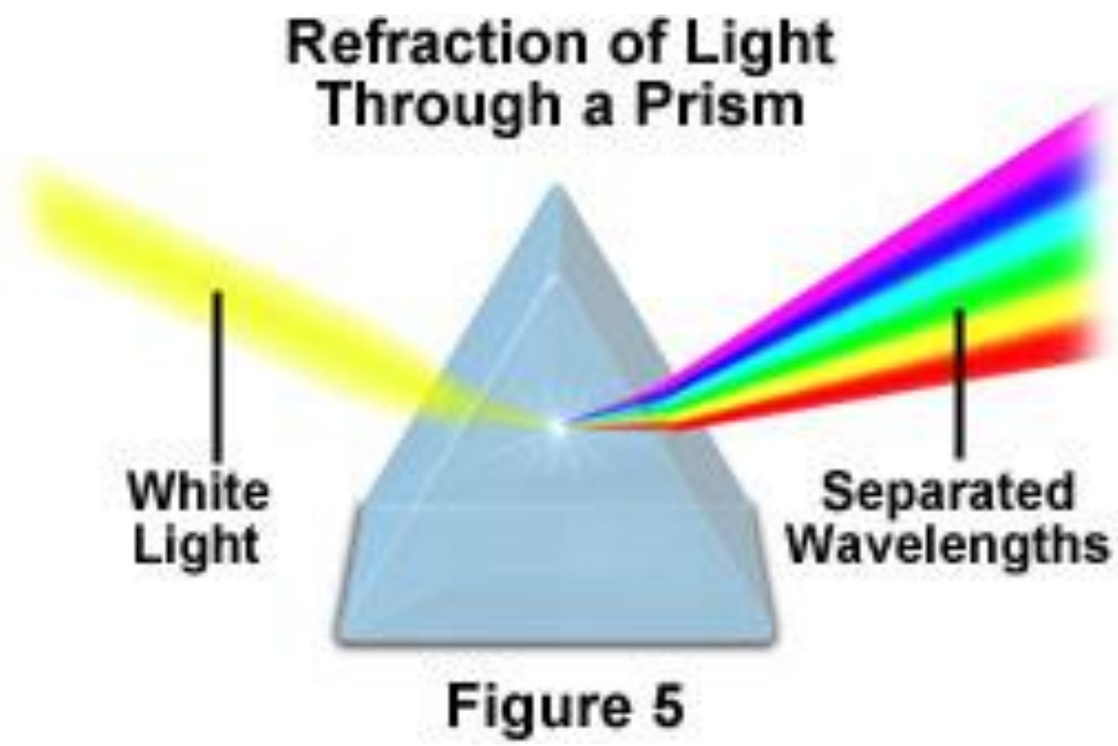
- $f(x) = 1/f^{\alpha}$
- Correlated vs. uncorrelated temporal structure

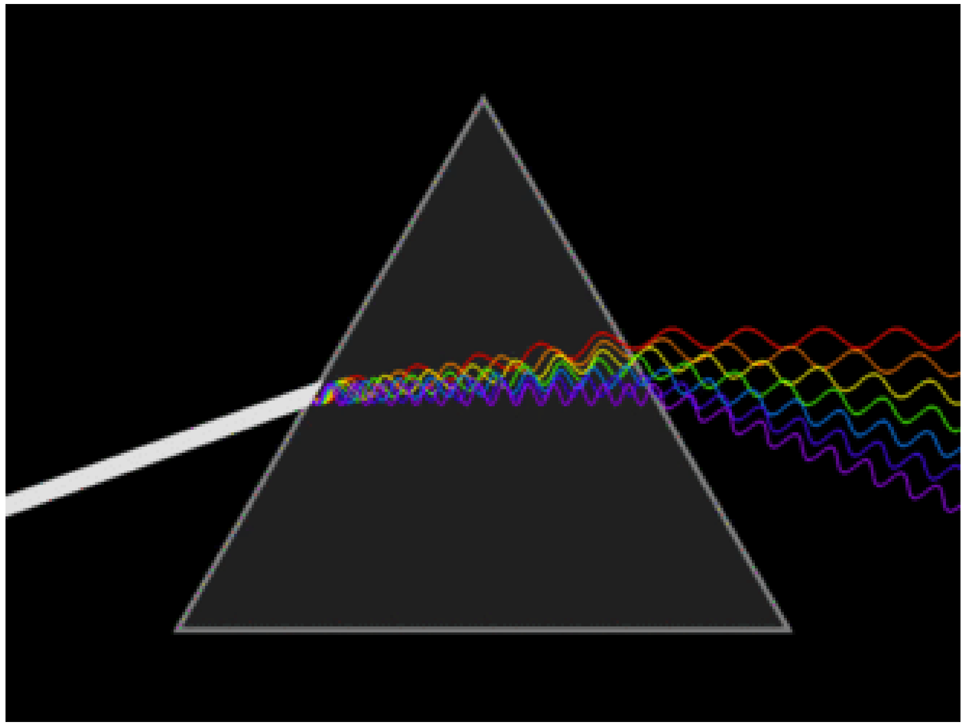
➔ Temporal correlations

- Structured ←→ Unstructured
- e.g., ACF, …

Frequency domain analysis

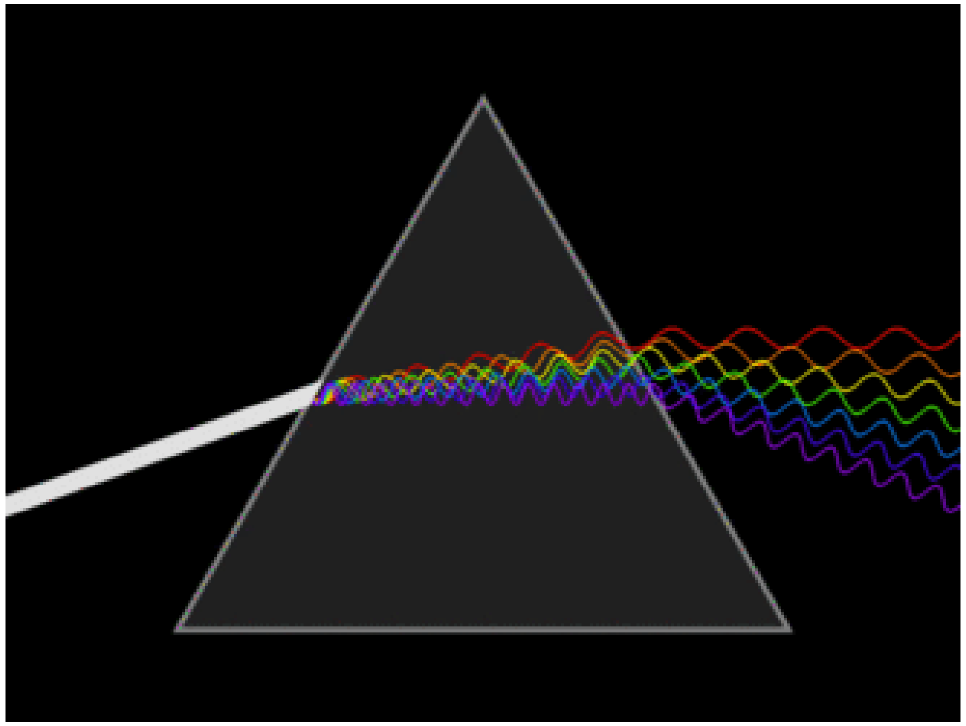
- Changes over time (ms)
- Frequencies of change (Hz)





Frequency domain analysis

Changes over time →

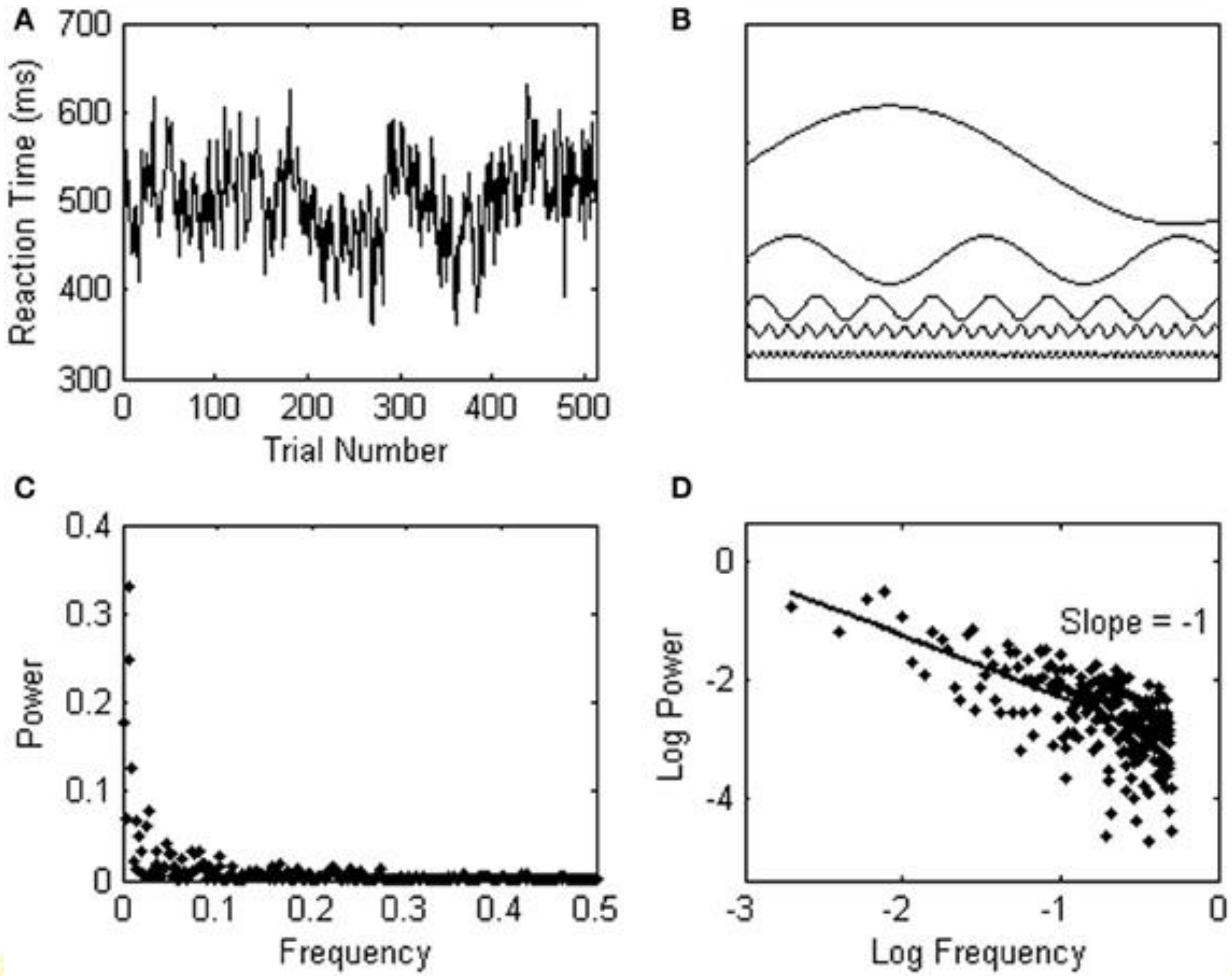


→ Constituent frequencies of a given amplitude

Fourier Transform

Spectral analysis: from time to frequency domain

Fourier transformation:
Any waveform can be duplicated by the superposition of sine and cosine waves



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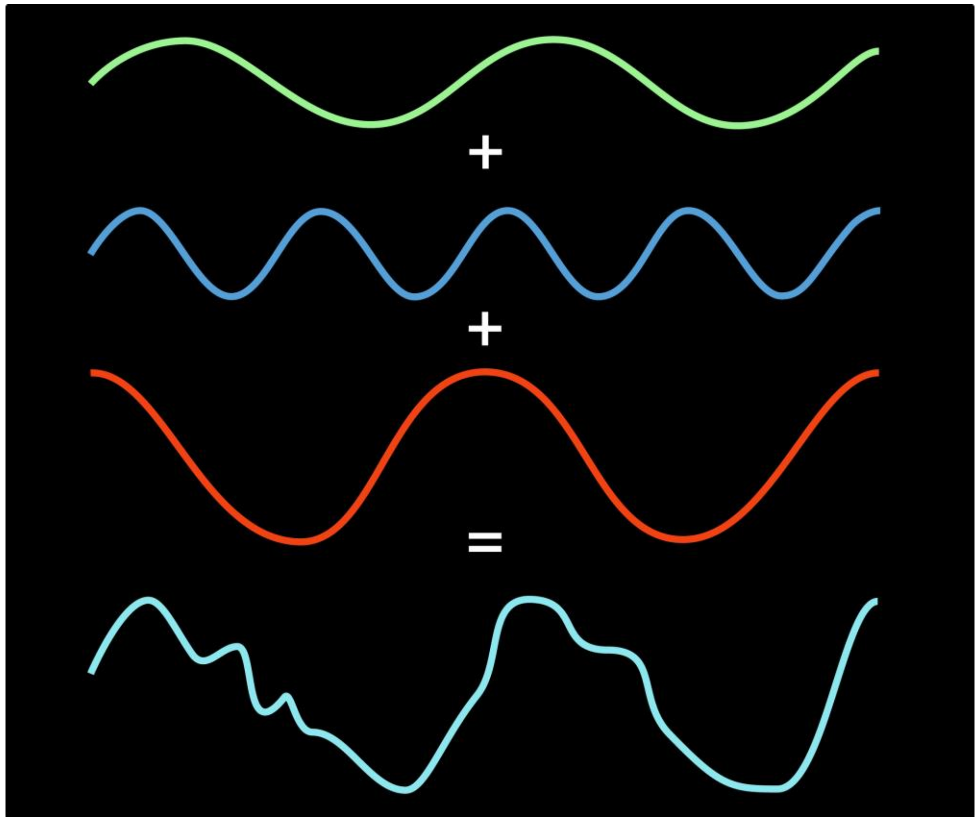

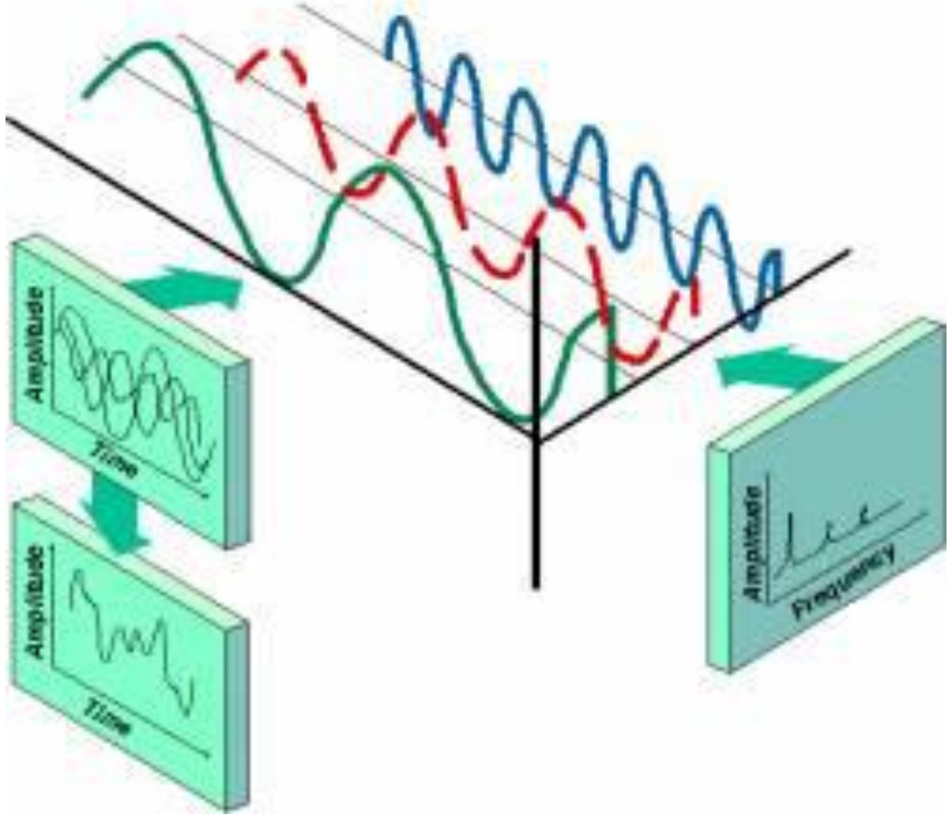

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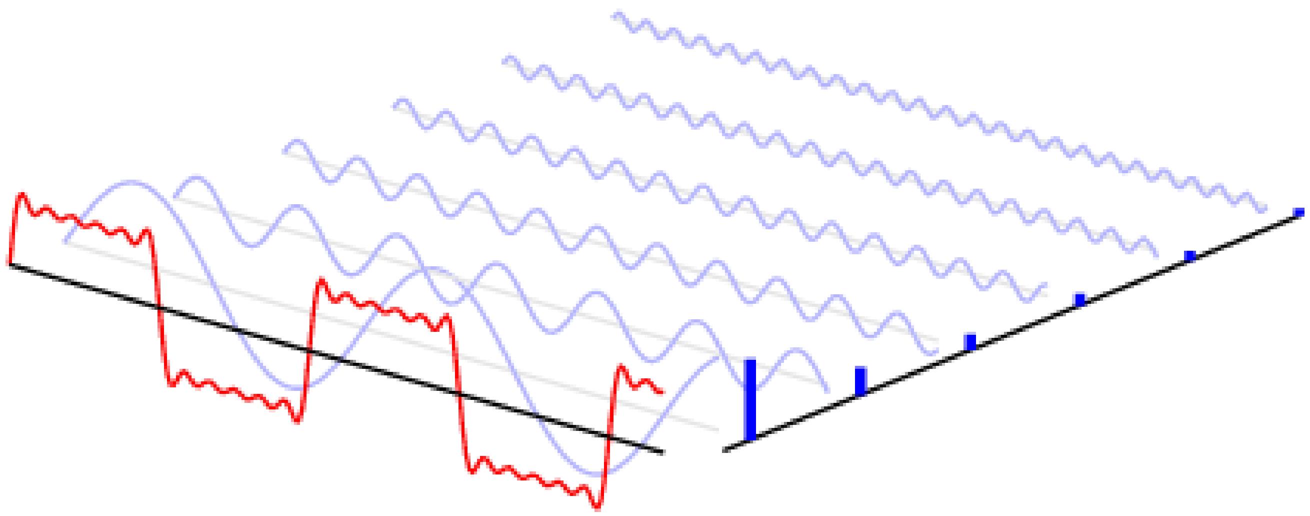
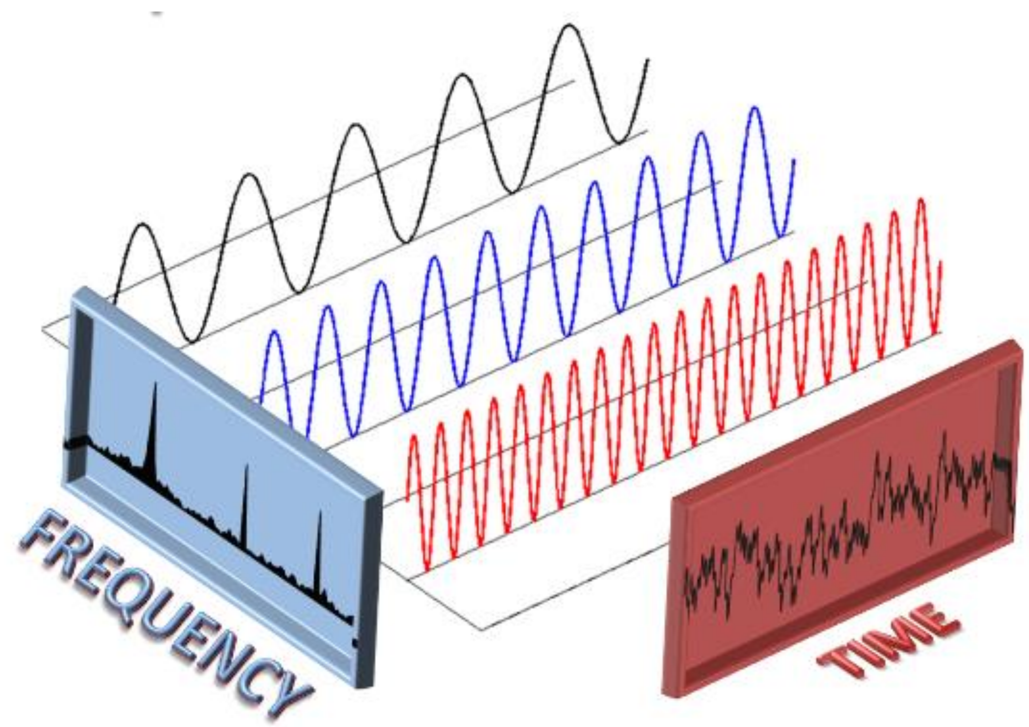
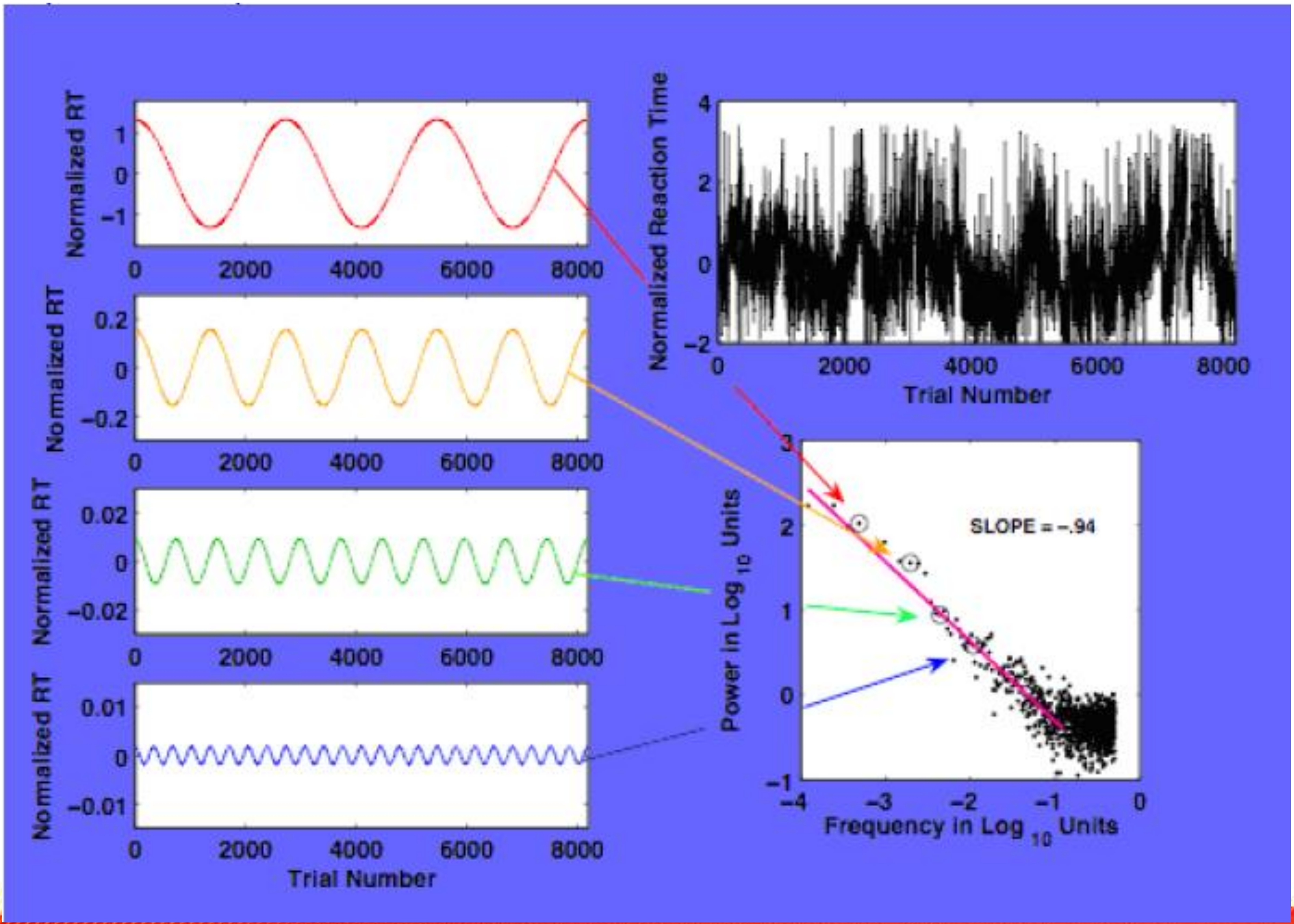




Spectral analysis: from time to frequency domain



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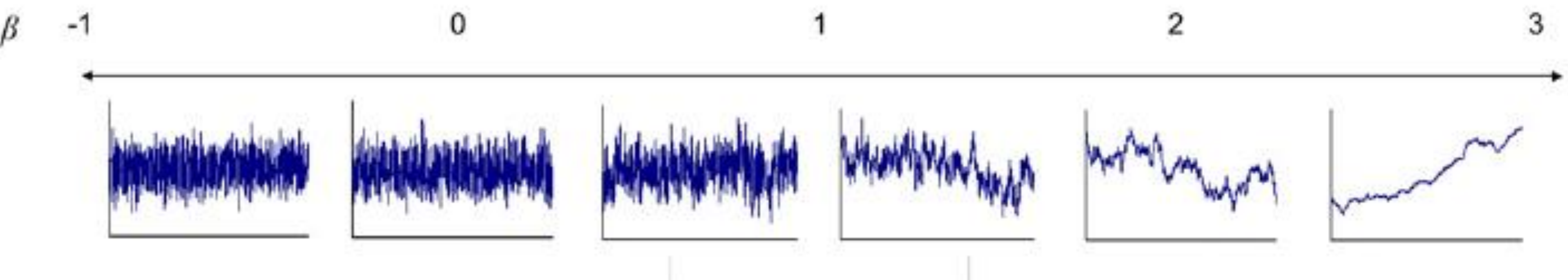
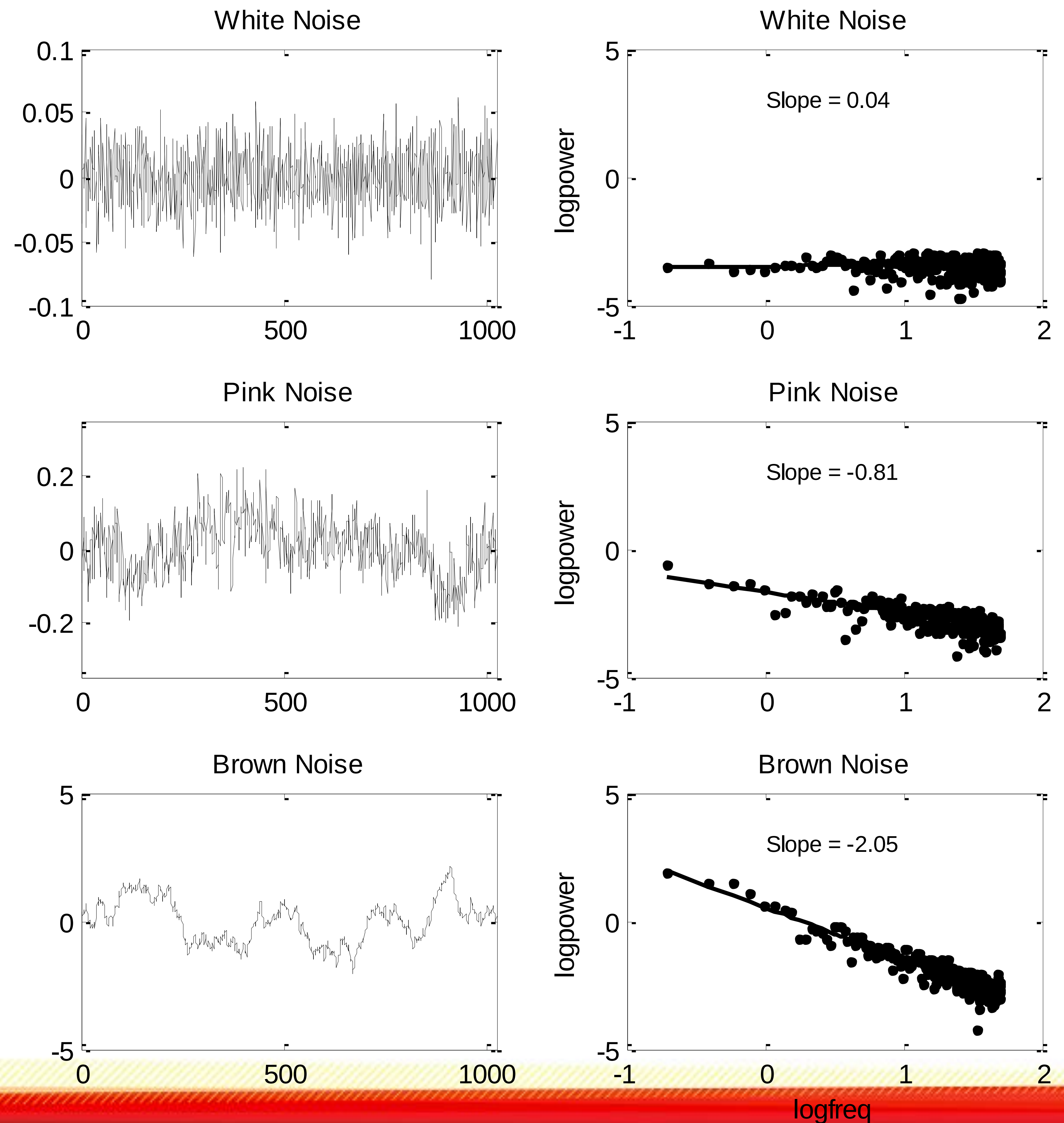


$f(x) = 1/f^{\alpha}$



Disorganized

Self-affinity

Rigid & persistent

Spectral analysis

- Only stationary signals

- Time series length
  - Power of 2
    - Truncation or zero-padding
  - Sufficiently long

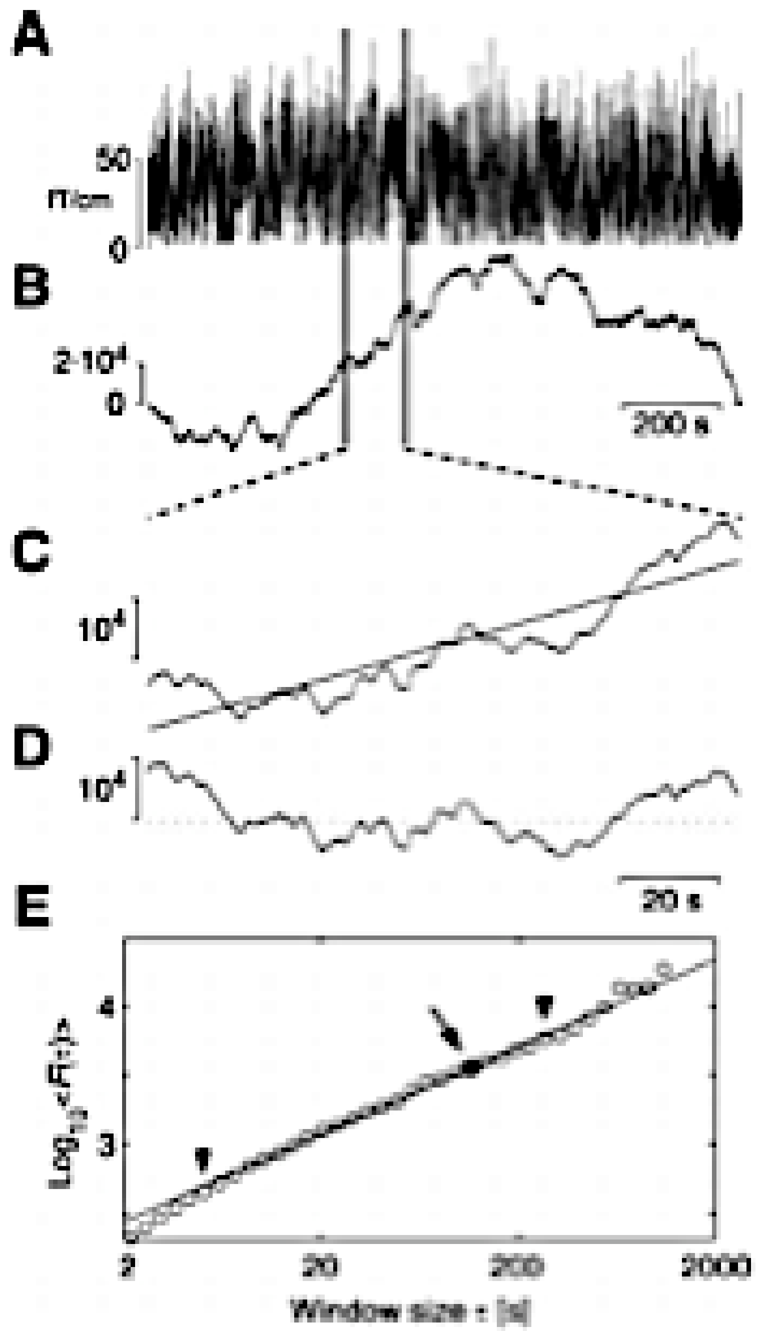
- Linear trends may disrupt the outcome
  - May be seen as a low-frequency fluctuation
    - Linear (and quadratic) detrending prior to analysis

Detrended Fluctuation Analysis

Same logic as SDA except:

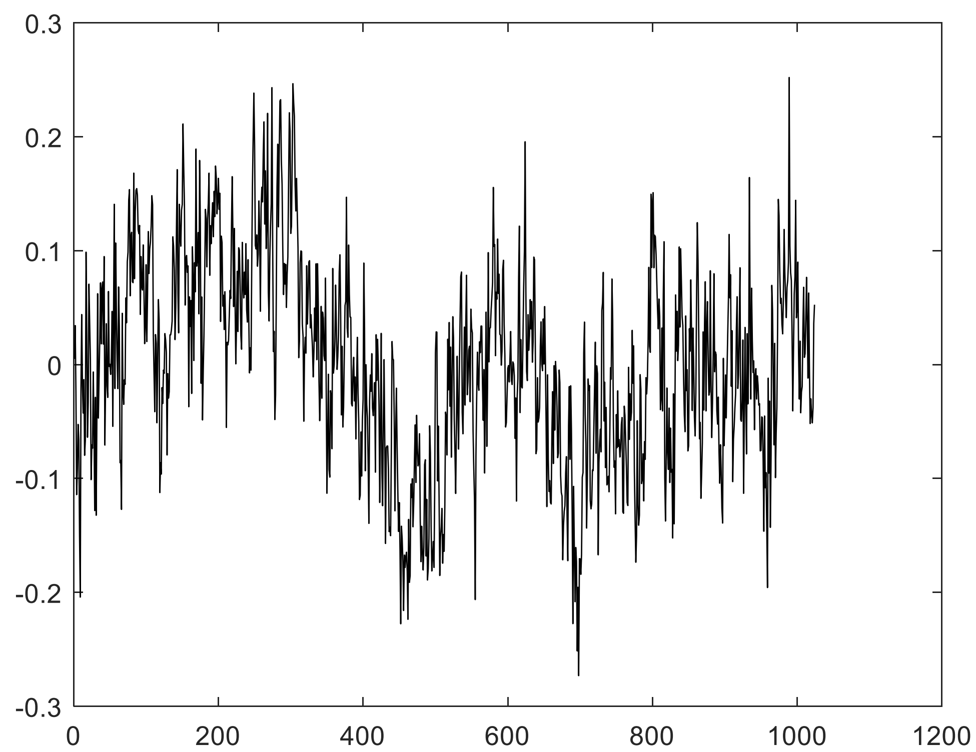
- **A.** Signal is integrated
- **B.** Divided into bins
- **C.** Detrended (linear)
- **D.** Remaining SD is the dispersion measure
- **E.** Plot on Log_{10} scale and calculate slope (alpha)

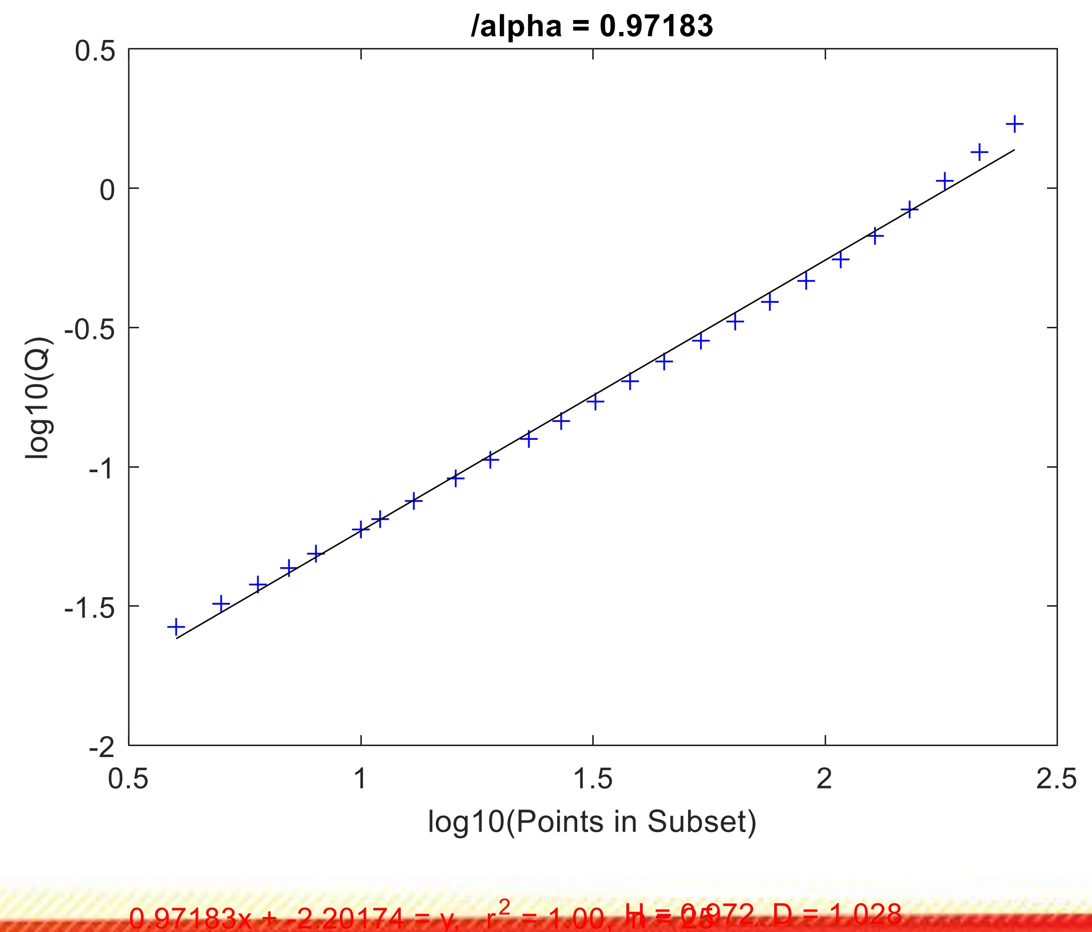
Or **C** & **D** in one step: fit a line in the bin and take SD of residuals… same result.



DFA: Pink noise

- Fit the slope:
  - α =.5 → white noise
  - α = 1 → pink noise
  - α = 1.5 → Brownian noise





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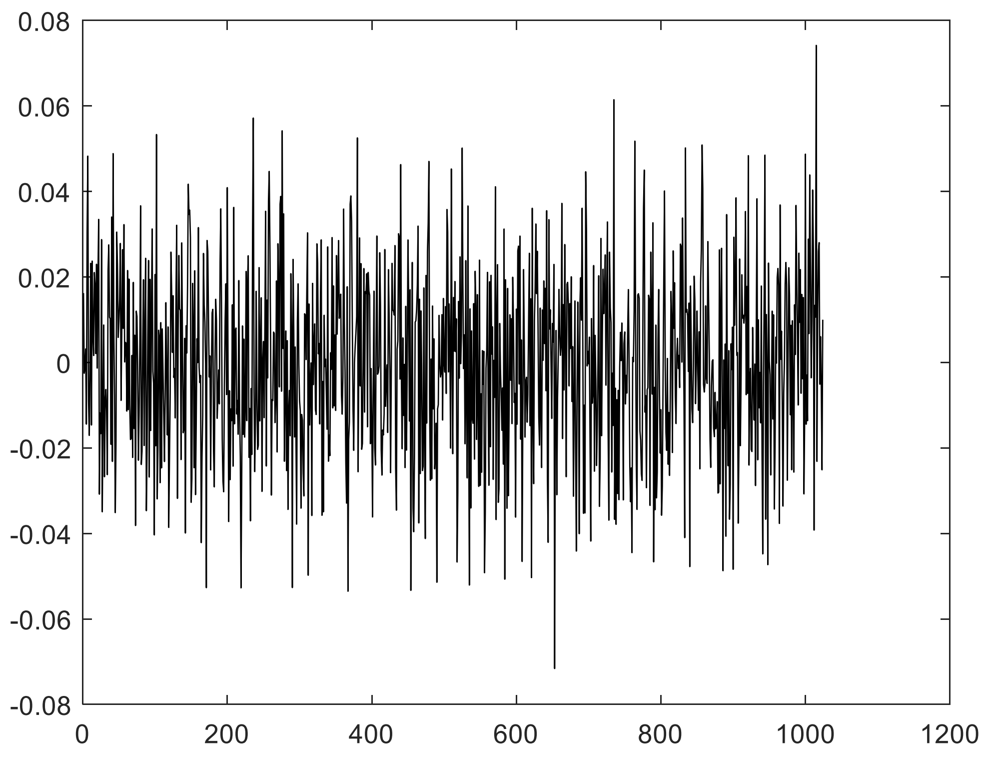

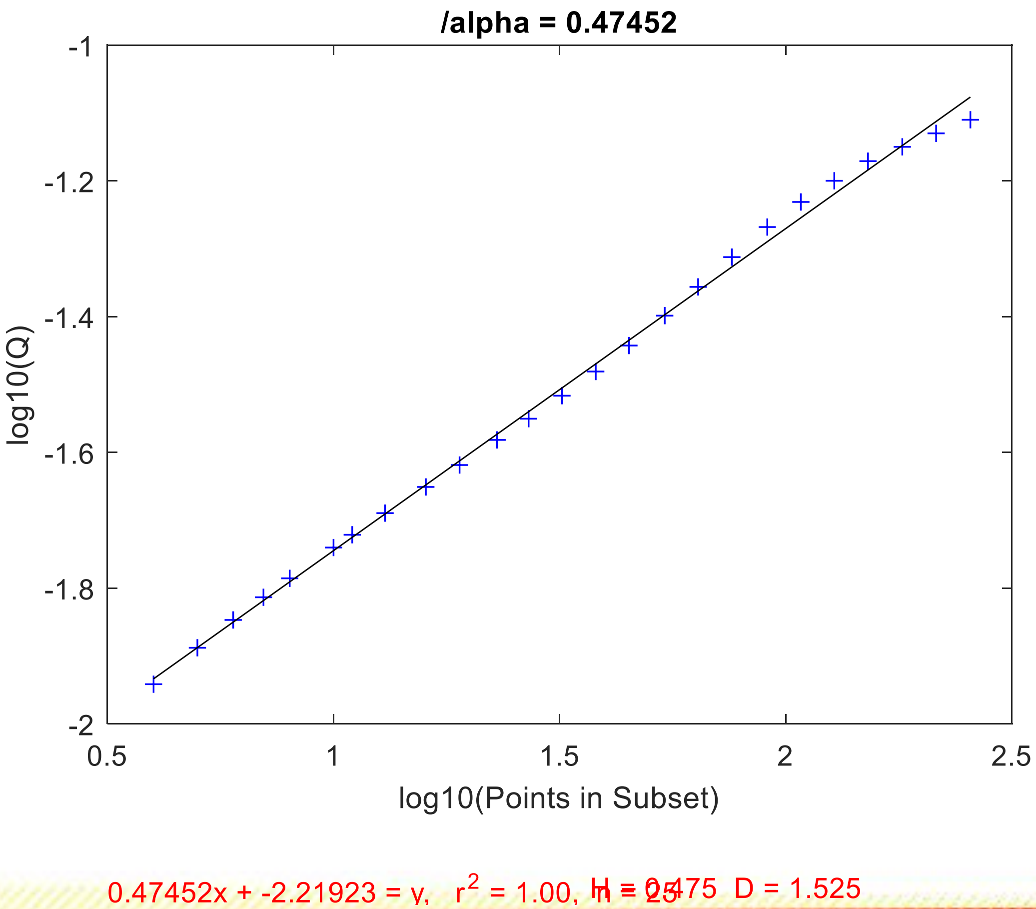

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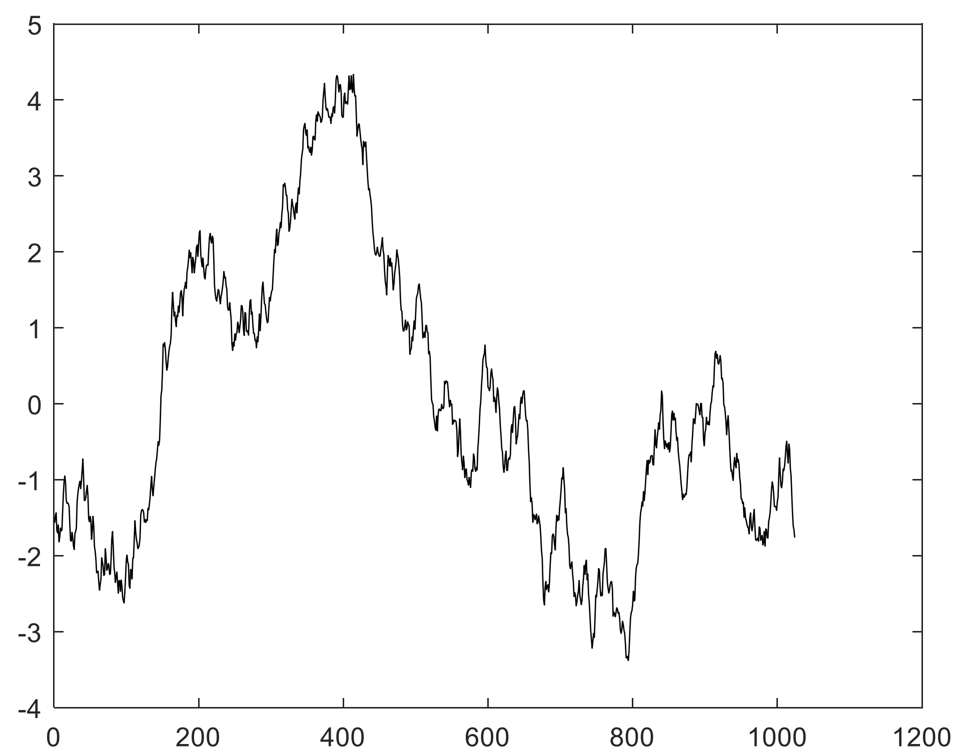
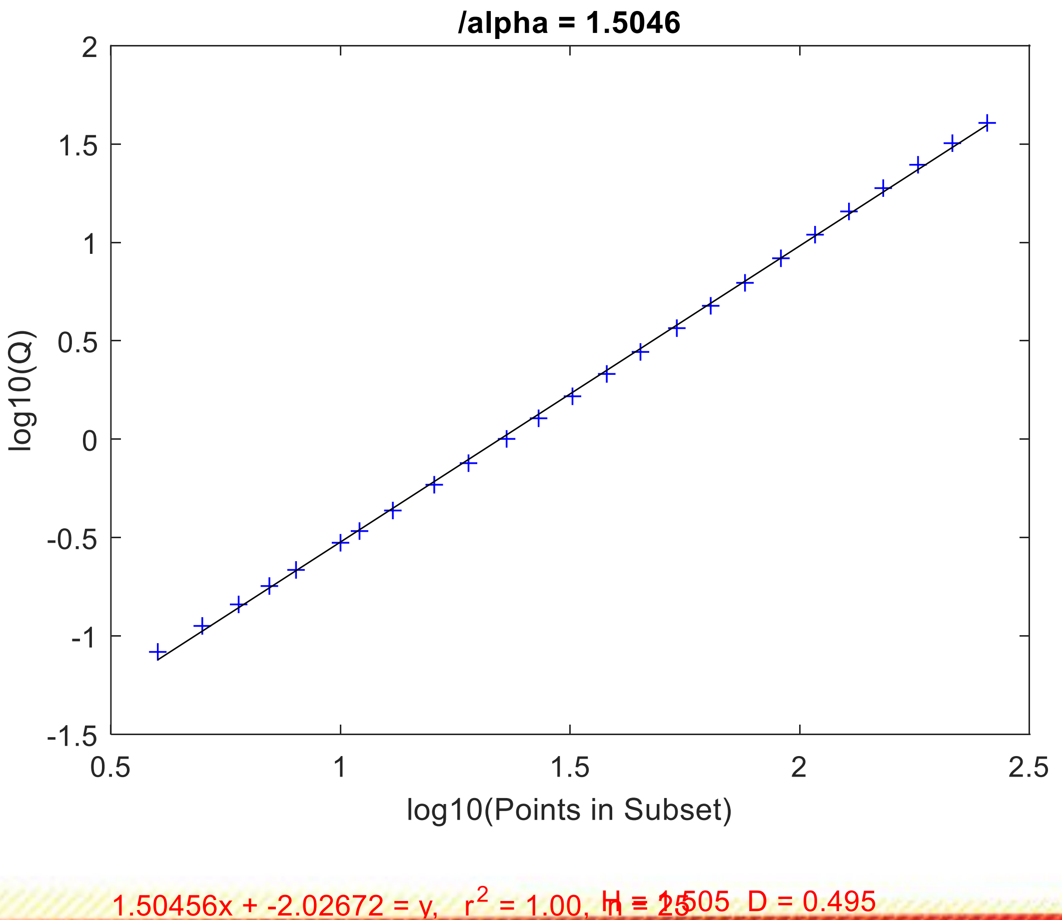




DFA

- Works for non-stationary signals

- Time series length
  - Power of 2
  - Sufficiently long

- Linear trends may do not disrupt the outcome
  - Detrending is an inherent part of the calculation

Applications

Empirical timeseries

- Do empirical timeseries actually reveal 1/f noise?
- Does the value of your scaling exponent matter?

  - Medicine & Physiology
  - Neuroscience
  - Cognition

Fractal physiology

- A healthy heart fluctuates a 1/*f* noise

- Deviations from 1/f noise correlate with mortality risk (Mäkikallio et al., 2001)
  - Congestive heart failure
  - Ventricular arrhythmia (Goldberger, 1997; Peng et al., 1995)

- Smaller deviations from 1/*f* noise
  - Aging (Goldberger, 2002)
  - Obese children (Vanderlei, Pastre, Júnior, & de Godoy, 2010)
  - Adults with down syndrome (Mendonca, Pereira, & Fernhall, 2011)

Fractal physiology

- A healthy respiratory system emits 1/*f* noise

- Breathing rhythm
  - 1/*f* noise → white noise
    - Aging (Peng et al., 2002; West, 2006)
  - White noise → 1/*f* noise
    - With gestational age in fetal development (Govindan, Wilson, Murphy, Russel, & Lowery, 2007)

- Also:
  - Asthma patients with more pronounced 1/*f* signatures in breathing rhythm show better recovery after treatment (Frey et al., 2005).

Fractal physiology

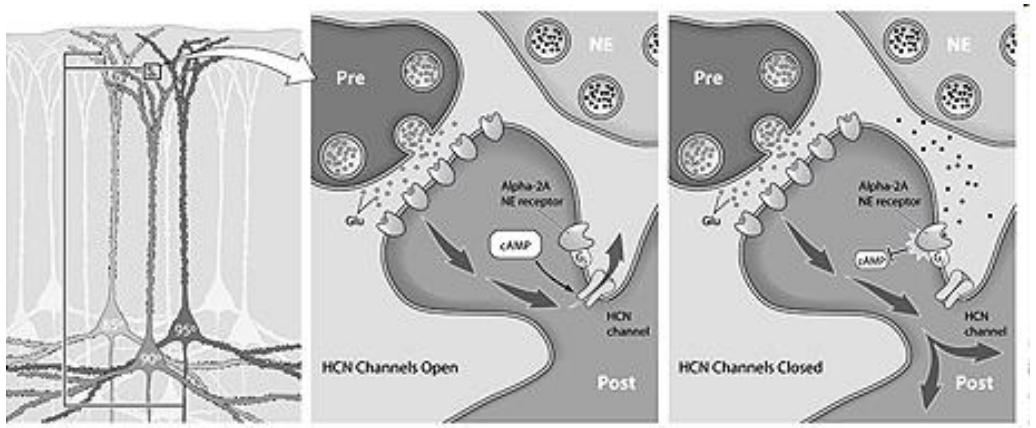
- Blood pressure fluctuates as $1/f$ noise (Mutch et al., 2000, Brogan et al., 2007)
  - Diabetic patients show reduced $1/f$ noise in glucose fluctuations in the blood flow compared with healthy controls (Ogata et al., 2007; Yamamoto et al., 2010).

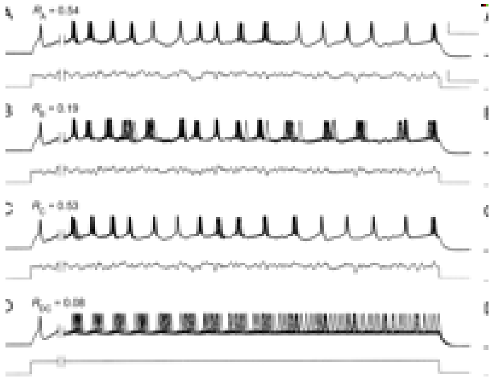
Fractal physiology

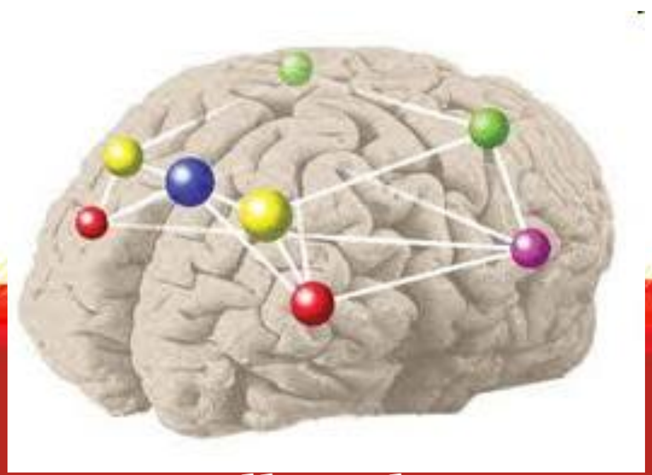
- Colon pressure
  - Patients hospitalized for slow transit constipation showed colon pressure fluctuations deviating from $1/f$ noise towards Brown noise (Yan, Yan, Zhang, & Wang, 2008).

Fractal neuroscience

- Ion Channels Opening and Closing Times
  - (Liebovitch & Krekora, 2002; Liebovitch & Shehadeh, 2005; Lowen , Cash, Poo, & Teich, 1997; Takeda, Sakata, & Matsuoka, 1999, Varanda, Liebovitch, Figueiroa, & Nogueira, 2000)
- Neural Spike Intervals
  - (Bhattacharya, Edwards, Mamelak, & Schuman, 2005; Giugliano, Darbon, Arsiero, Luescher, & Streit, 2004; Grüneis et al., 1993, West & Deering, 1994)
- Larger Scale Neural Assemblies
  - (Buzsàki, 2006; Bressler & Kelso, 2001; Freeman, Holmes, Burke, & Vanhatalo, 2003; Spasic, Kesic, Kalauzi, & Saponjic, 2010; Tognoli & Kelso, 2009; Varela, Lachaux, Rodriguez, & Martinerie, 2001; Werner, 2007)







Fractal neuroscience

- Deviations from 1/*f* noise in EEG
  - Major-Depressive Disorder (Linkenkaer-Hansen et al., 2005)
  - Mania (Bahrami, Seyedsadjadi, Babadi, & Noroozian, 2005)
  - Autism (Lai et al., 2010)
  - Epilepsy (Ramon, Holmes, Freeman, McElroy, & Rezyanian, 2008)
  - Alzheimer's Disease (Abásolo, Hornero, Gómez, García, & López, 2008)
  - ...

Some comprehensive review and discussion papers

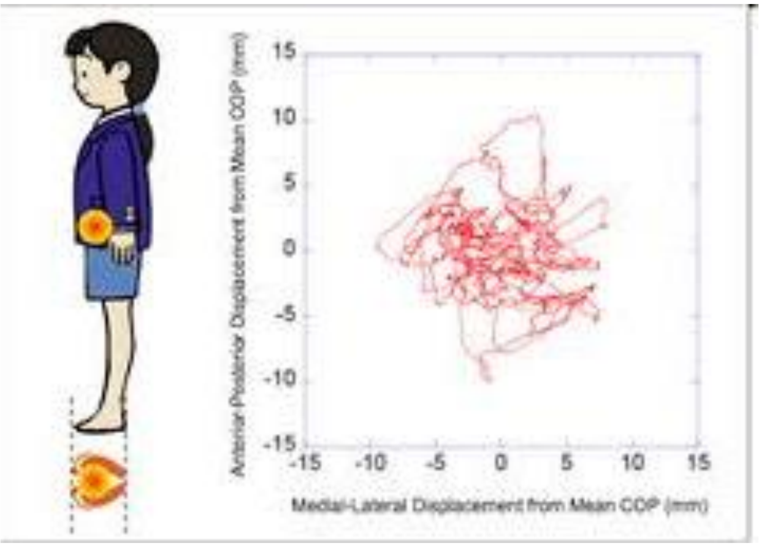
Temporal complexity is commonplace in different disciplines:

- Fractals in medicine
- Fractals in dentistry
- Fractals in pathology
- Fractals and cancer
- Fractals in finance
- Fractals in cell biology
- Fractals in cosmology
- Fractals in the neurosciences
- A link to the Frontiers in Fractal Physiology journal

Motor Control

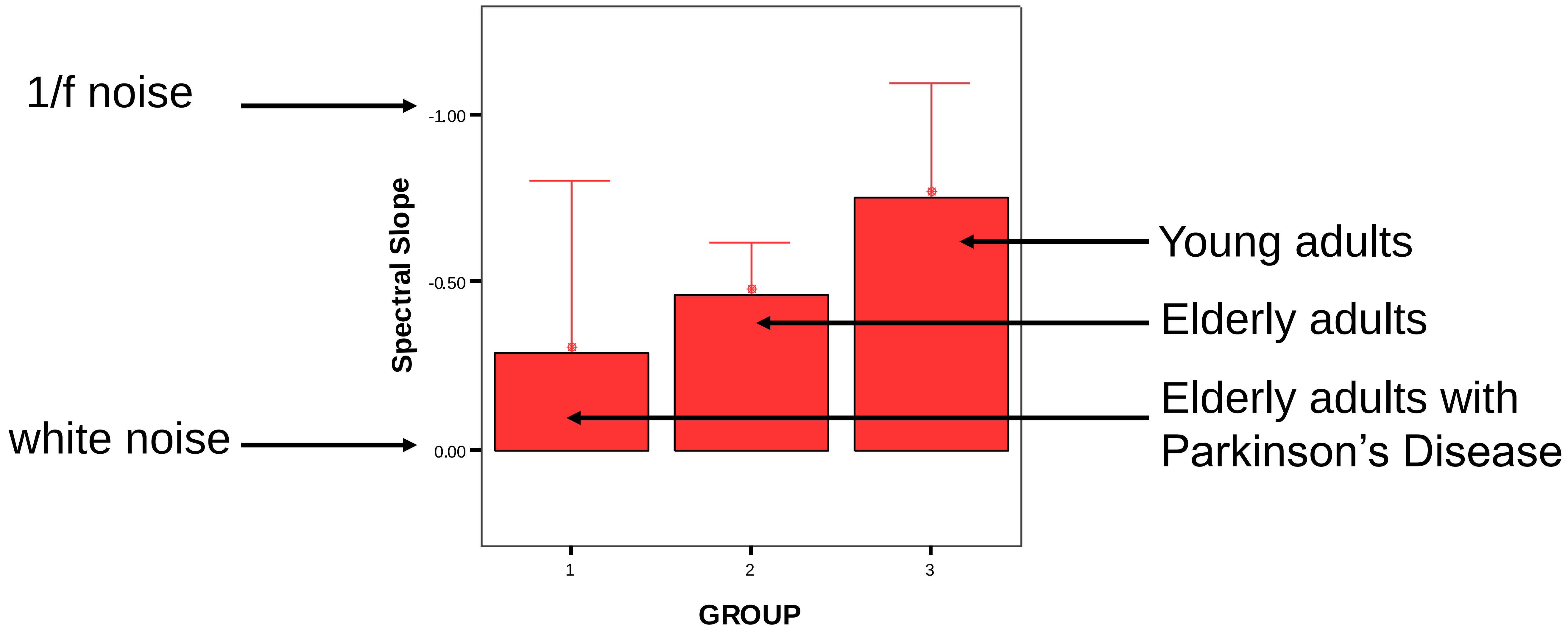
Posture

- A decrease in postural stability is accompanied by deviations from 1/f noise (Hong et al., 2006)



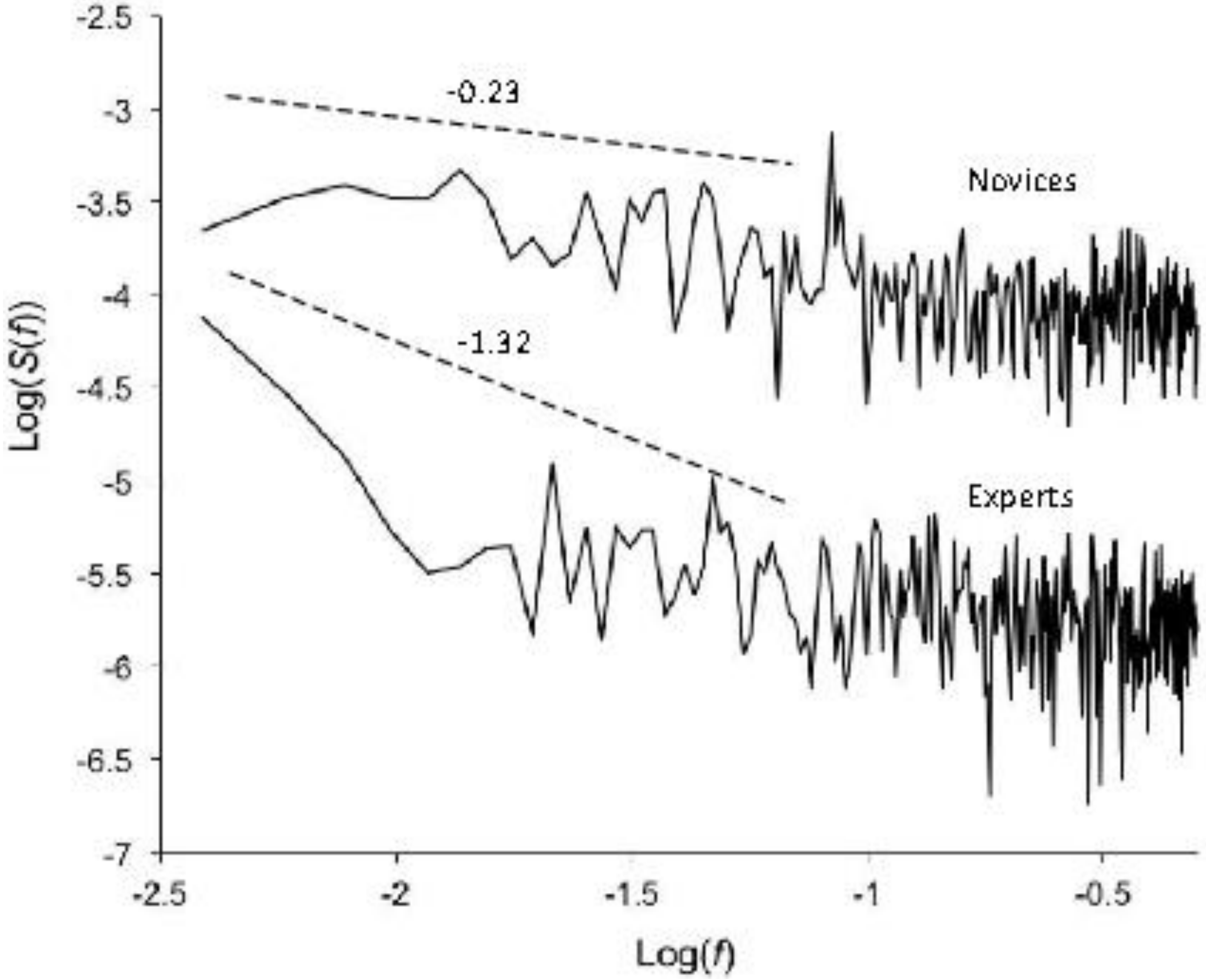
Correlation fractal dimension and falling risk in elderly (r = .78, $p < .0005$; Hausdorff, 2007)

Gait intervals



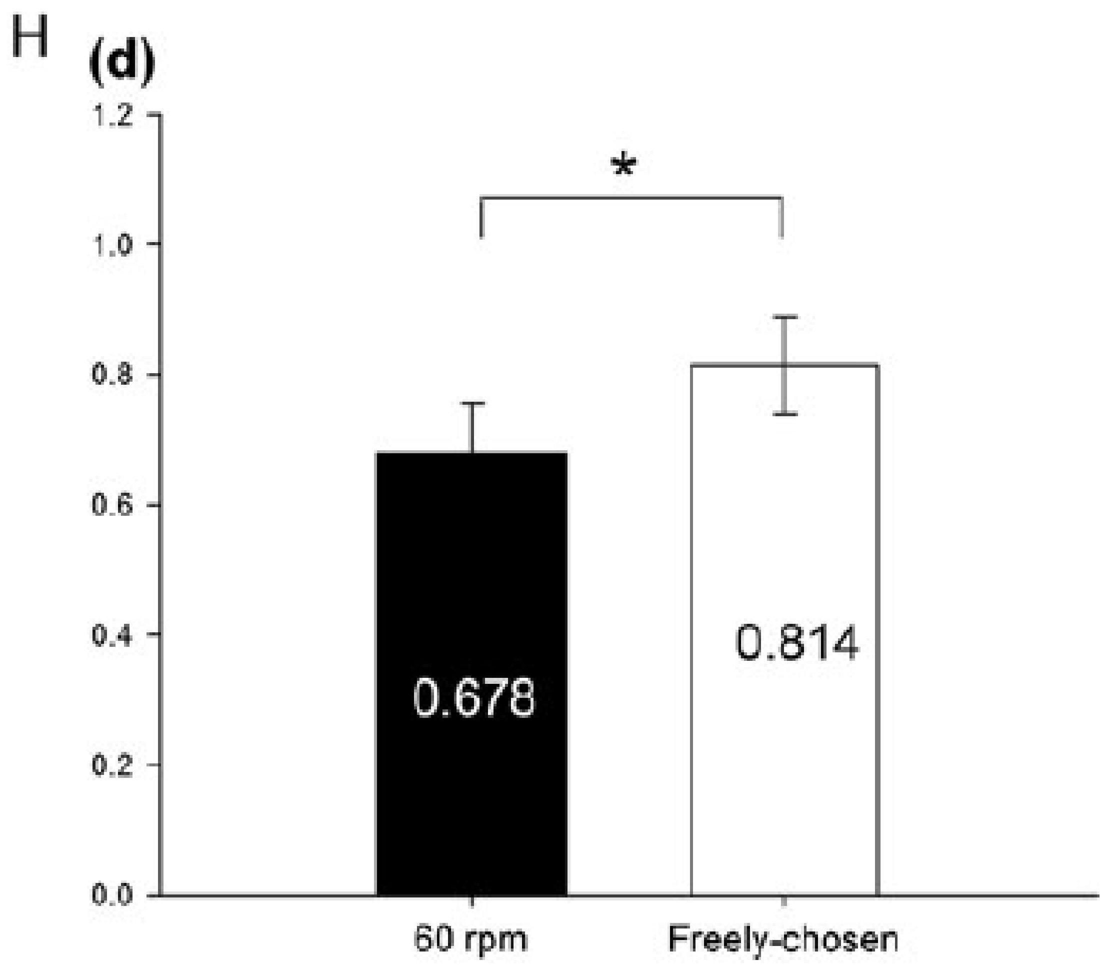
(Hausdorff, 2007)

Skiing



Nourrit-Lucas et al., 2014

Cycling

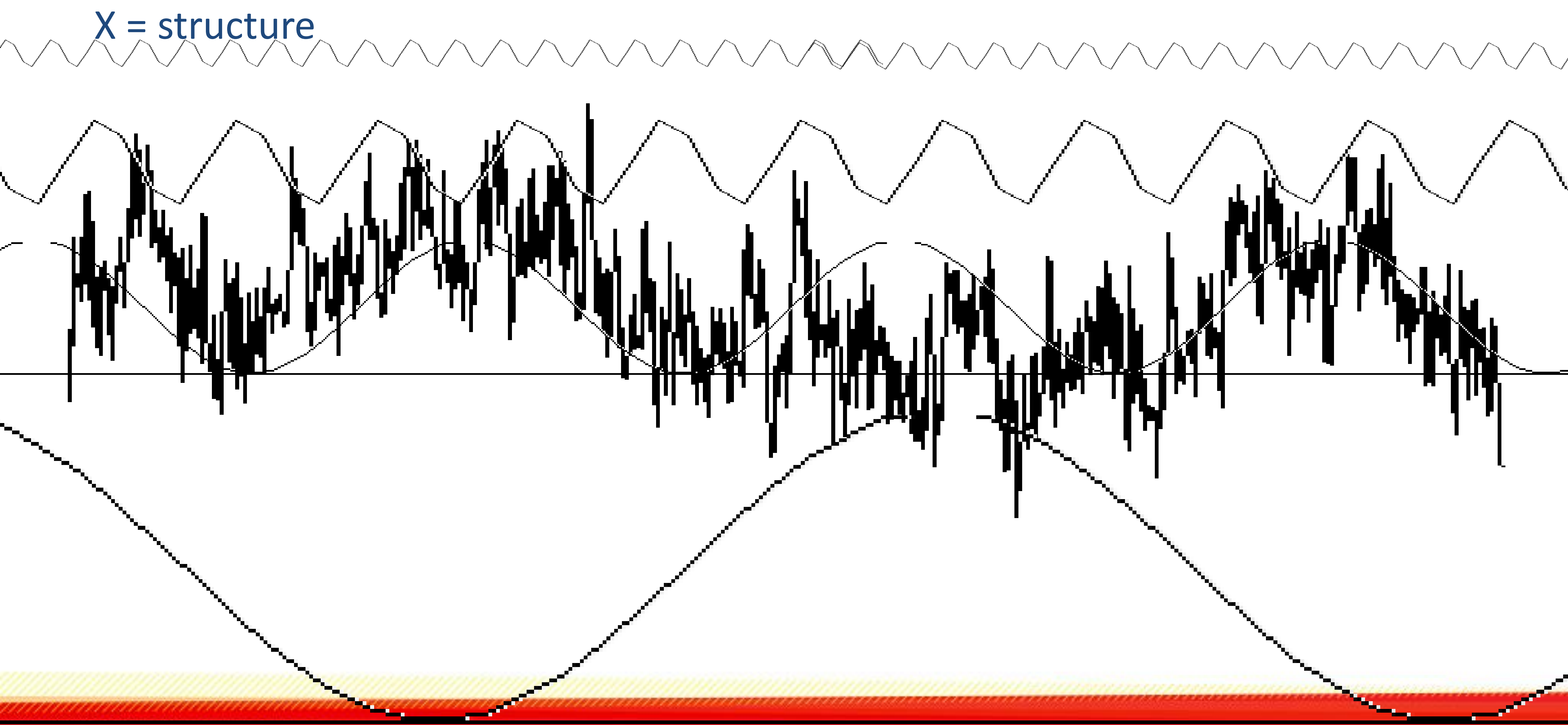


Warlop et al., 2013

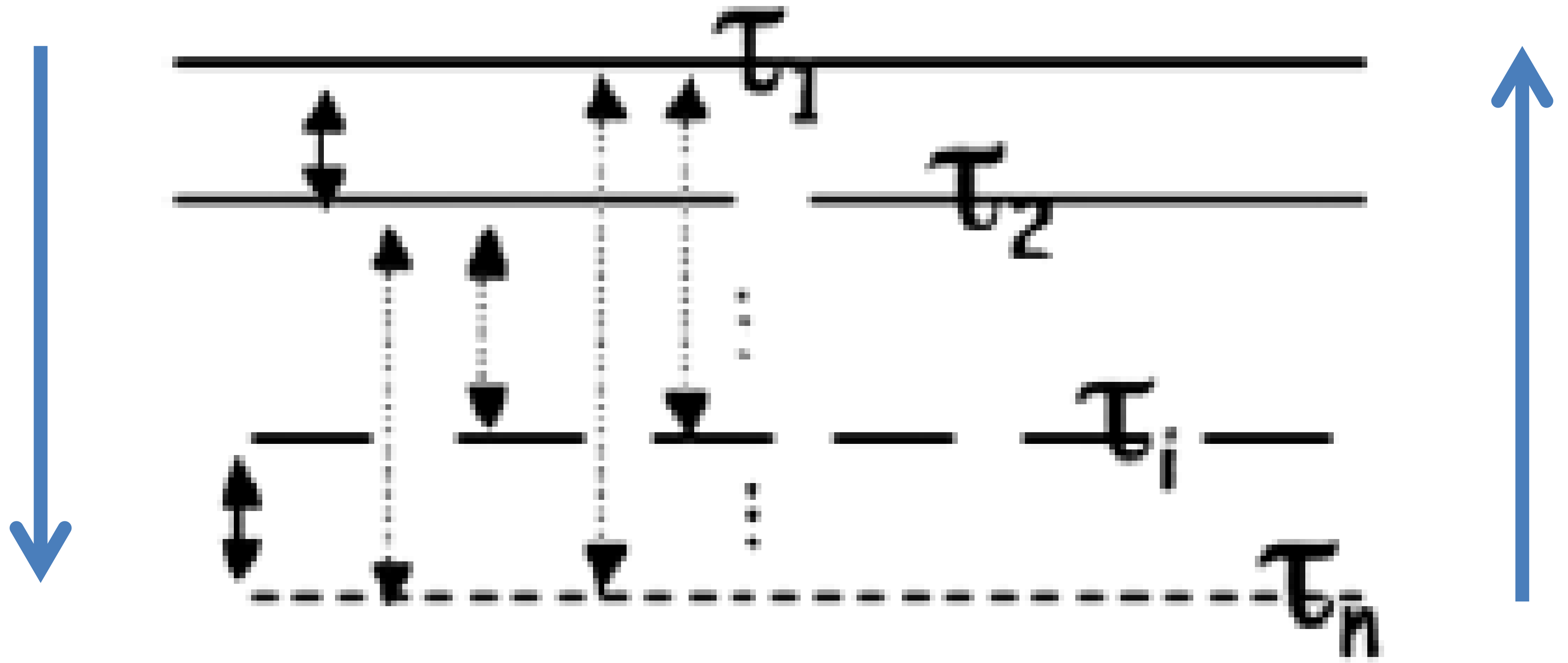
What can we learn from 1/f noise in cognitive performances?

Maarten Wijnants

Interaction-dominant dynamics



A hallmark of complexity



Changes on multiple time scales are coupled to changes on other timescales

- 1/f noise turns up in a lot of time series in psychological experiments

Elementary "production" tasks:
Repeated production of a Spatial or a Temporal interval

Elementary "Motor" tasks:
Postural sway
Tapping and walking
Swinging pendula
Juggling

Patterns of mood change:
Repeated judgments of self-esteem (2 per day, over 512 days!)

Classic "Cognitive" tasks:
Simple reaction time
Perceptual learning
Visual search
Classification
Word naming
Lexical decision
Mental rotation

1/*f* scaling and cognition

- Individual response times provide an incomplete description of actual cognitive performances
  - 'basic features of a performance cannot simply be averaged out.'

- Interaction-dominant dynamics

  - 1/f emerges through coordinated interactions between components
  - Components at different scales change each others dynamics
  - No statistically independent components:
    – A single process extends across all time scales of variation

e.g. Holden, Van Orden & Turvey, 2008

Coordination

- Proof of the pudding
  - Can we systematically manipulate the strength of long-range correlations?
    - E.g. skilled performances
  - Can we seperate internal fluctuations (system dynamics) from external fluctuations (perturbations)?

Task constraints

External perturbations add extraneous random variation to the measured performances: Accuracy feedback

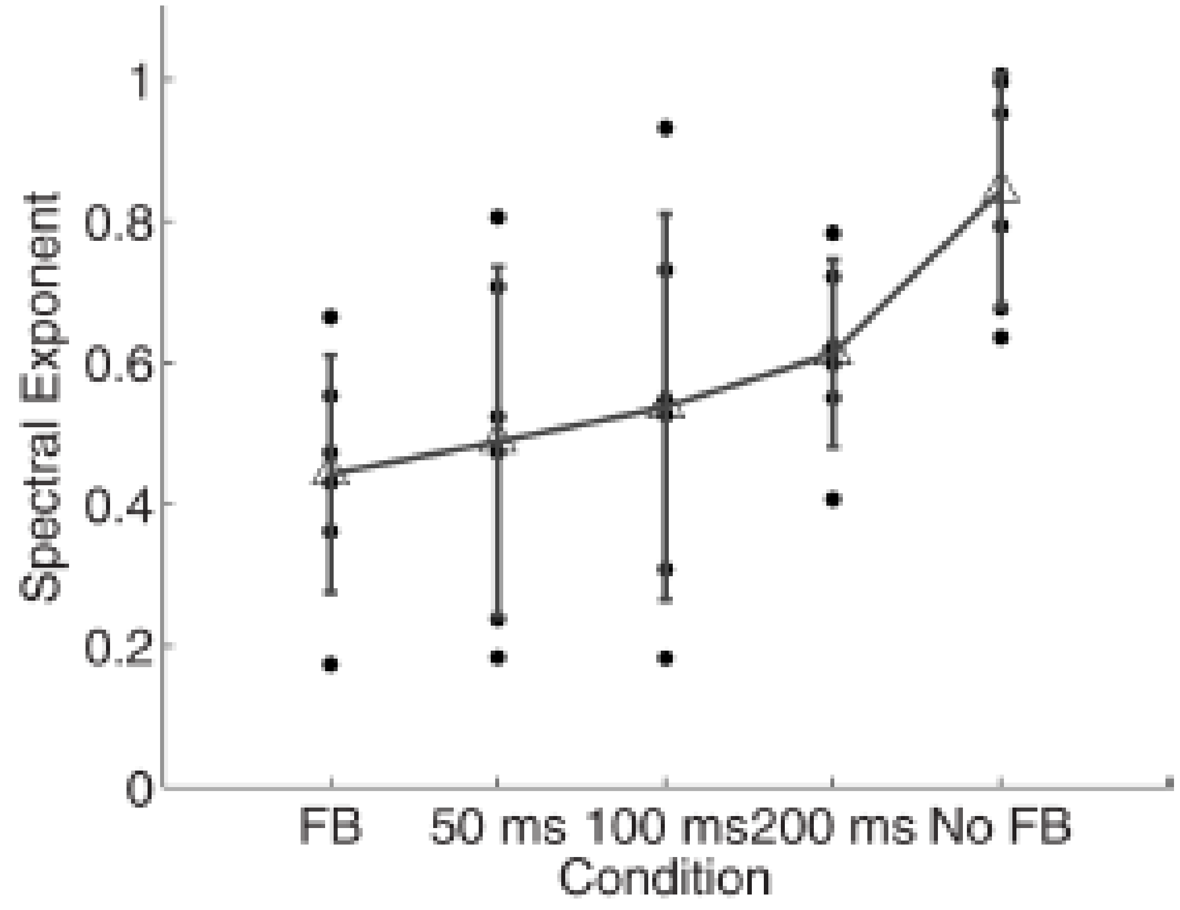


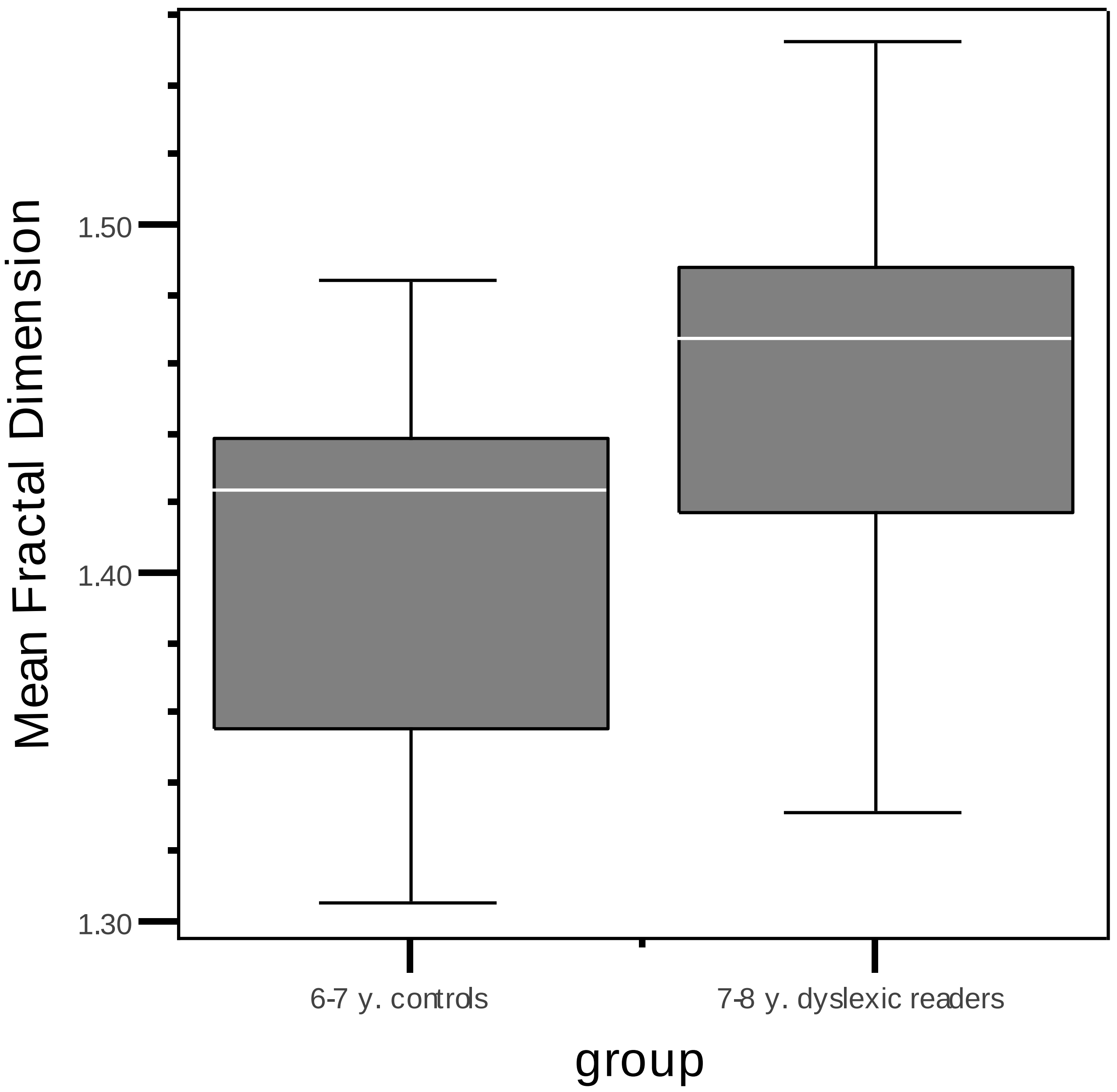
FIGURE 3 | Spectral exponents of the time estimates. Spectral exponents α closer to 0 imply presence of white noise whereas values closer to 1 suggest pink noise. Individual points represent observations from individual participants. Error bars plot within-condition SD.

Kuznetsov & Wallot (2011)

Word-naming

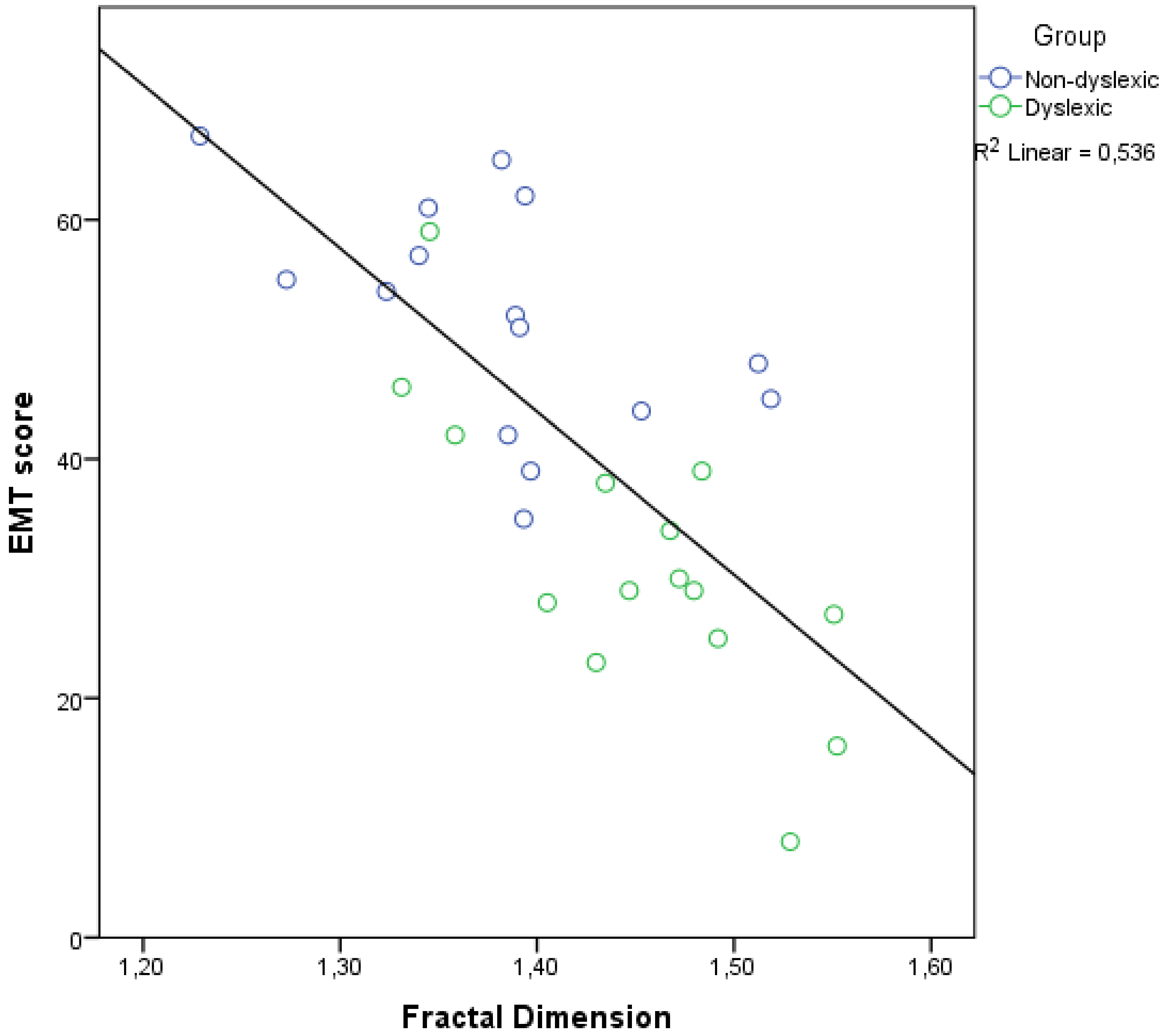
- 7-8 year old Dyslexic Readers
- 6-7 year old Controls
- 1 Block of 550 Word Stimuli

- ➔ Dyslexic Readers Show Reduced 1/f Noise



Word-naming

- Oral reading fluency is regarded as the sole best indicator of reading problems (Fuchs, Fuchs, Hosp, & Jenkins, 2001)



Within-Group Correlations: dyslexics vs. non-dyslexics

		Fractal Dimension	Recurrence Rate	Determinism	Entropy	Meanline
Dyslexics (N = 15)	Mean RT	.56*	-.70**	-.88**	-.81**	-.77**
	St. Dev. RT	.68**	-.71**	-.84**	-.76**	-.74**
	EMT	-.77**	.84**	.75**	.79**	.83**
Non-Dyslexics (N = 15)	Mean RT	.24	-.10	-.12	-.25	-.24
	St. Dev. RT	.49	.39	.33	.23	.24
	EMT	-.28	.37	.53*	.43	.41

** $p < 0.01$, * $p < 0.05$ (two-tailed).

➔ 1/f noise and RQA outcomes are strongly correlated with the severity of the reading impairment