Radboud Summer School

Complexity Methods for Behavioural Science

Dr. Maarten Wijnants

Guest Lecture: Applications of fractal analysis

Faculty of Social Sciences
Nijmegen

change perspective

Radboud University

Different faces of variability

High variability

Low variability

Variability as noise

- $X = T + E$

➔ Amount of variability

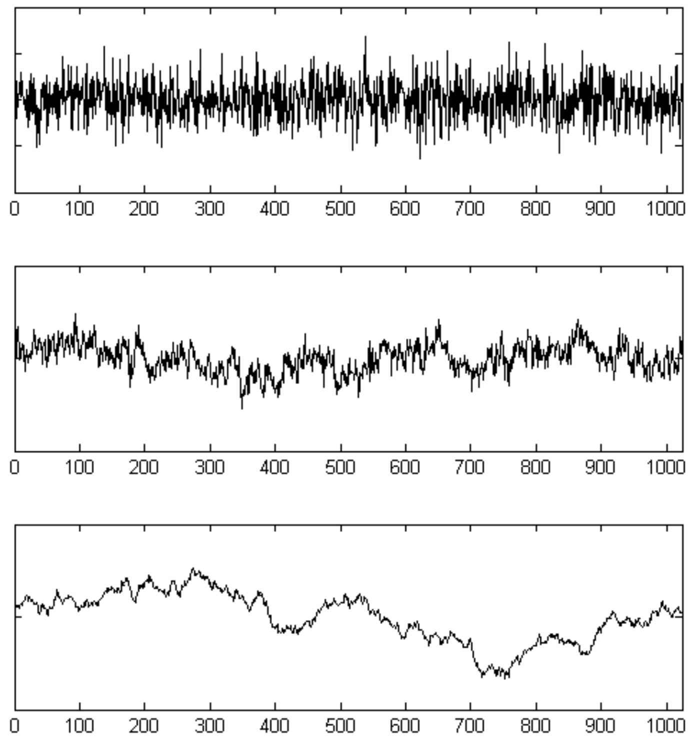
- Low ←→ High
- e.g., standard deviation

Variability as structure

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

➔ Temporal correlations

- Structured ←→ Unstructured
- e.g., ACF, roughness, entropy, DFA, SDA, spectral analysis,…



White noise ($1/f^0$)
SDA: FD = 1.5
DFA: α = 0.5
Spectral: β = 0

Pink noise ($1/f^1$)
SDA: FD = 1.2
DFA: α = 1
Spectral: β = -1

Brownian noise ($1/f^2$)
SDA: FD = 1.1
DFA: α = 1.5
Spectral: β = -2

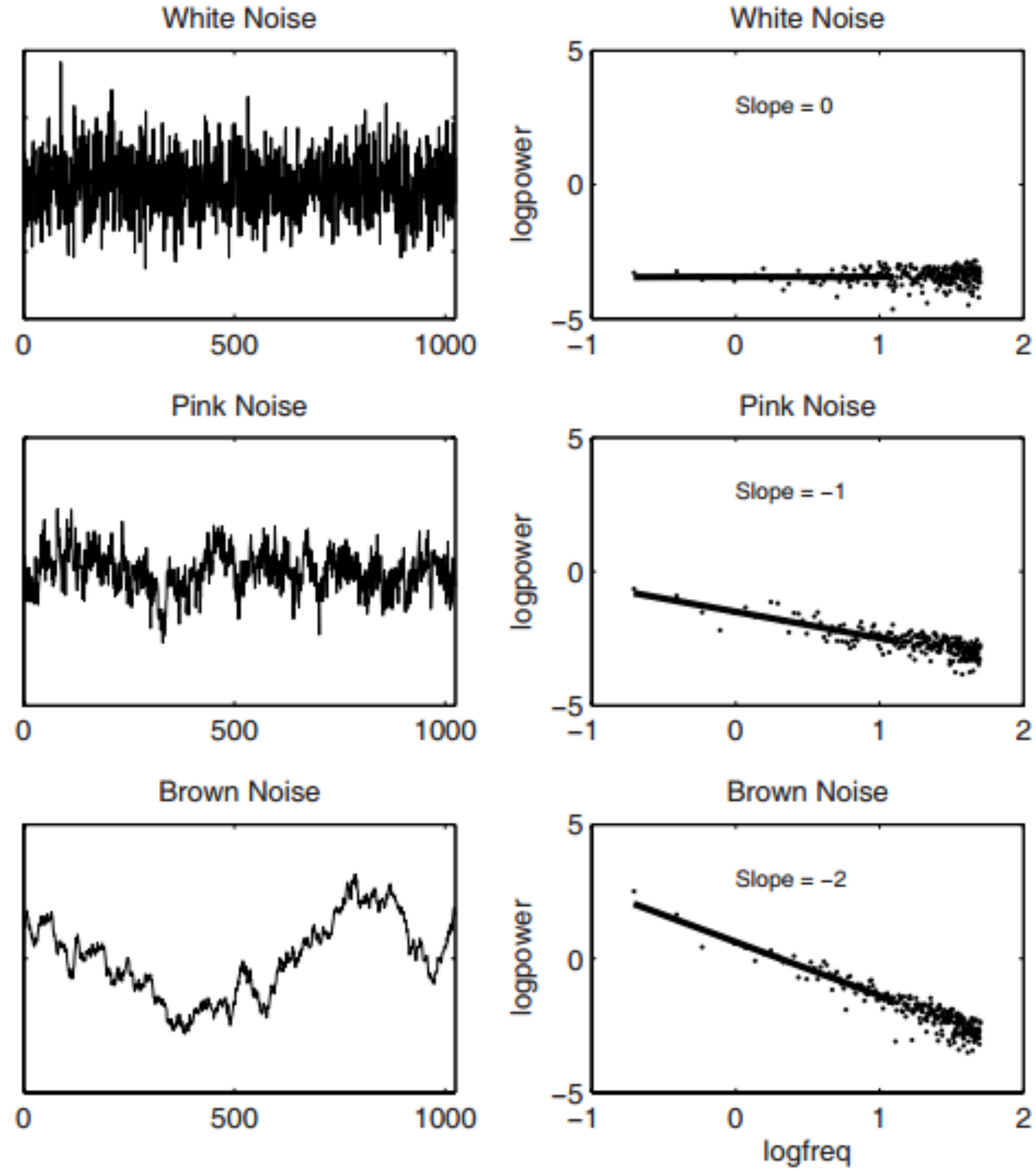
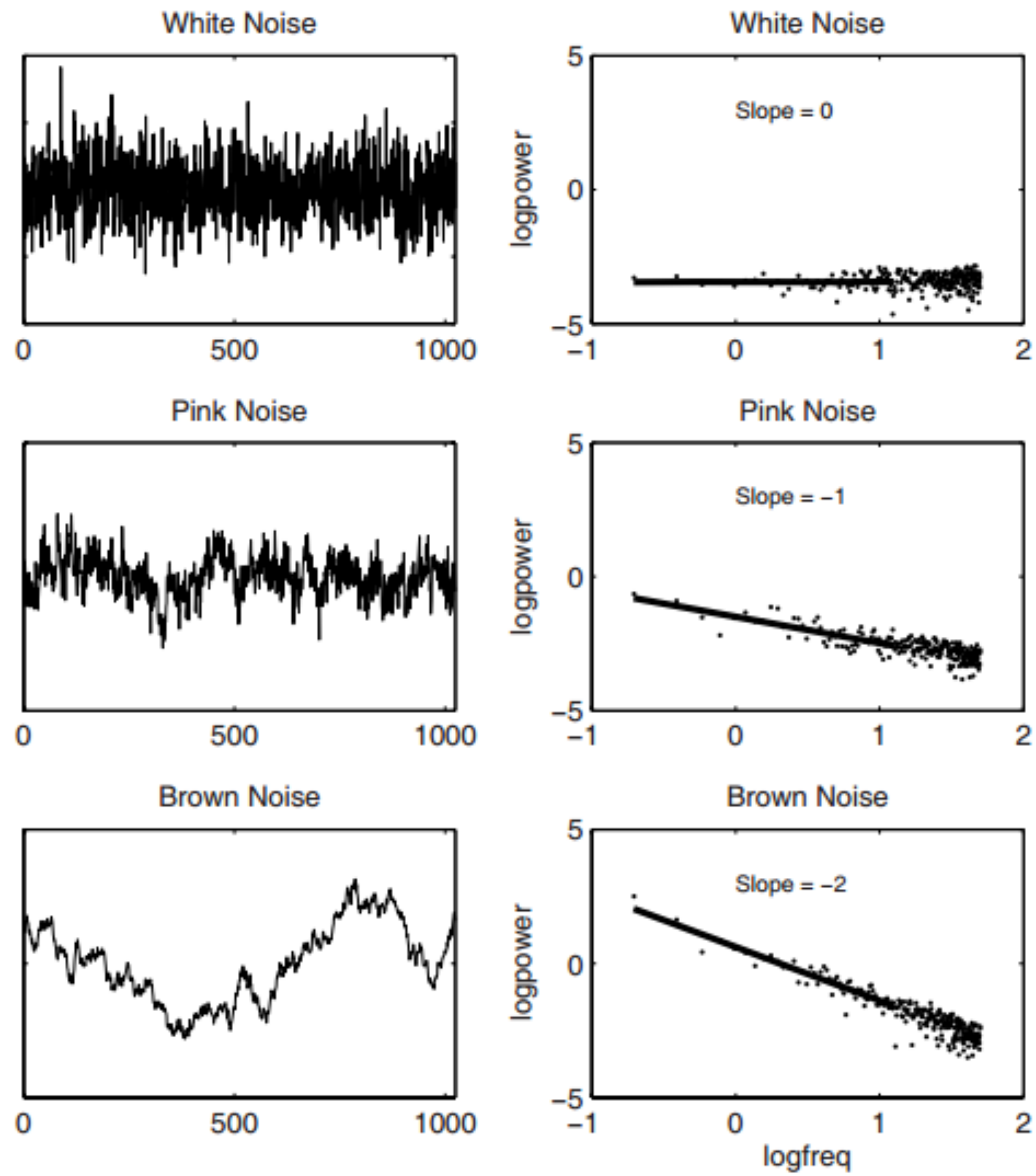


FIGURE 3 | Three different classes of temporal variability, white noise (upper left panel), 1/*f* scaling (middle left panel), and Brownian noise (lower left panel), and their respective power spectra are shown in the respective panels at the right.

<u>White noise ($1/f^0$)</u>
Unconstrained
Random
Independent behavior

<u>Pink noise ($1/f^1$)</u>
Reduced degrees of freedom
Statistical self-similarity
Every data point participates
in a larger, scale-free pattern

<u>Brownian noise ($1/f^2$)</u>
Highly constrained
Persistent
Strong serial dependence



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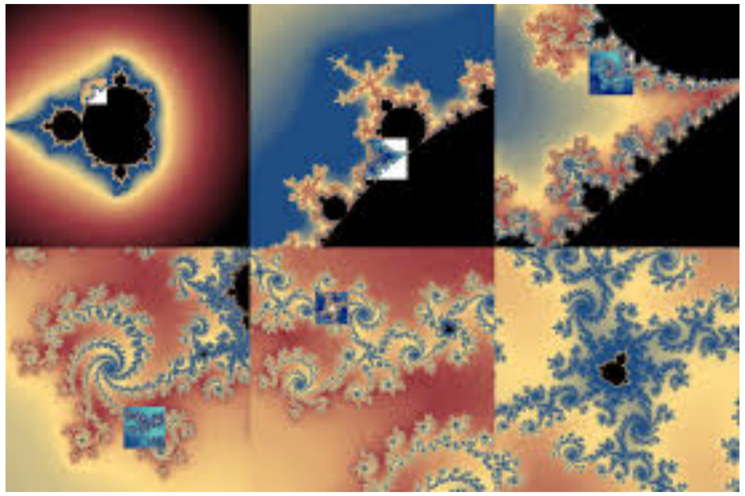
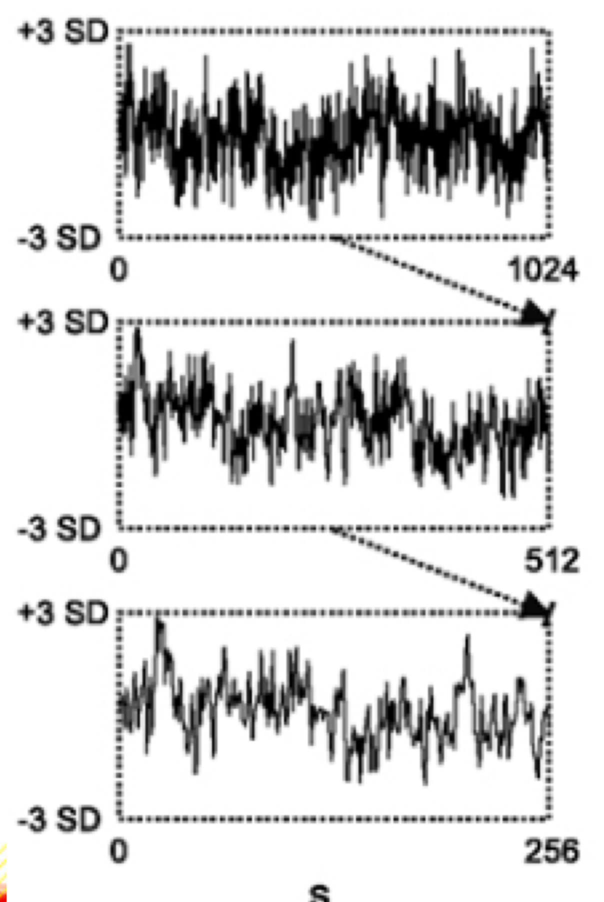
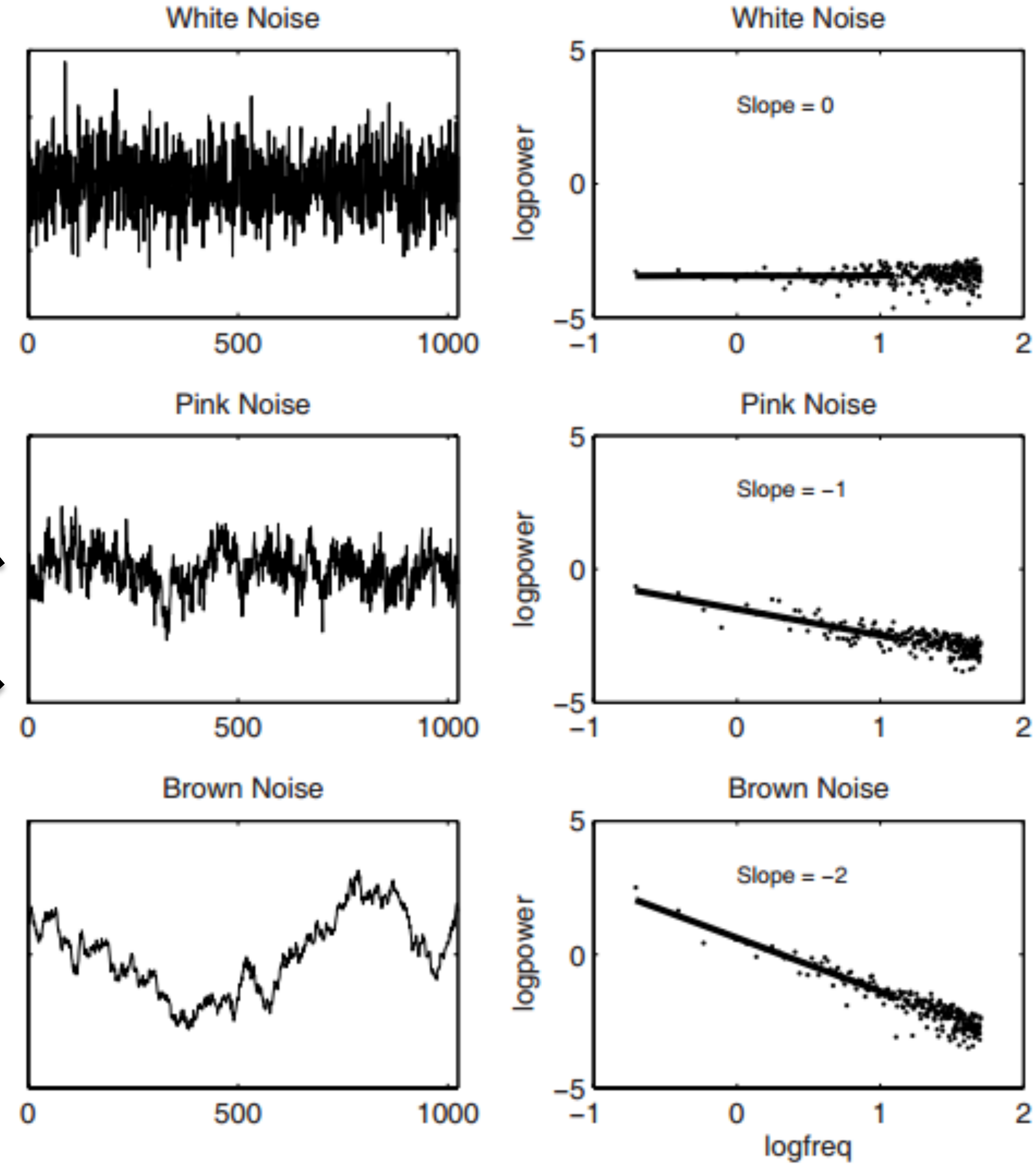
Every data point participates in a larger, scale-free pattern







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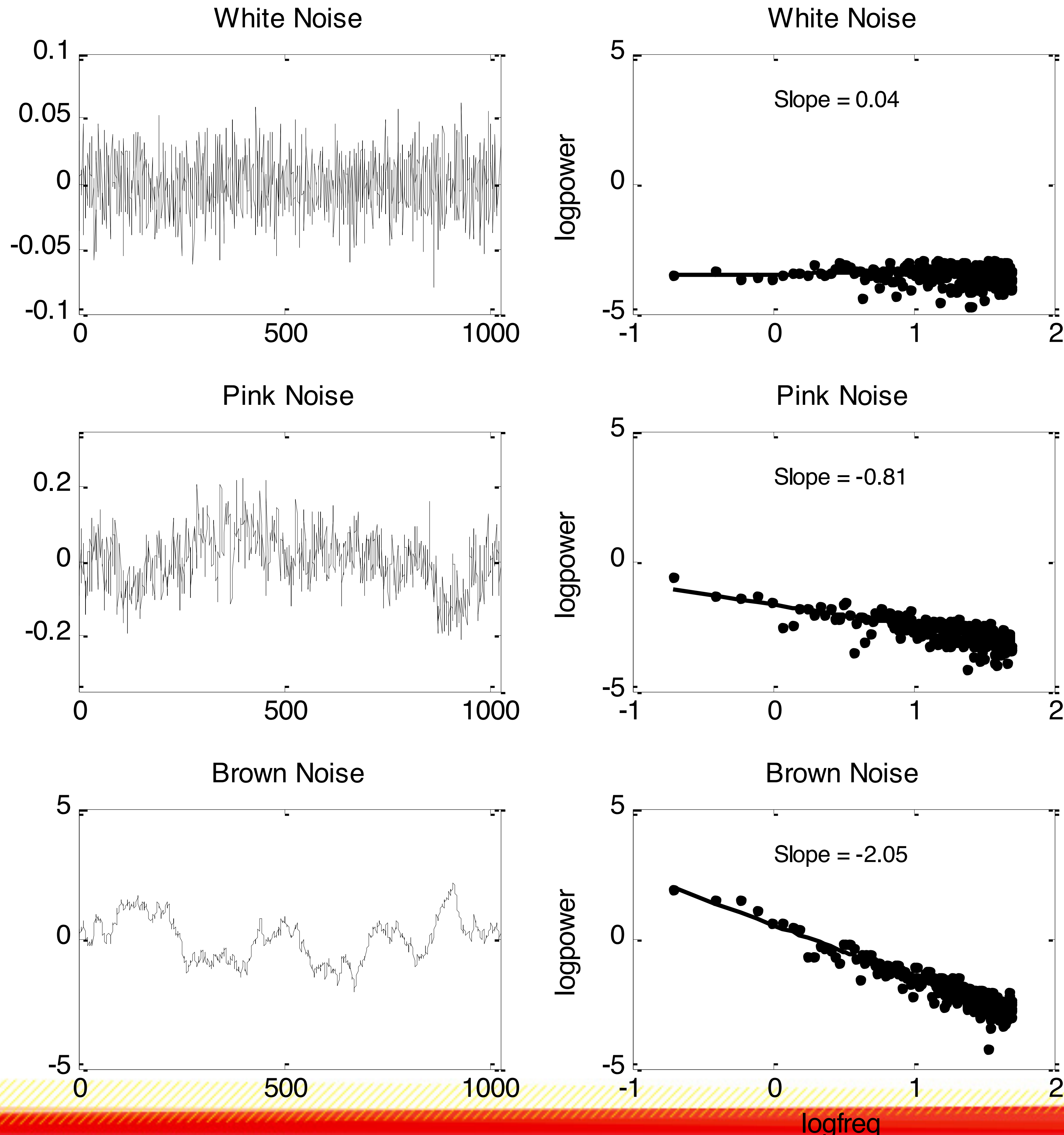
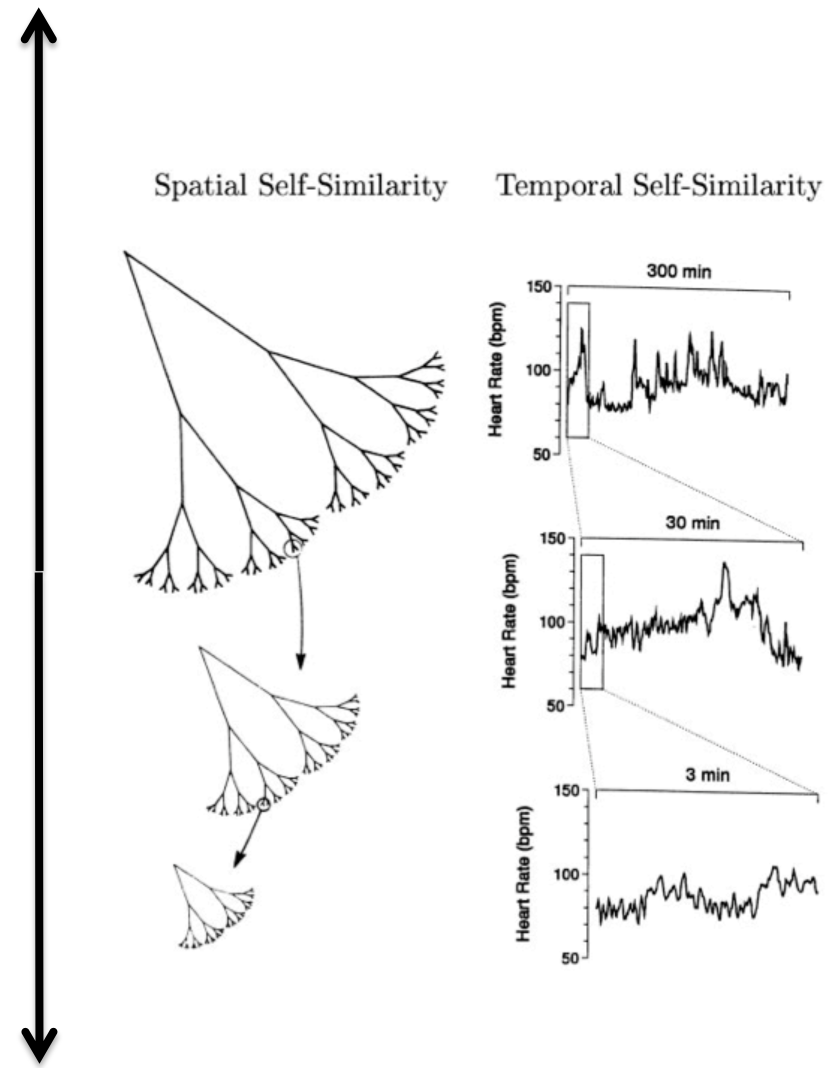
$f(x) = 1/f^{\alpha}$

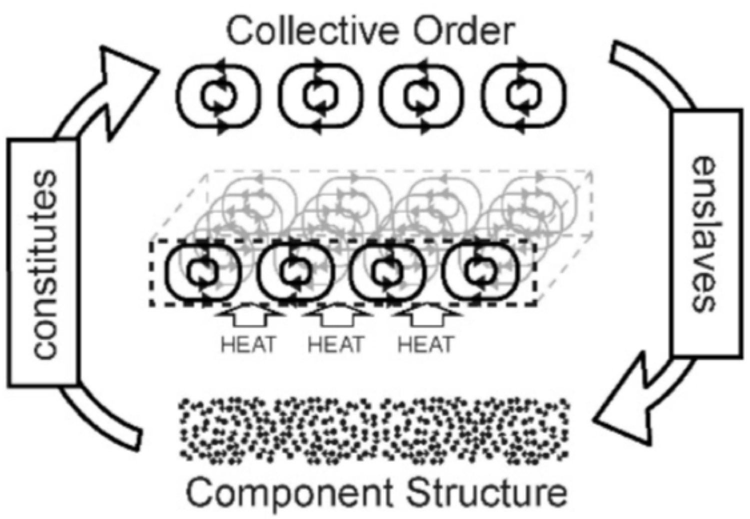


Disorganized



Rigid & persistent

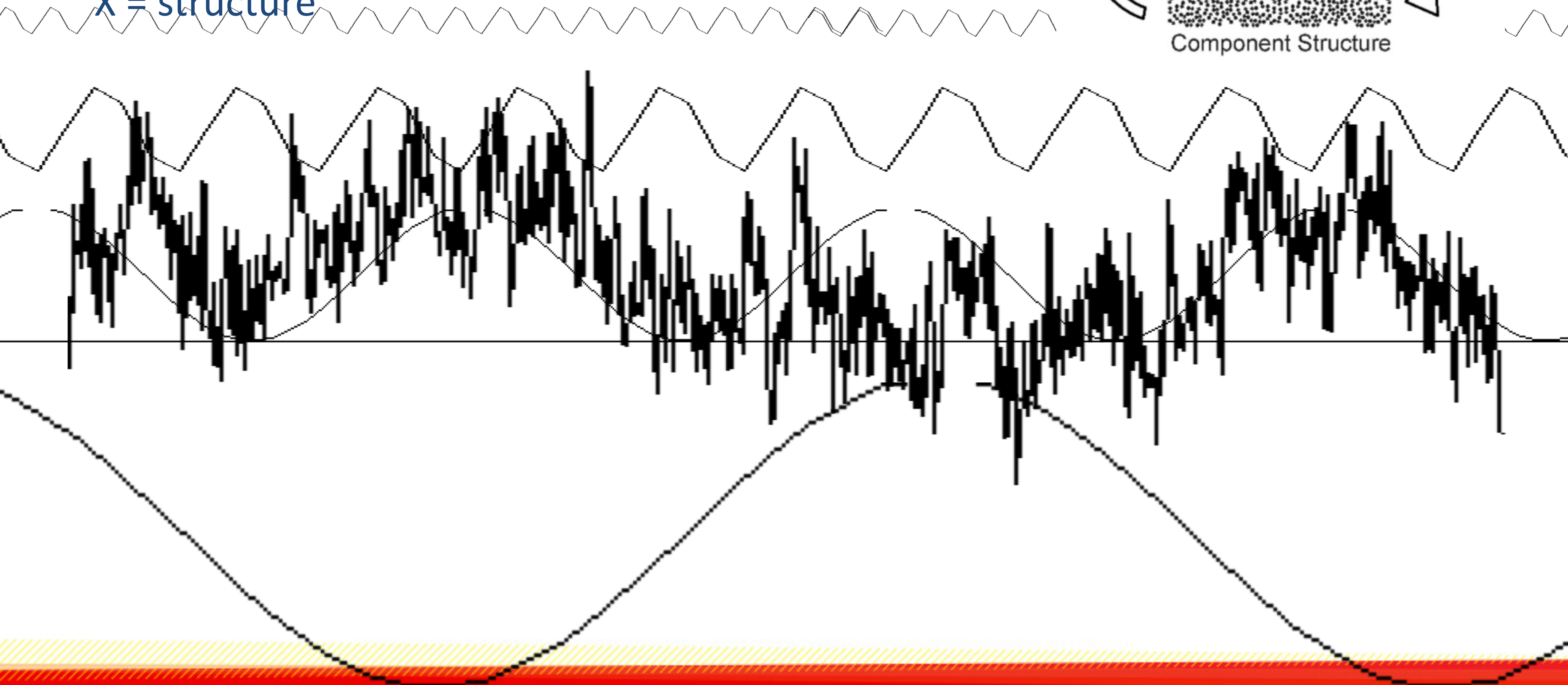
Interaction-dominant dynamics



1/*f* noise = fingerprint of self-organized systems

Part-whole relation

X = structure



Empirical timeseries (Applications)

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

- Medicine & Physiology
- Neuroscience
- Cognition

Fractal physiology

A healthy heart fluctuates as 1/*f* noise

Loss of function = loss of complexity

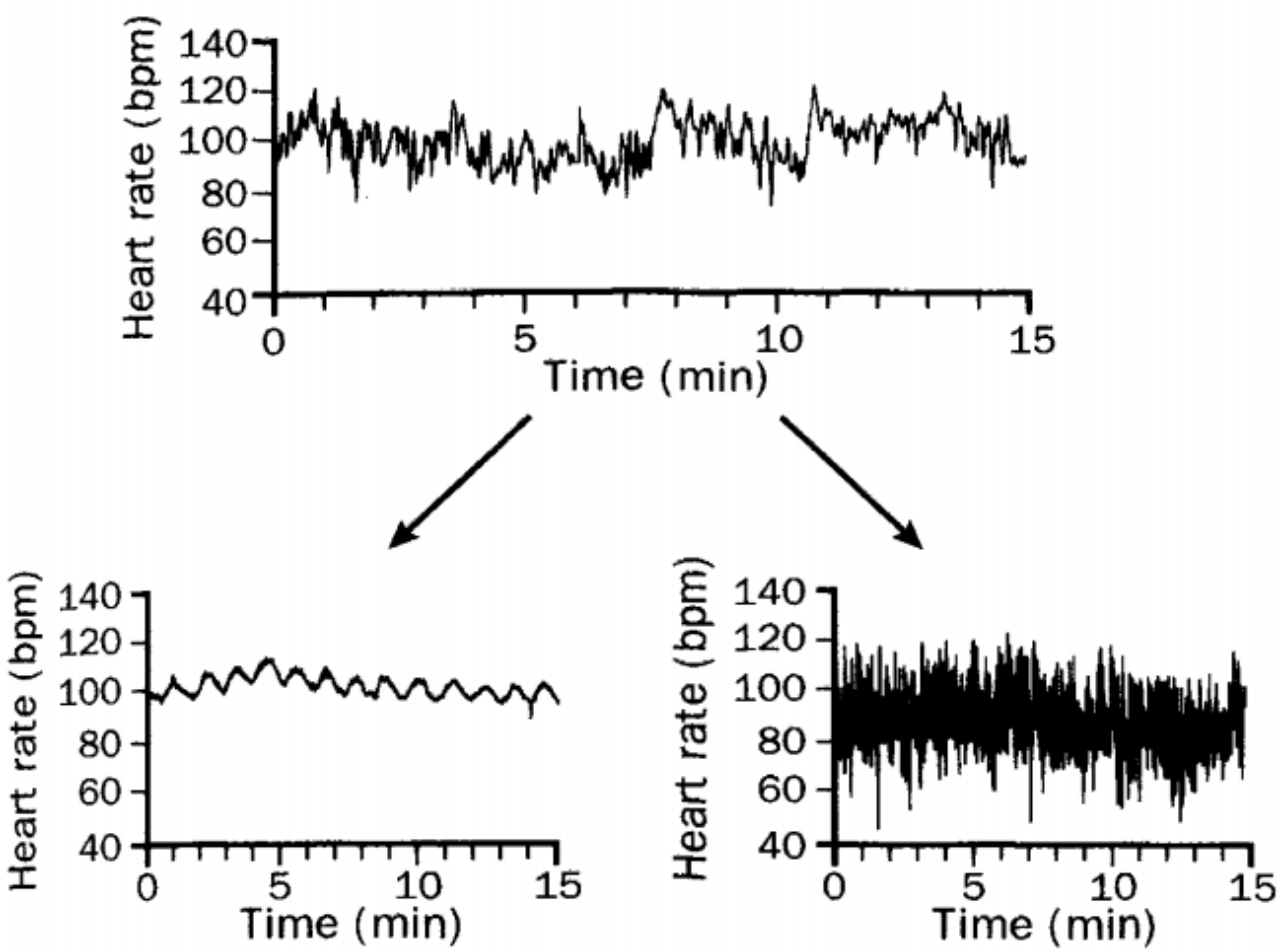


Figure 2: **Healthy dynamics (top), showing multiscale, long-range order; pathological breakdown of fractal dynamics, leading to single-scale (bottom left) or uncorrelated randomness (bottom right)**

Top heart-rate time-series is from a healthy individual; bottom left is from patient with heart failure, and bottom right from patient with atrial fibrillation.

Fractal physiology

A healthy heart fluctuates as 1/*f* noise

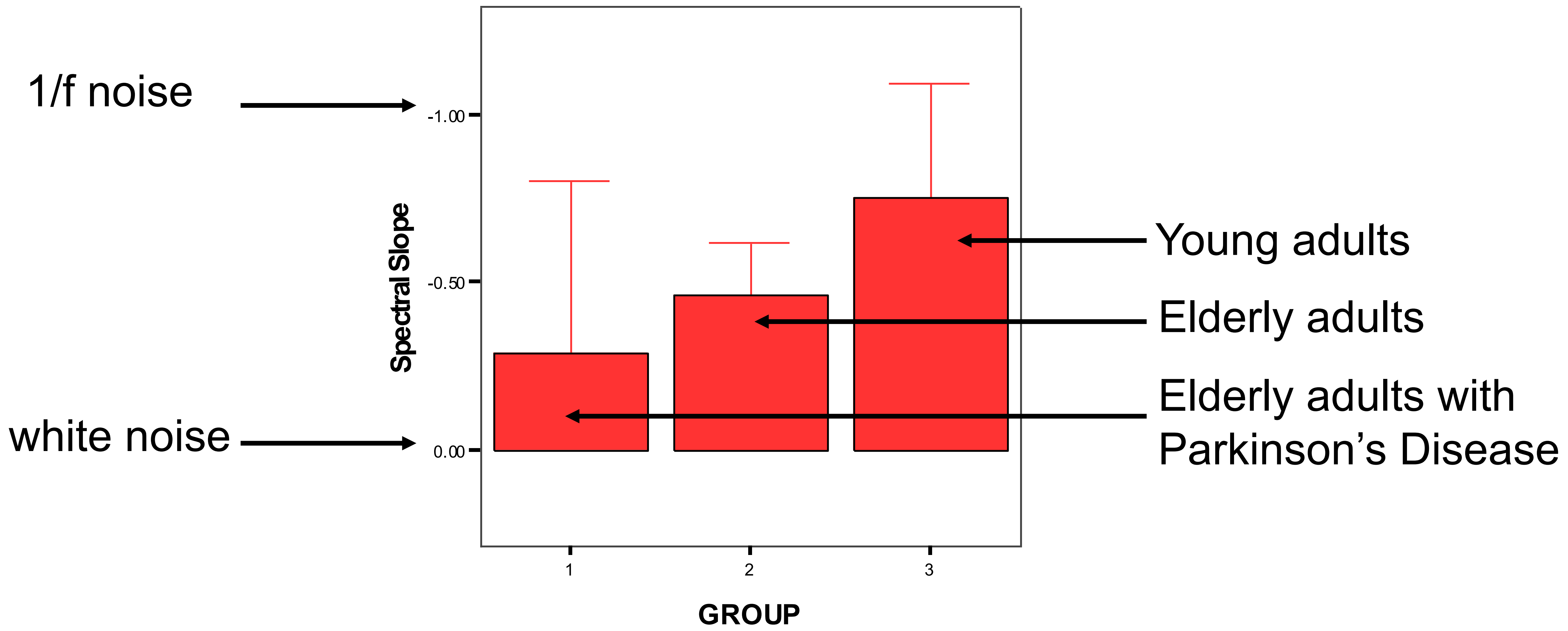
Deviations from 1/f noise correlate with mortality risk (Mäkikallio et al., 2001)

- Congestive heart failure
- Ventricular arrhythmia (Goldberger, 1997; Peng et al., 1995)

More subtle deviations from 1/*f* noise

- Aging (Goldberger, 2002)
- Obese children (Vanderlei, Pastre, Júnior, & de Godoy, 2010)
- Adults with down syndrome (Mendonca, Pereira, & Fernhall, 2011)

Gait intervals



(Hausdorff, 2007)

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)

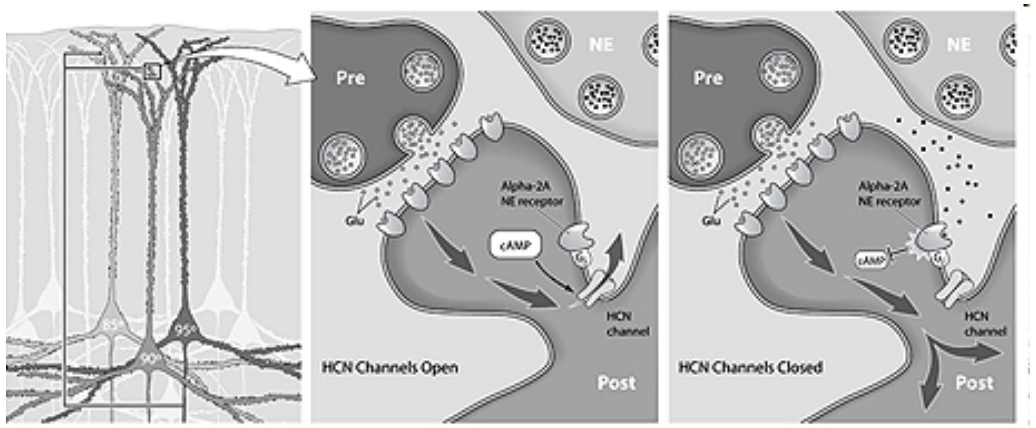
- Diabetic patients show reduced 1/*f* noise in glucose fluctuations in the blood flow compared with healthy controls (Ogata et al., 2007; Yamamoto et al., 2010).

Fractal physiology

Colon pressure

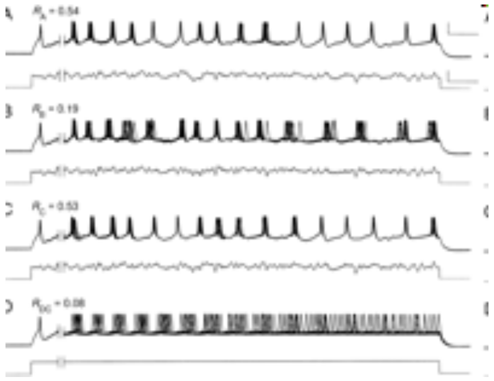
- Patients hospitalized for slow transit constipation showed colon pressure fluctuations deviating from $1/f$ noise towards Brownian noise (Yan, Yan, Zhang, & Wang, 2008).

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)

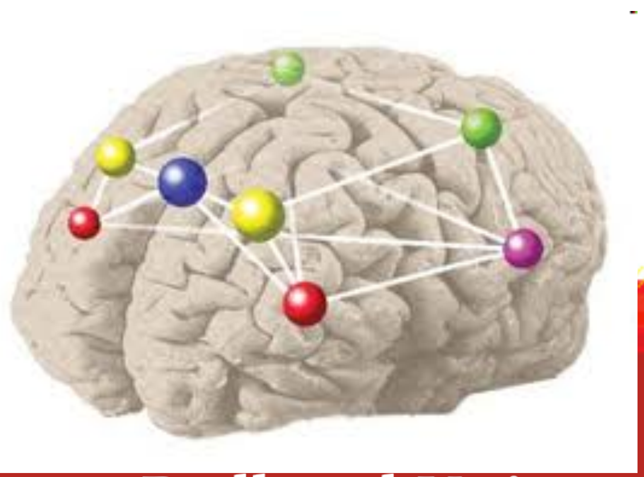


Neural Spike Intervals

- (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

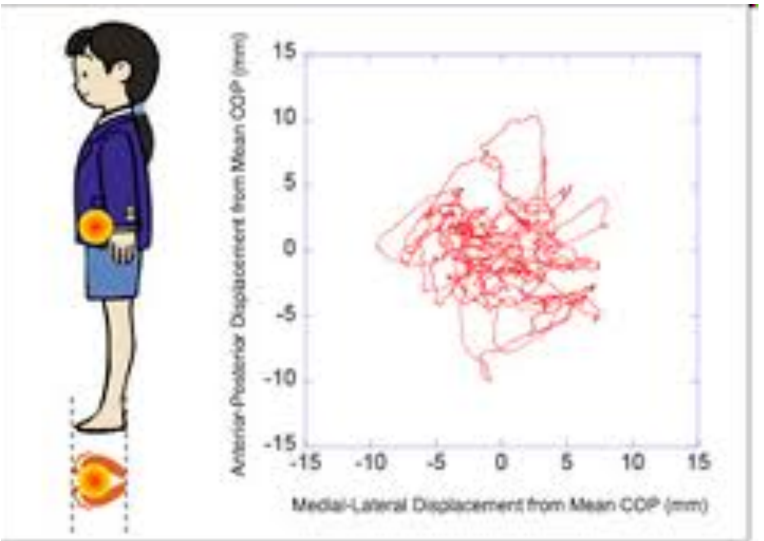
Deviations from 1/*f* noise in EEG

- 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)
- ...

Motor Control

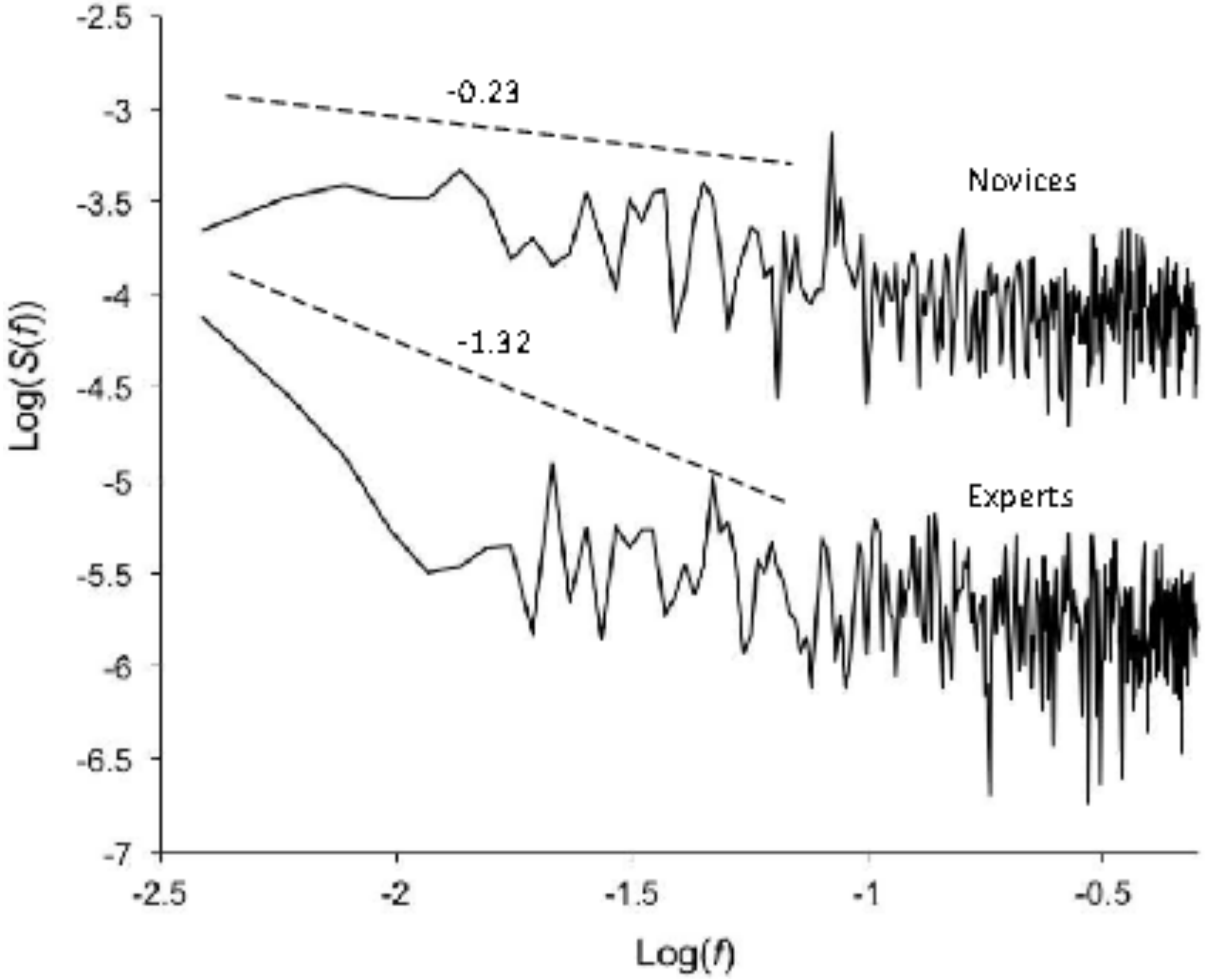
Posture

- 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)

Skiing



Nourrit-Lucas et al., 2014

Rowing

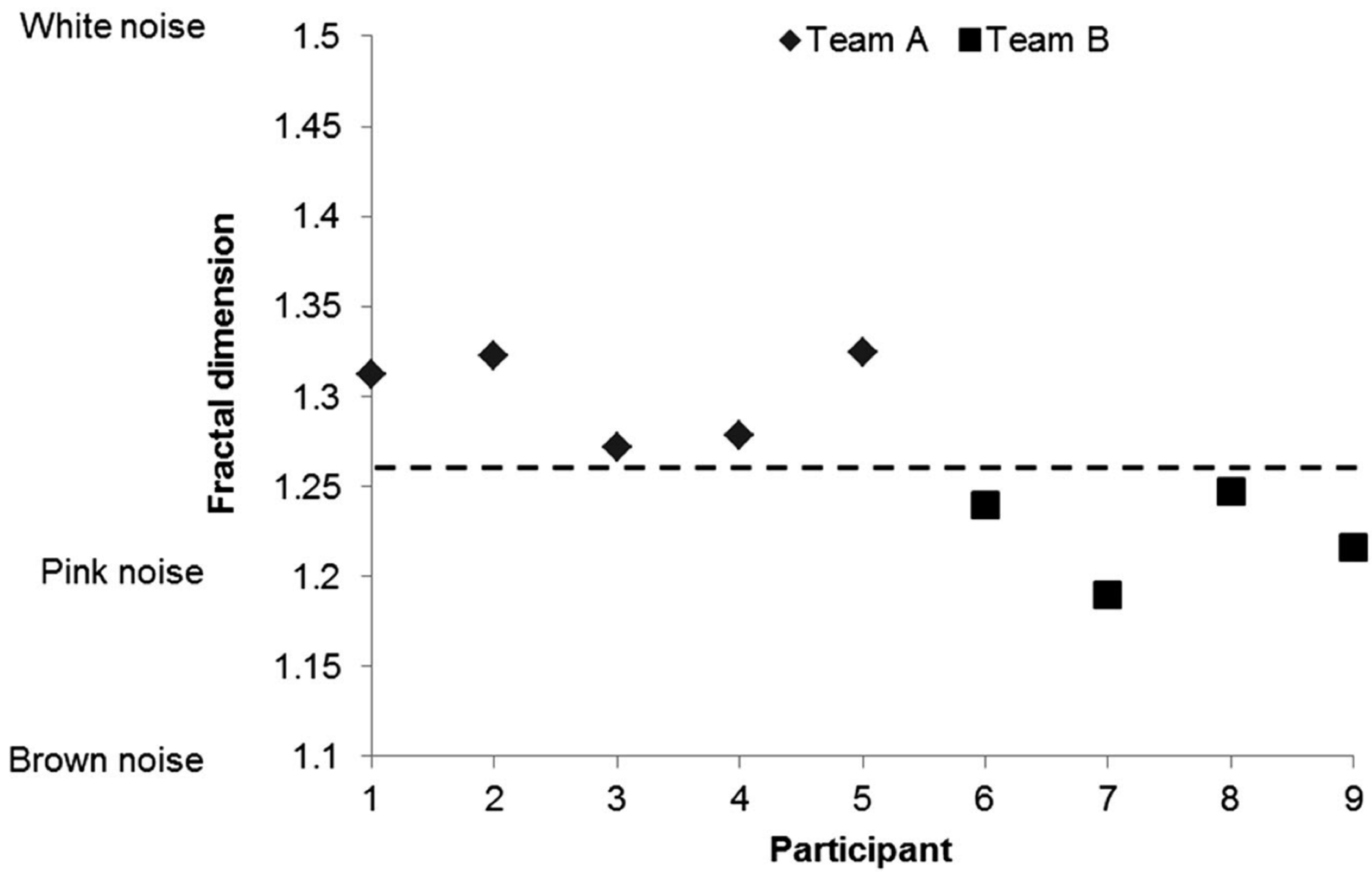
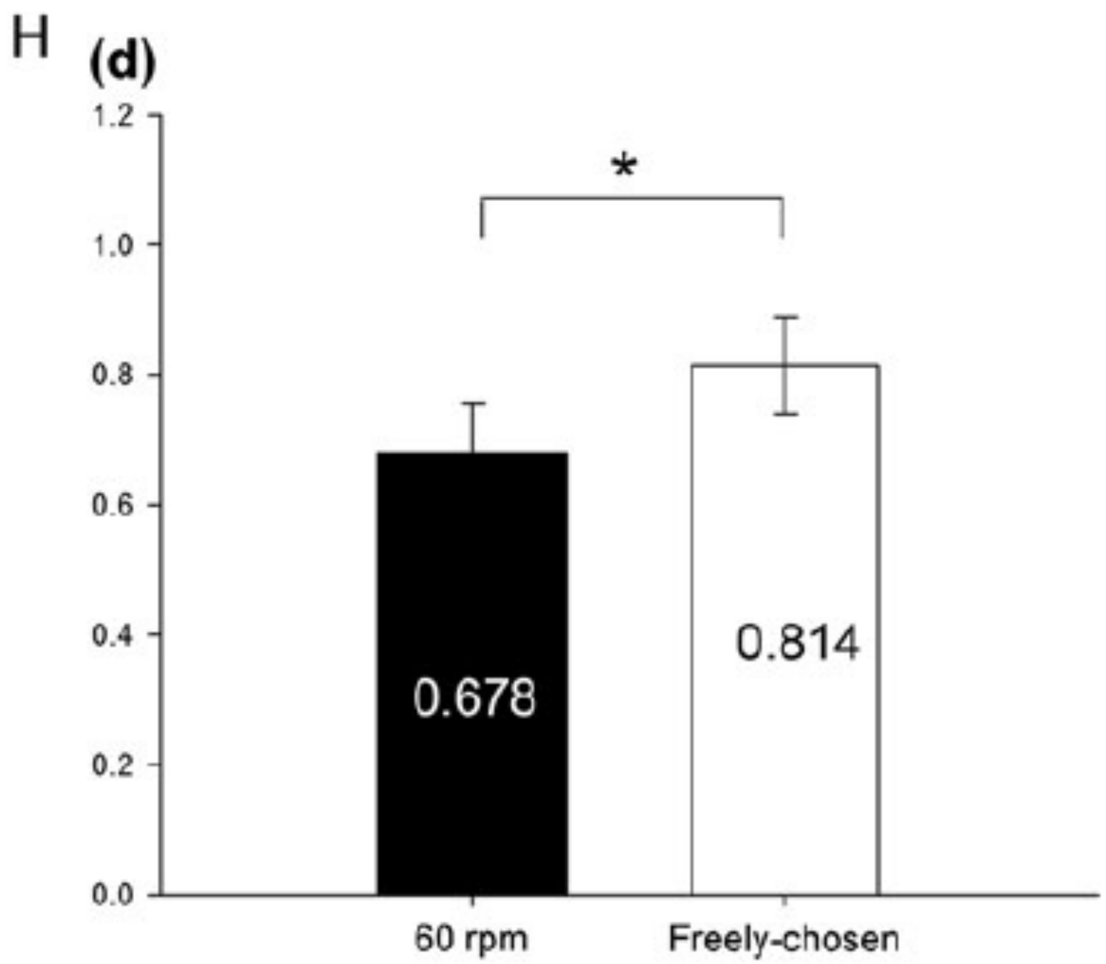


Figure 4 — Fractal dimensions of lower-skilled participants (Team A) and high-skilled participants (Team B). The dashed line separates the rowers of the two teams.

Den Hartigh et al., 2015

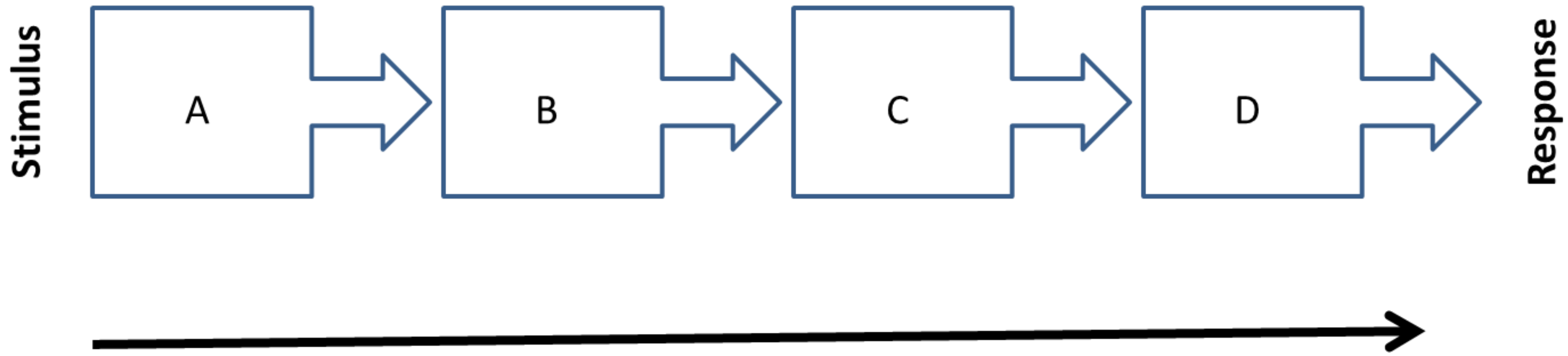
Cycling



Warlop et al., 2013

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

Maarten Wijnants



A + B + C + D = RT
E.g., 84ms + 46ms + 128ms + 304ms = 562ms

Component-dominant dynamics ???

1/*f* Noise in Human Cognition

D. L. Gilden,* T. Thornton, M. W. Mallon

When a person attempts to produce from memory a given spatial or temporal interval, there is inevitably some error associated with the estimate. The time course of this error was measured in a series of experiments where subjects repeatedly attempted to replicate given target intervals. Sequences of the errors in both spatial and temporal replications were found to fluctuate as 1/*f* noises. 1/*f* noise is encountered in a wide variety of physical systems and is theorized to be a characteristic signature of complexity.

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, task coordination

- Can we seperate internal fluctuations (system dynamics) from external fluctuations (perturbations)?

Task constraints

Temporal estimation

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

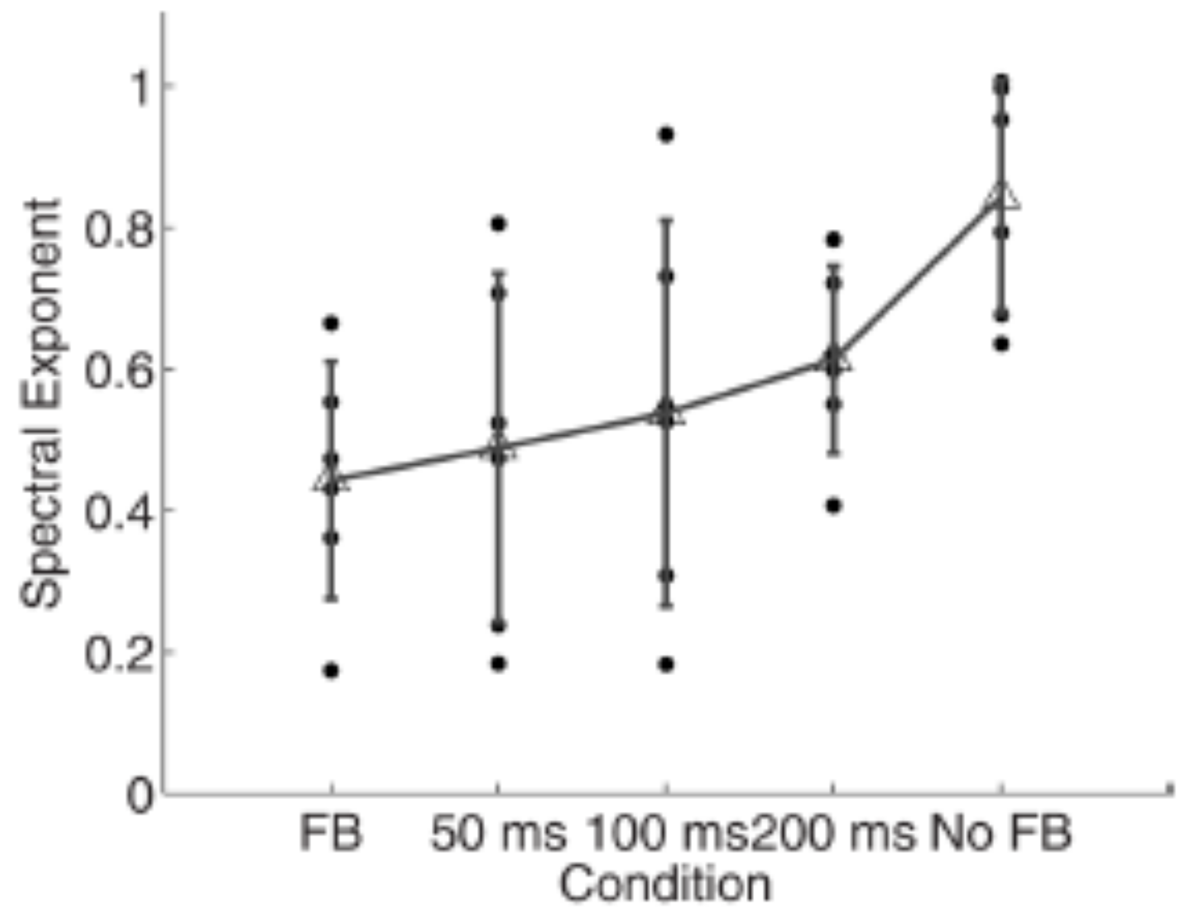


FIGURE 3 | Spectral exponents of the time estimates. Spectral exponents α closer to 0 imply presence of white noise whereas values closer to 1 suggest pink noise. Individual points represent observations from individual participants. Error bars plot within-condition SD.

change perspective

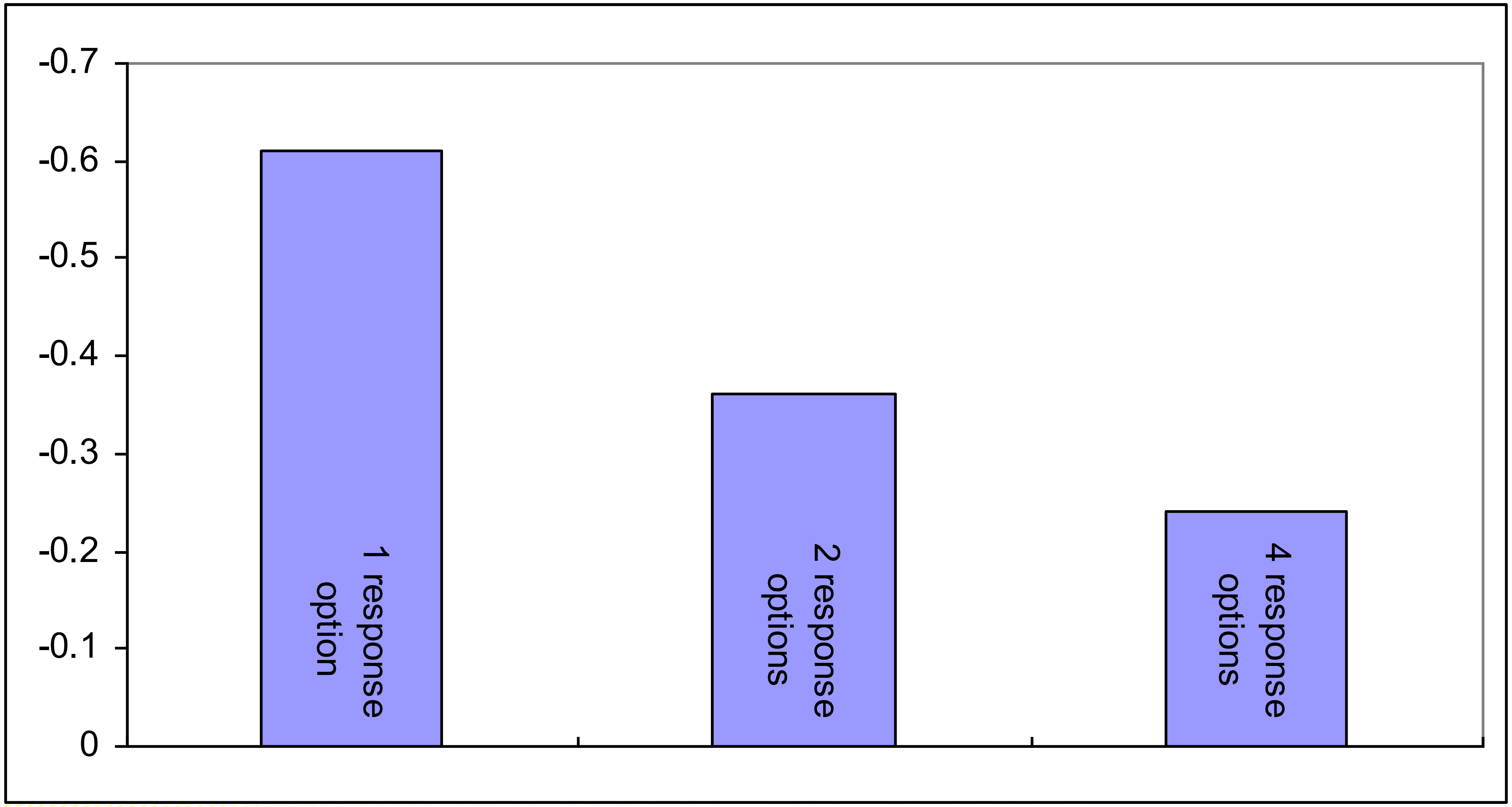
Kuznetsov & Wallot (2011)

Choice reaction task

External perturbations add extraneous random variation to the measured performances: Number of response options

1/f noise →

Random →



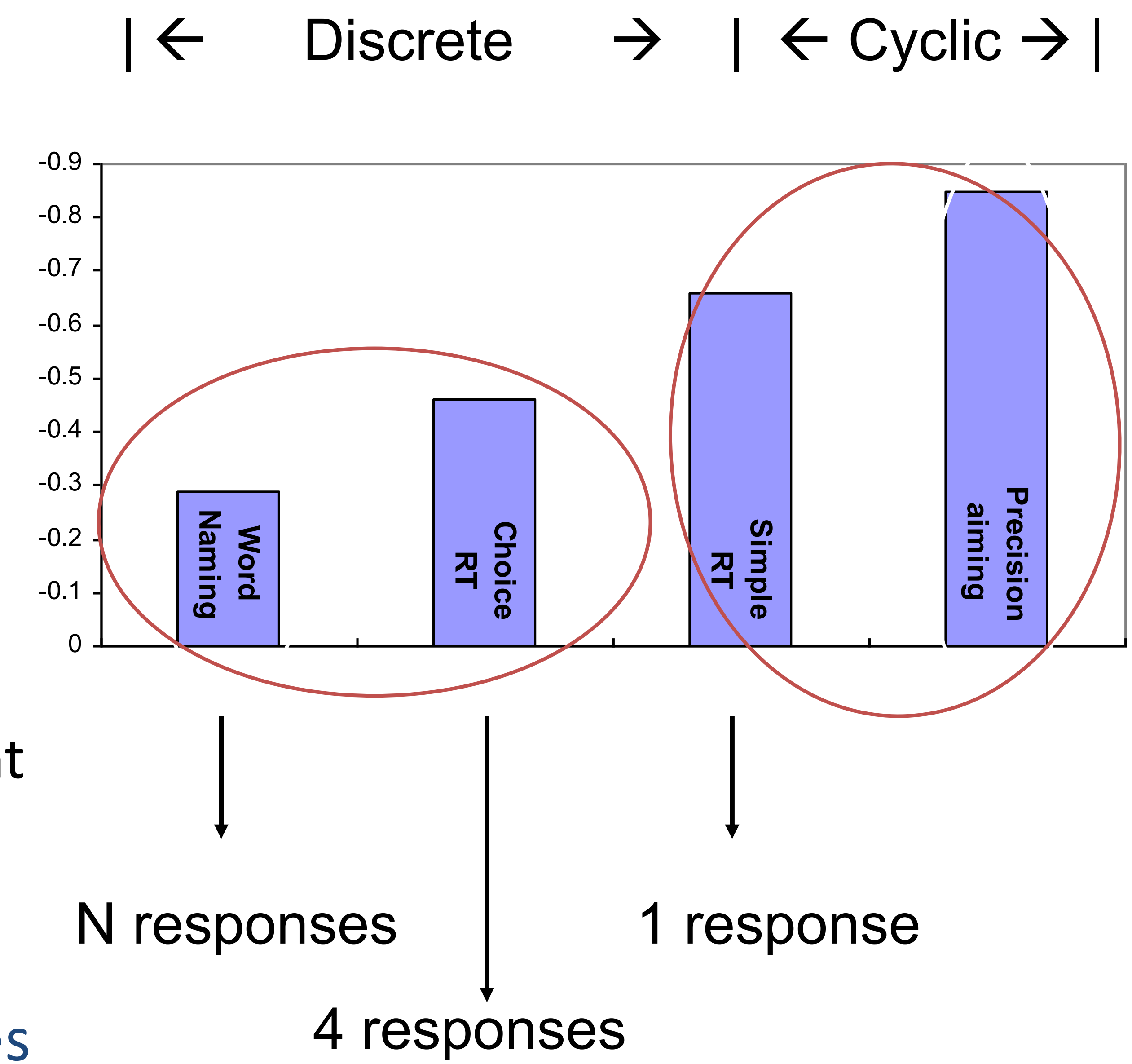
Choice Reaction Task

Ward and Richard (2001)

Task constraints: across tasks

- **Simple RT, Precision aiming:**
  - Each trial is identical:
    same SIGNAL to respond and same RESPONSE
  - EXTERNAL sources of variation in Response Time are minimized
- ➔ Variation must largely reflect INTERNAL sources

- **Choice RT, Word-naming**
  - Experimental trials differ:
    A different SIGNAL to respond and a different RESPONSE
  - EXTERNAL sources of variation in Response Time are introduced to the measured values
- ➔ Variation must reflect INTERNAL sources to a lesser extent

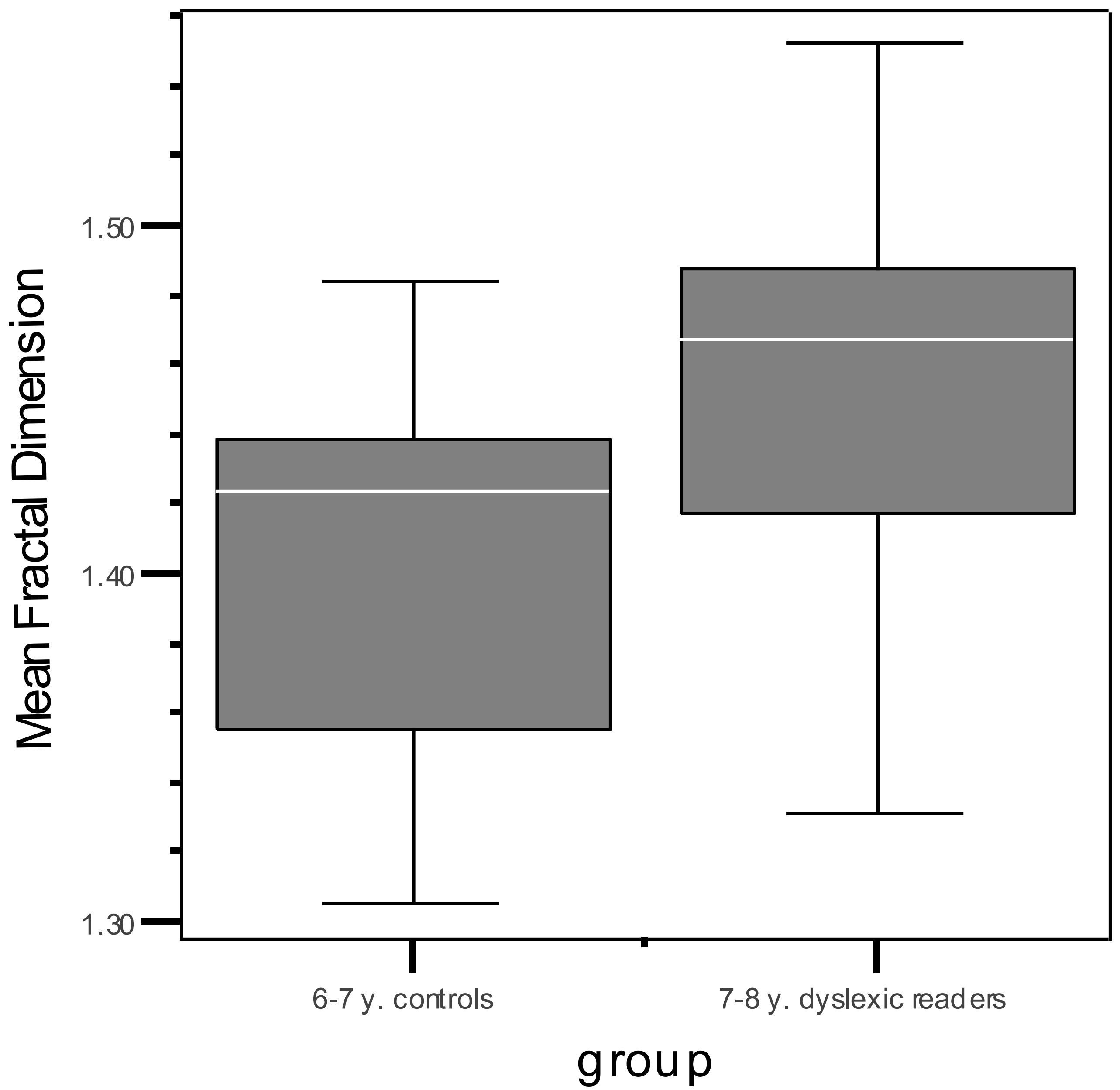


Data from: Van Orden, Holden, & Turvey, 2003; Kello, Beltz, Van Orden, & Turvey, 2007; Wijnants et al., 2009

Word-naming

- 7-8 year old Dyslexic Readers
- 6-7 year old Controls
- 1 Block of 560 Word Stimuli

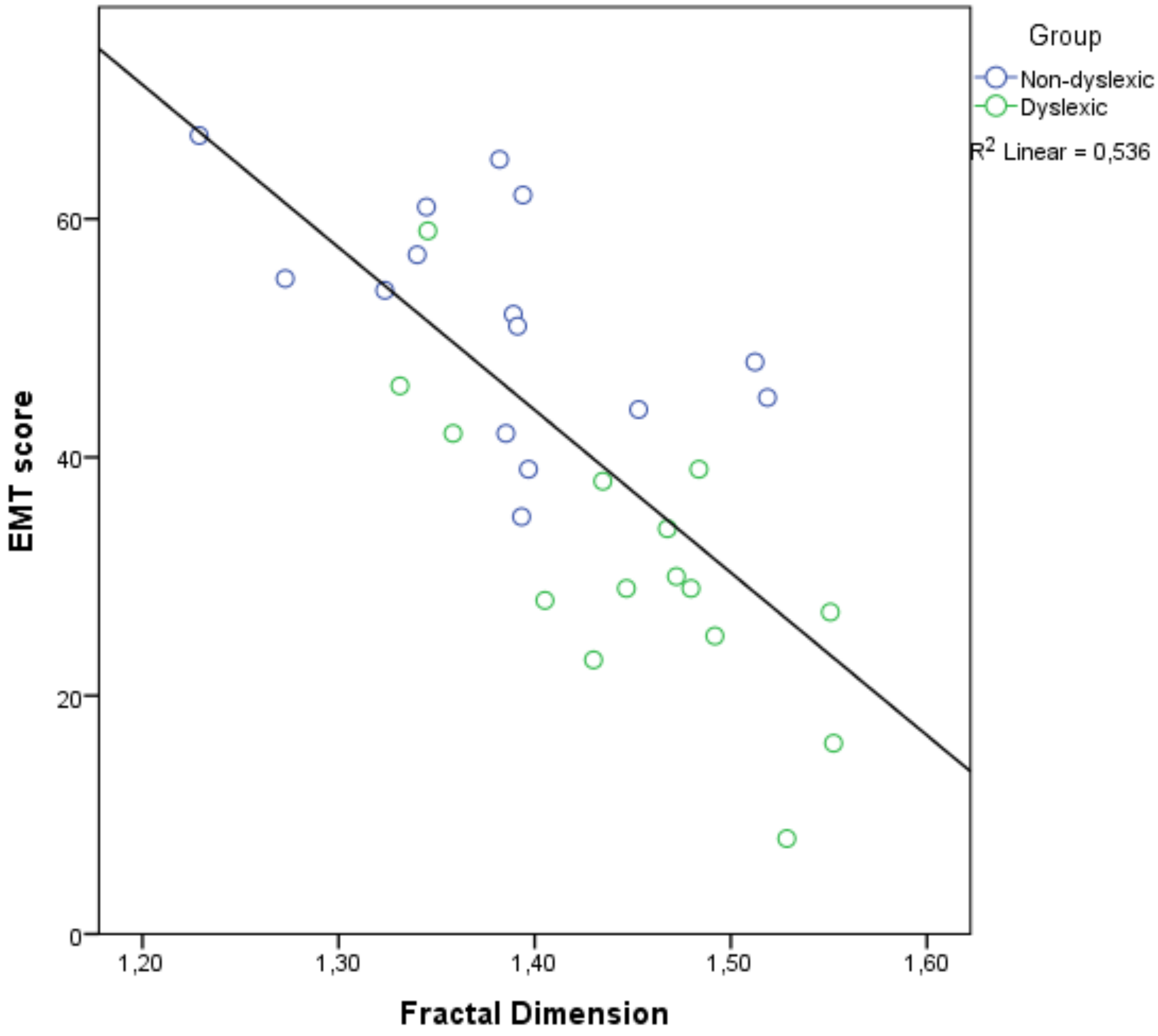
- ➔ Dyslexic Readers Show Reduced 1/f Noise in RTs



Word-naming

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

- 1/*f* noise correlates strongly with reading fluency



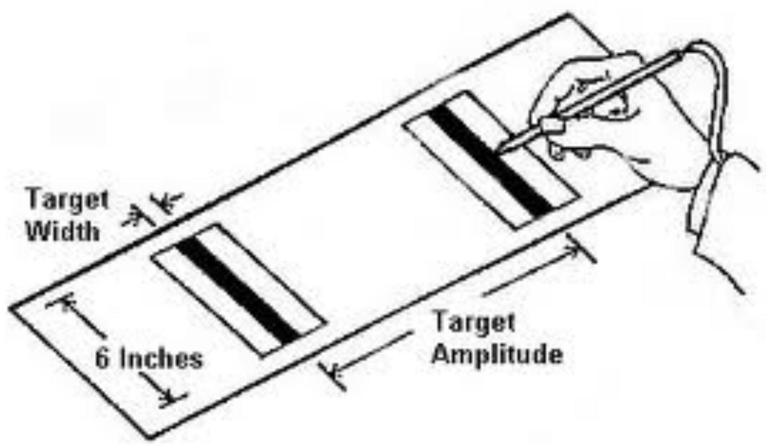
Within-Group Correlations: dyslexics vs. non-dyslexics

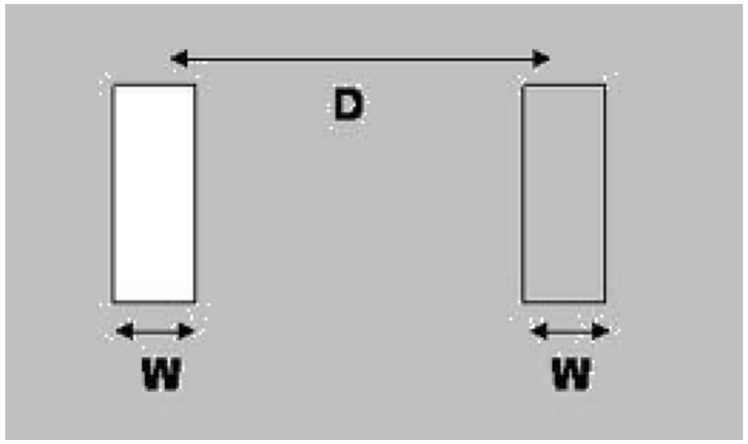
		Fractal Dimension	Recurrence Rate	Determinism	Entropy	Meanline
Dyslexics (N = 15)	Mean RT	.56*	-.70**	-.88**	-.81**	-.77**
	St. Dev. RT	.68**	-.71**	-.84**	-.76**	-.74**
	EMT	-.77**	.84**	.75**	.79**	.83**
Non-Dyslexics (N = 15)	Mean RT	.24	-.10	-.12	-.25	-.24
	St. Dev. RT	.49	.39	.33	.23	.24
	EMT	-.28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

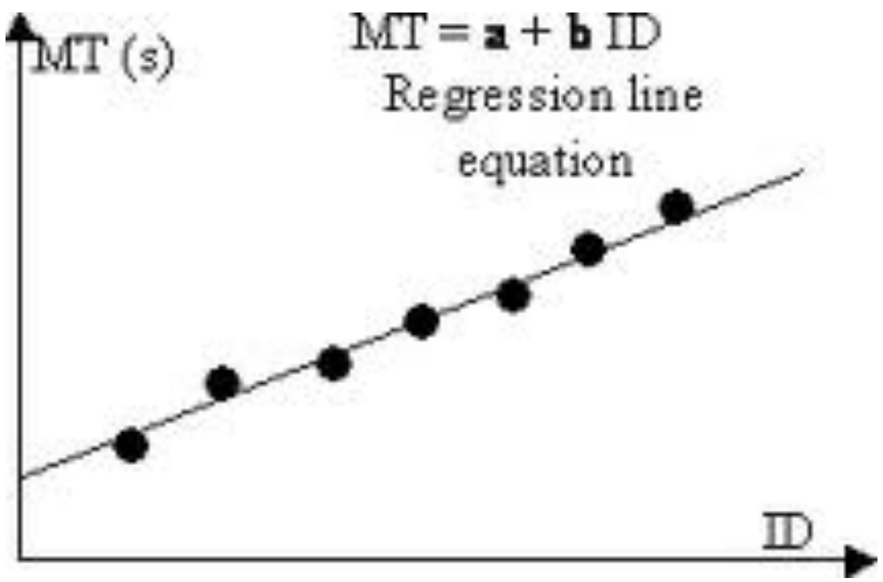
** $p < 0.01$, * $p < 0.05$ (two-tailed).

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

Fitts task: Motor learning





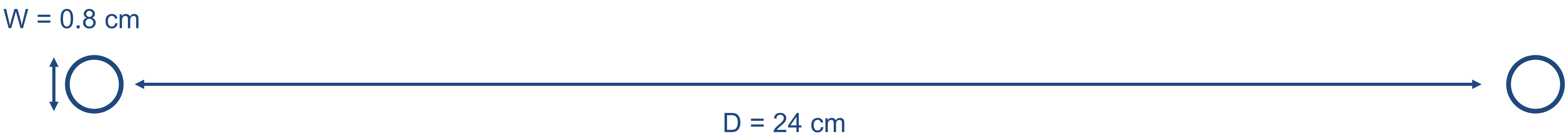


Time *Distance*

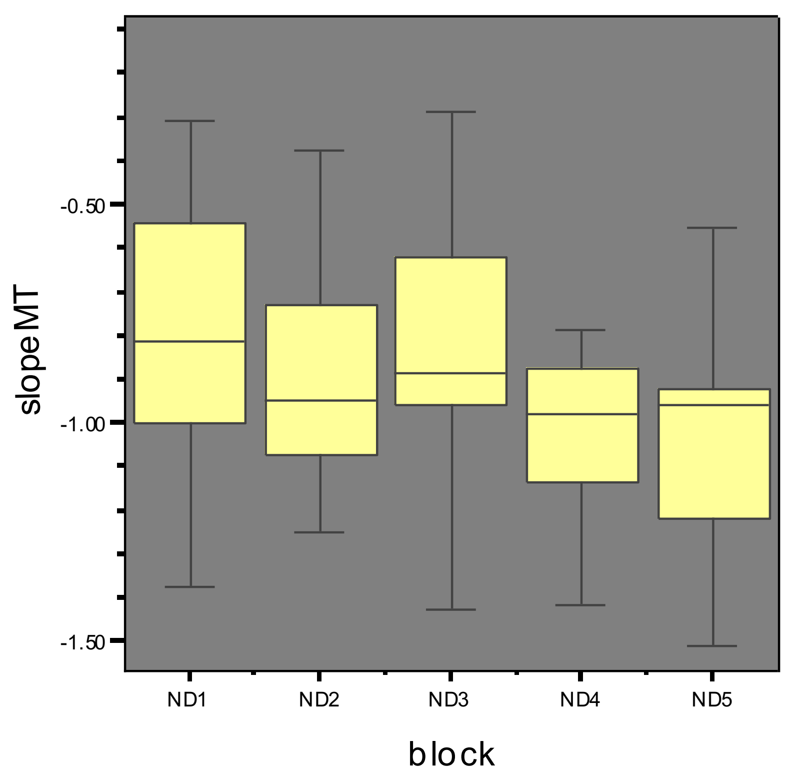
$$T = a + b \log_2\left(2\frac{D}{W}\right)$$

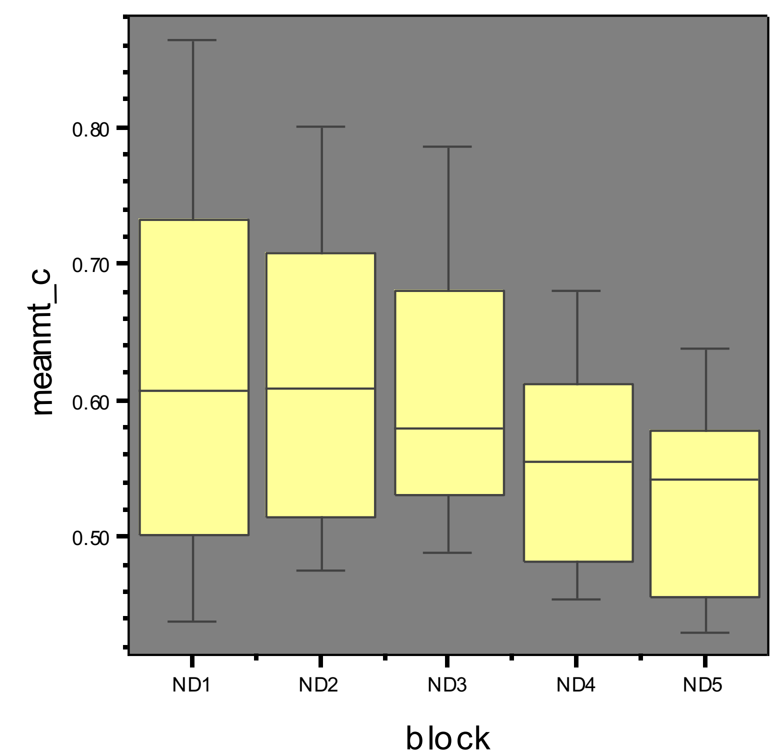
Coefficients *Width*

Motor Learning



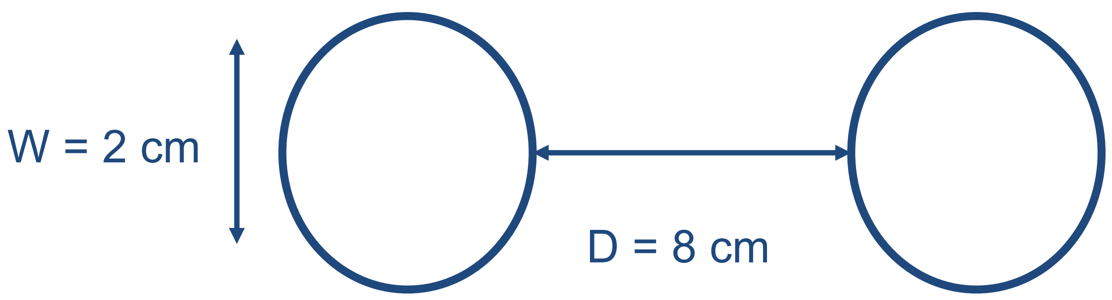
- 5 blocks x 1100 trials
- Non-dominant hand





(Wijnants, Bosman, Hasselman, Cox, & Van Orden, 2009)

No Motor Learning



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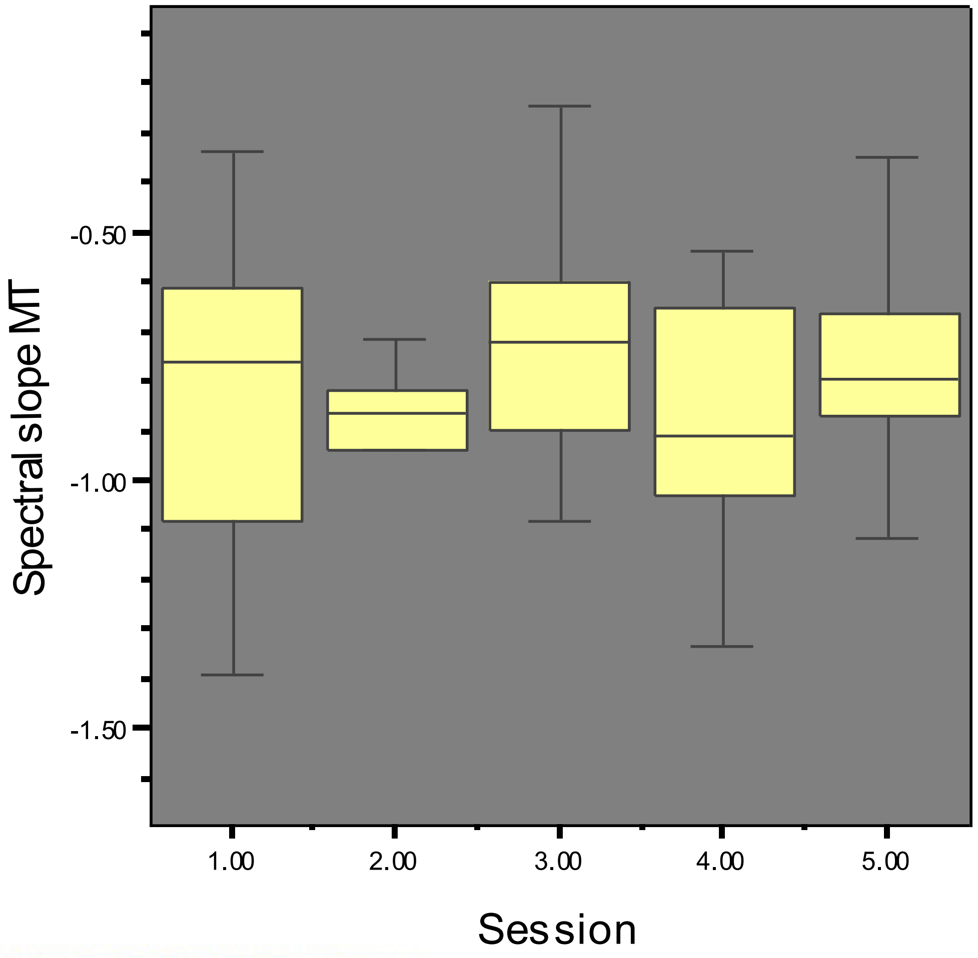

Speed-Accuracy Trade Off

Fast Performance

- Not very accurate
  - Speed vs. Accuracy: r = -.77**

- Recruits slow-timescale dynamics of the fractal pattern to the <u>measurement of speed</u> (Movement Time)
  - r = .62*
  - Faster participants show more 1/f scaling in their MT dynamics

- Does not recruit slow-timescale dynamics of the fractal pattern to the <u>measurement of accuracy</u> (Line Length)
  - r = -.58*
  - Faster participants show reduced 1/f scaling in their LL dynamics

Wijnants et al. (2012)

Accurate Performance

- Not very fast
  - Speed vs. Accuracy: r = -.77**
- Recruits slow-timescale dynamics of the fractal pattern to the <u>measurement of accuracy</u> (Line Length)
  - r = .45*
  - More accurate participants show more 1/f scaling in their LL dynamics
- Does not recruit slow-timescale dynamics of the fractal pattern to the <u>measurement of speed</u> (Movement Time)
  - r = -.71*
  - Accurate participants show reduced 1/f scaling in their MT dynamics

Wijnants et al. (submitted) (2012)

		Harmonicity	Movement time	Accuracy
Difficult condition	FD MT	−0.61**	0.52*	0.70**
	SampEn MT	−0.66**	0.45*	0.74**
	FD MA	0.50*	−0.45*	−0.48*
	SampEn MA	0.75**	−0.64**	−0.74**
Easy condition	FD MT	−0.13	0.00	0.15
	SampEn MT	−0.12	0.03	0.05
	FD MA	−0.31	0.33	0.30
	SampEn MA	0.03	−0.08	0.33

$^{**}p < 0.01$, $^{*}p < 0.05$, *one-tailed.*

Wijnants et al. (2012)

Conclusion

- The coordination of perception and action emerges in a similar way as the coordination of neural and bodily processes
- Many diverse systems perform optimally when interacting across many scales
- Conjecture: These fractal fluctuations indicate healthy, adaptive and stable, well-coordinated systems