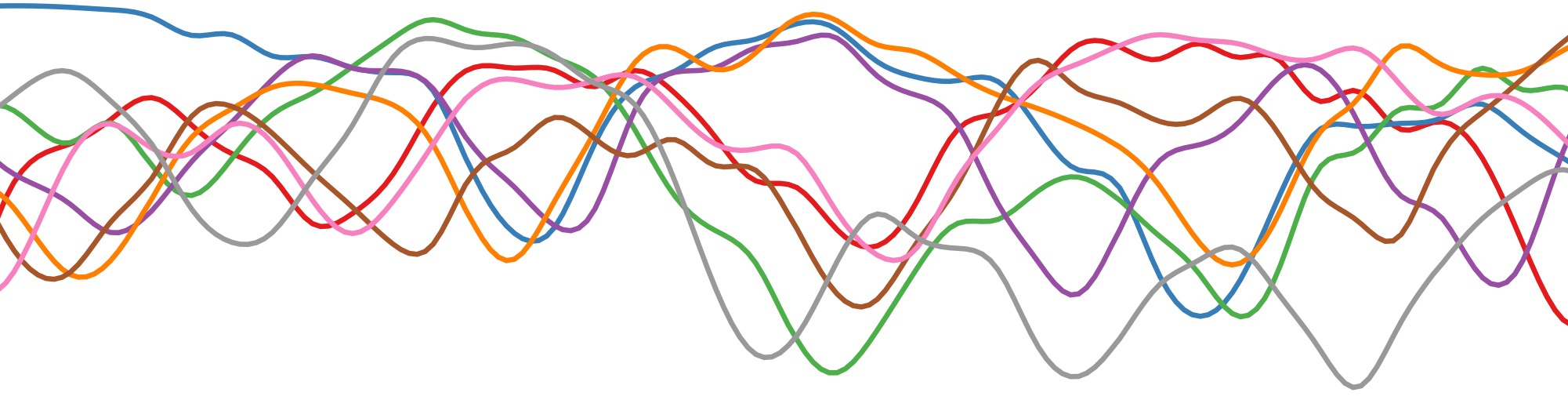
Information Theory Tools

for

Cognitive Neuroscience



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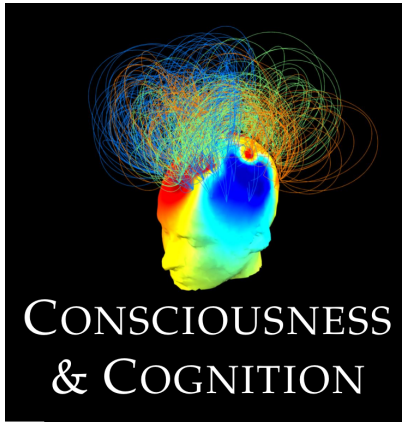
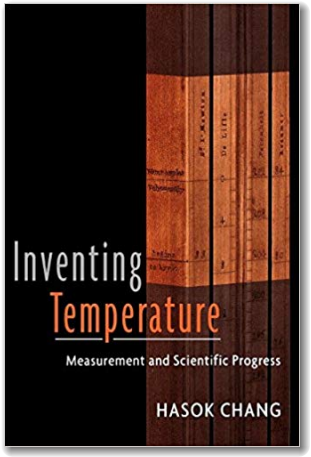


INTRODUCTION

MOTIVATION

- **Defining** and **measuring** consciousness.
- Inspiration: **thermodynamics**!
- Challenge: inventing temperature *and* thermometers at the same time.



MOTIVATION

Goal: theoretically- and empirically-informed revision of our tools to measure consciousness and cognition.

- What are our tools actually measuring?
- Does that match what we actually want to measure?
- Can we improve them?

ENTROPY AND INFORMATION

Framework: **information theory**.

- Information (entropy) in a signal can be split:

$$\underbrace{H(X_t)}_{\text{Present}} = \underbrace{I(X_t; \boldsymbol{X}_{-\infty}^{t-1})}_{\text{Inheritance}} + \underbrace{H(X_t|\boldsymbol{X}_{-\infty}^{t-1})}_{\text{Innovation}}$$

THIS TALK

PART I

Entropy, Lempel-Ziv complexity, and entropy-frequency effects

PART II

Information decomposition, synergy, and integrated information

ENTROPY AND COMPLEXITY

ENTROPY RATE

Measure of unpredictability in time series data.

$$H(X_t|\boldsymbol{X}_{-\infty}^{t-1})$$

Simple estimator of entropy rate: **Lempel-Ziv complexity**.

REM

High LZ

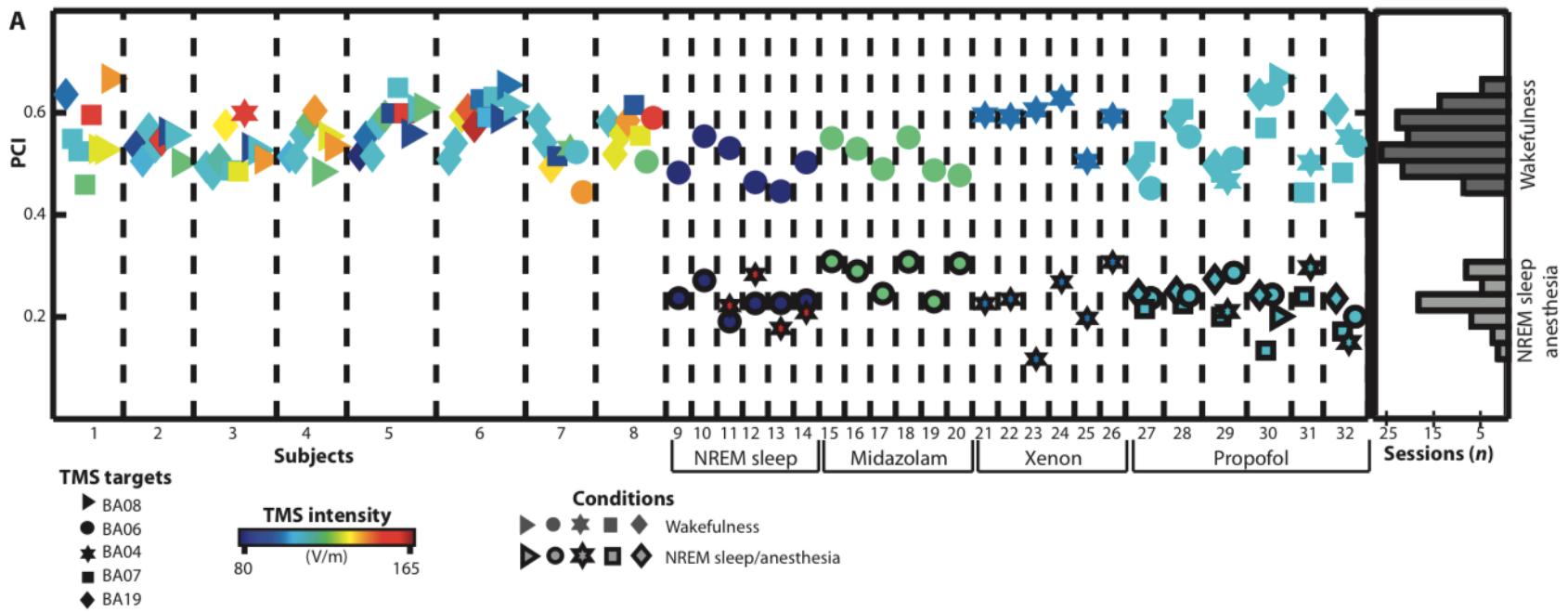
NREM

Low LZ

- LZ represents *complexity as diversity*.

LEMPEL-ZIV COMPLEXITY

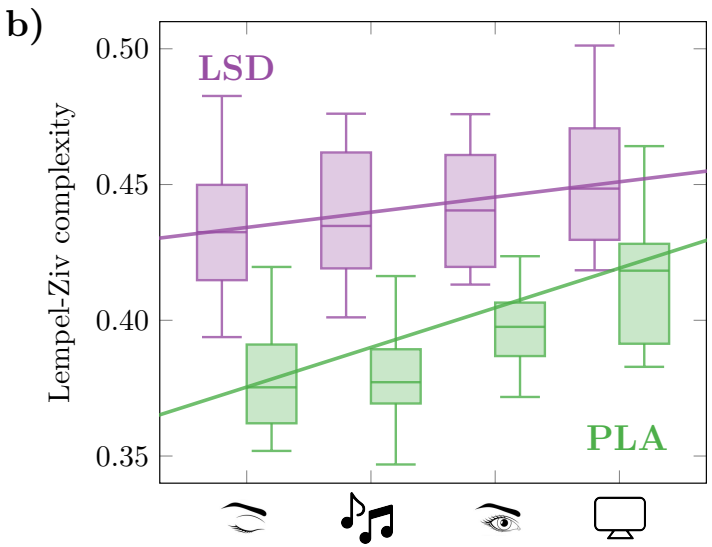
- **PCI**: EEG LZ after transcranial magnetic stimulation (TMS).

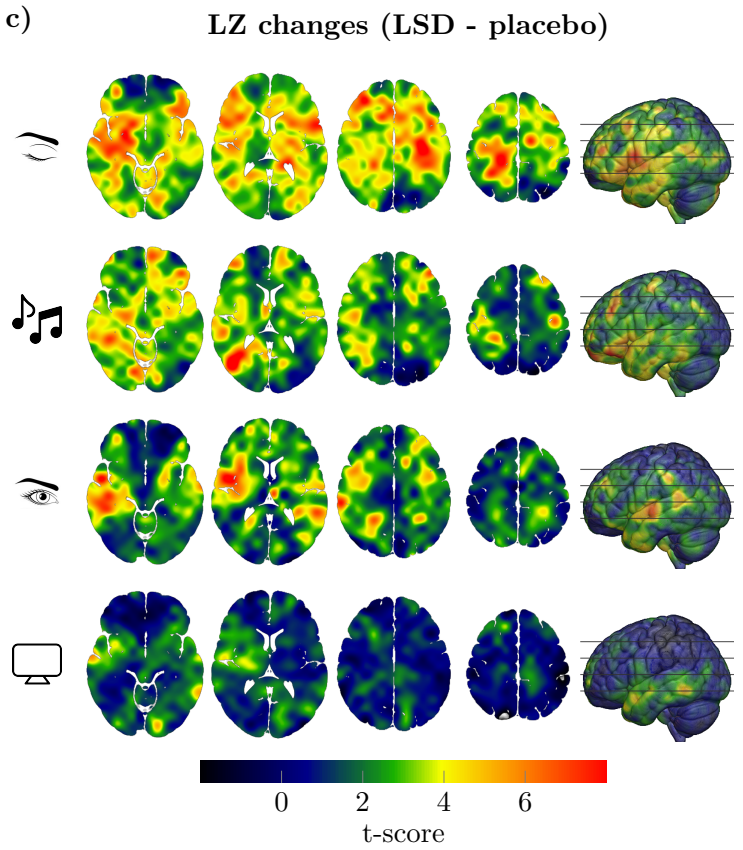


(Casali *et al.*, 2013)

LEMPEL-ZIV COMPLEXITY

LZ goes up on LSD, more so with your eyes closed.





(Mediano *et al.*, 2020)

PROBLEMS WITH LZ

Two important limitations of LZ:

1. Unclear relation between LZ and power spectrum.

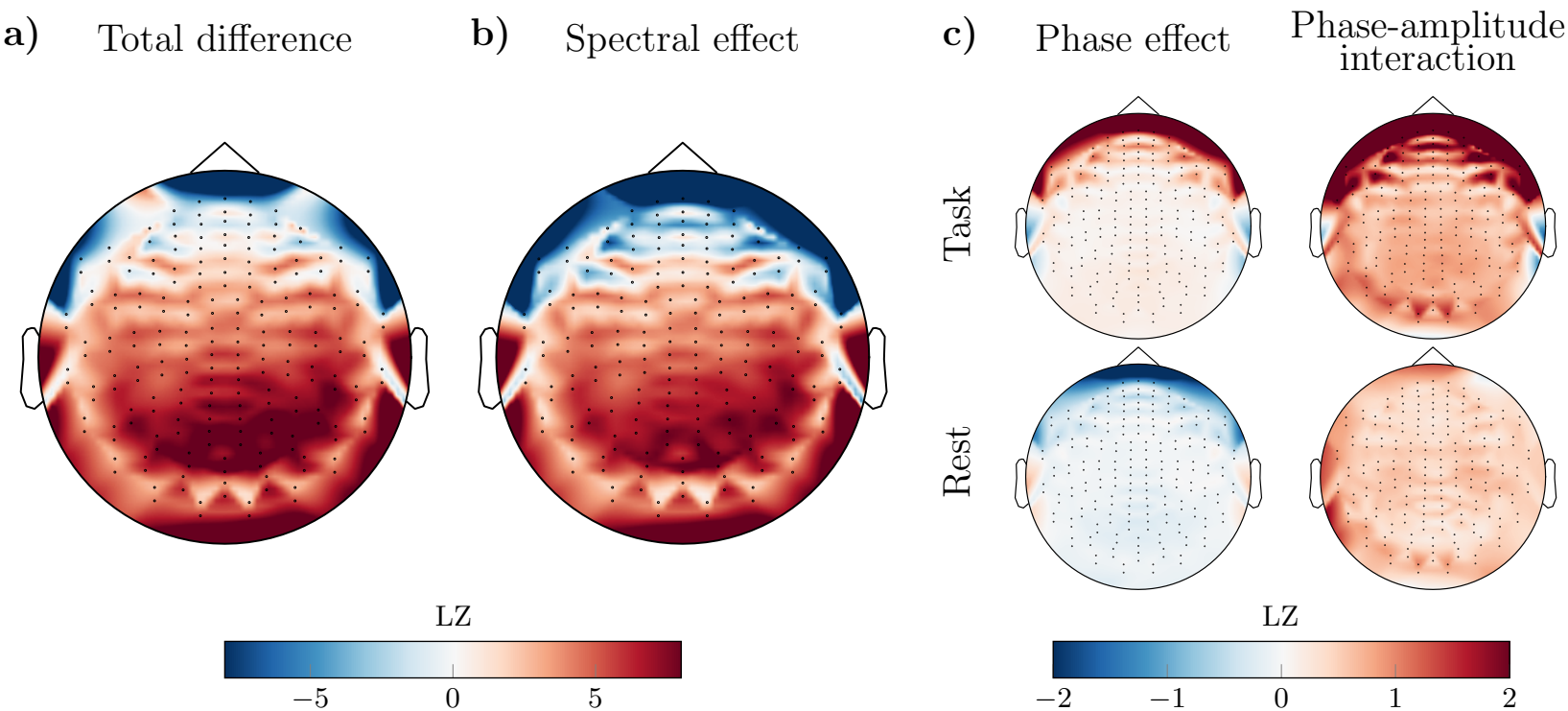
2. LZ has little spectral and temporal resolution.

LZ DIFFERENCE DECOMPOSITION

- Decomposition of LZ difference between two conditions:

$$\underbrace{\Delta}_{\text{Total}} = \underbrace{\Delta^{\phi}}_{\text{Phase}} + \underbrace{\Delta^{\text{A}}}_{\text{Spectrum}} + \underbrace{\Delta^{\text{i}}}_{\text{Interaction}}$$

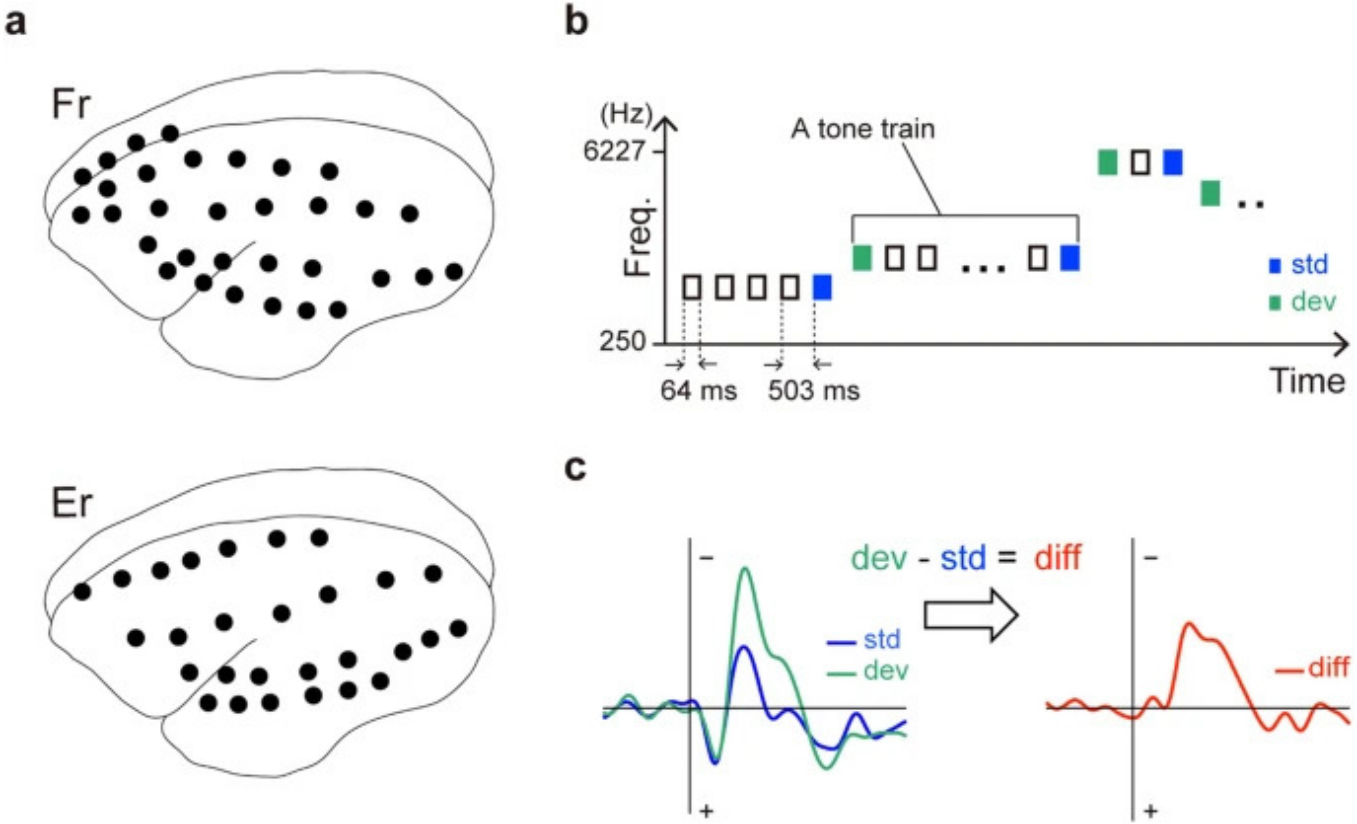
- Results comparing rest vs. a stop/no-go task:



(Mediano *et al.*, 2020)

INSTANTANEOUS COMPLEXITY

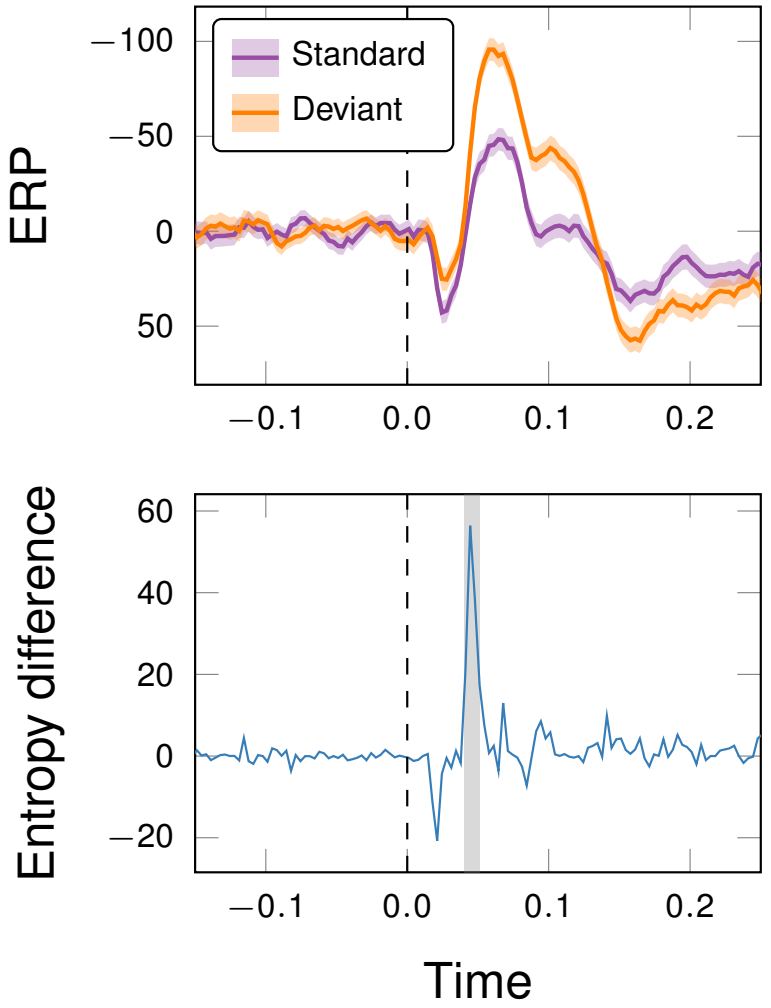
- So far, all examples rely on spontaneous activity – LZ as a "state" measure.
- Target application: mismatch negativity in the primate brain.



(Komatsu *et al.*, 2015)

INSTANTANEOUS COMPLEXITY

- New estimator based on state-space models.
- Compute prediction at each timestep to get an "instantaneous LZ."
- In an auditory oddball task, entropy changes *precede* ERP by 20 ms.



(Mediano *et al.*, in prep))

INFORMATION DECOMPOSITION

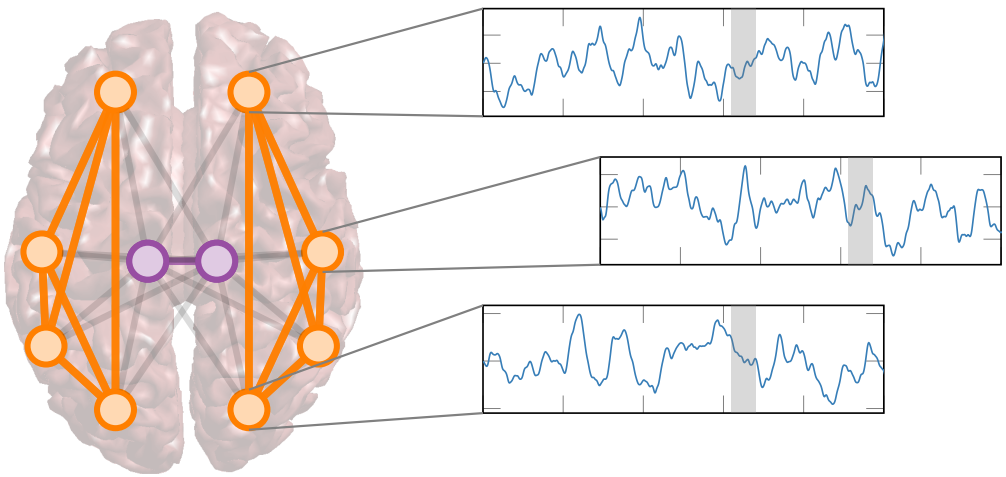
MUTUAL INFORMATION

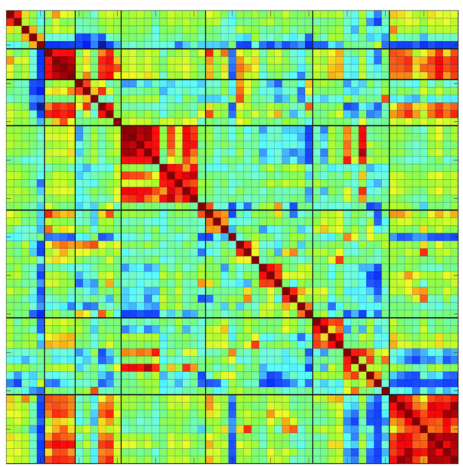
General measure of (in)dependence between two variables.

"Generalised" version of linear correlation coefficient.

$$I(X; Y)$$

Natural application: pairwise functional connectivity matrix.

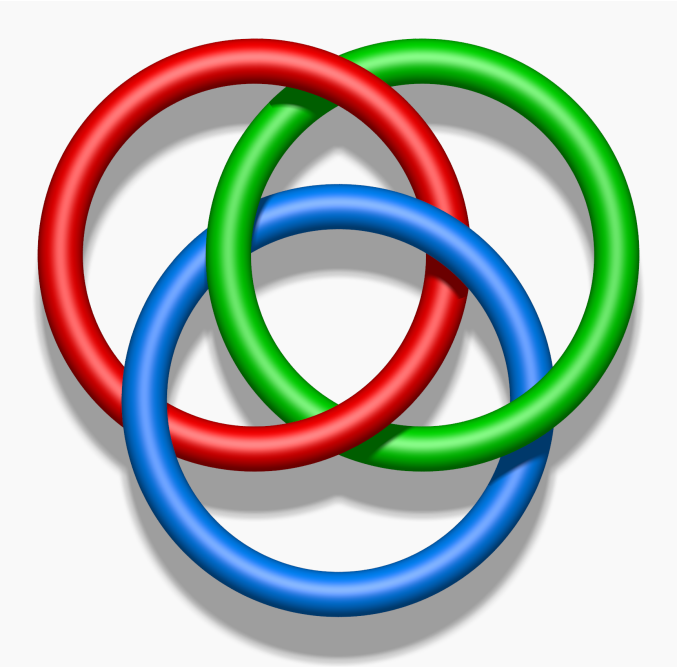




BEYOND FUNCTIONAL CONNECTIVITY

- **BUT** the brain has many more than two interacting parts.

  $\rightarrow$ Things are more complicated than they seem!



"Functional connectivity" is all zeros!

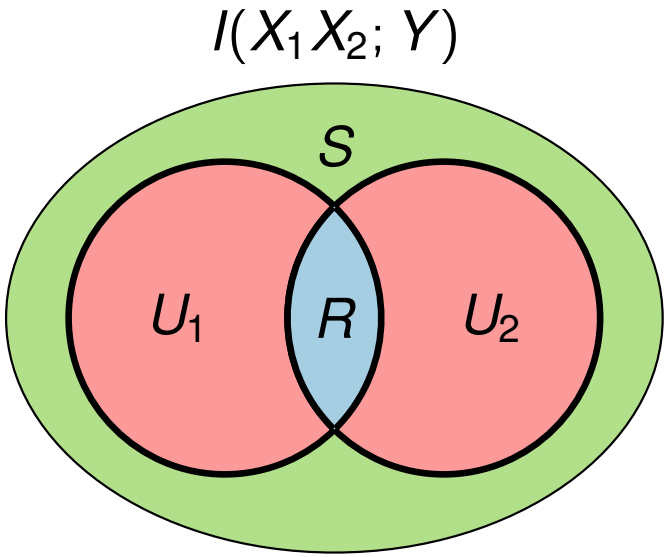
PARTIAL INFORMATION DECOMPOSITION

Can we decompose information shared between many variables?

Enter **Partial Information Decomposition** (PID).

In PID, mutual information is split into:

- Redundancy
- Unique information
- **Synergy**

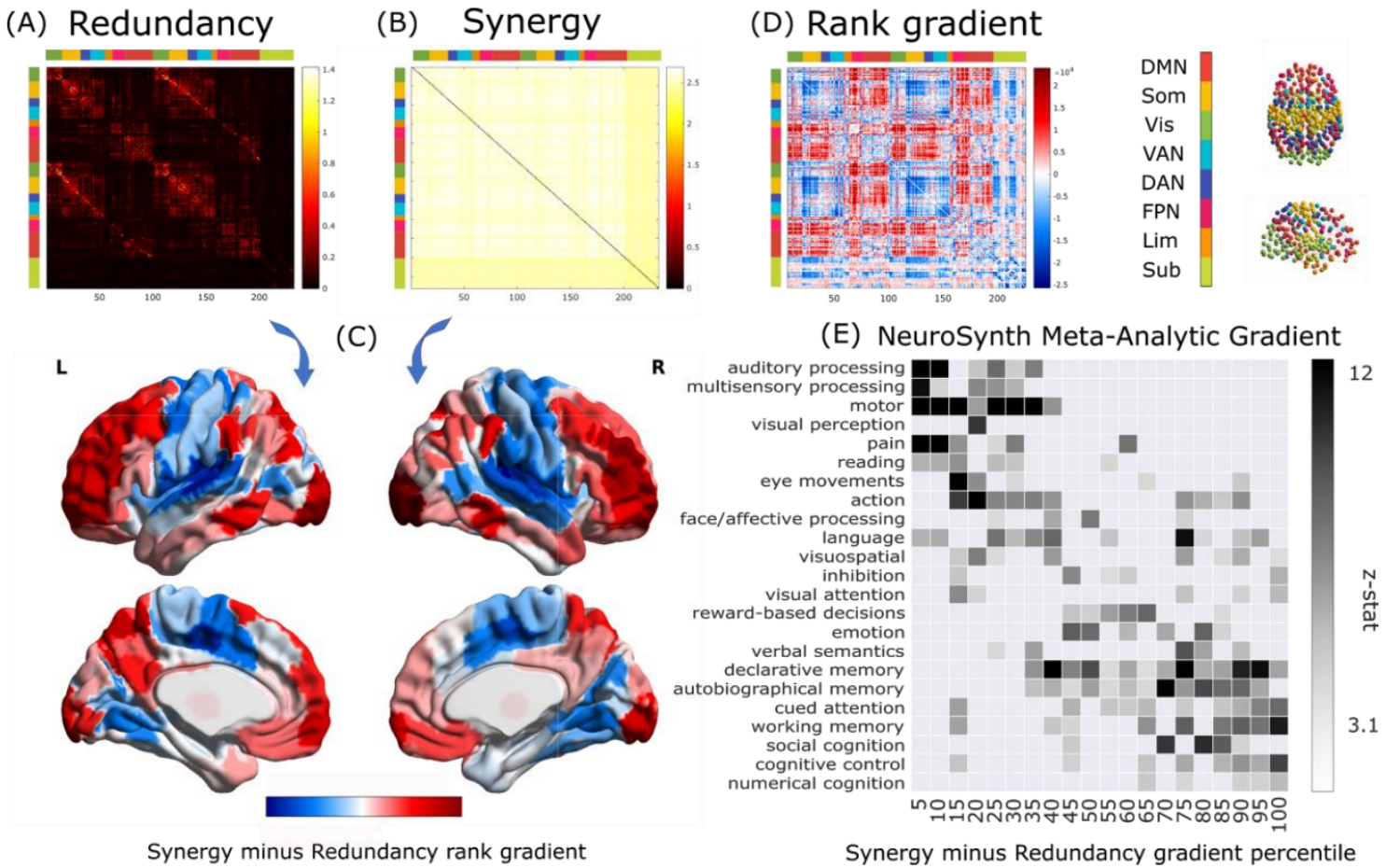


Synergy: information that is in the whole, but not in the parts.

(Williams & Beer, 2010)

SYNERGY AND REDUNDANCY IN FMRI

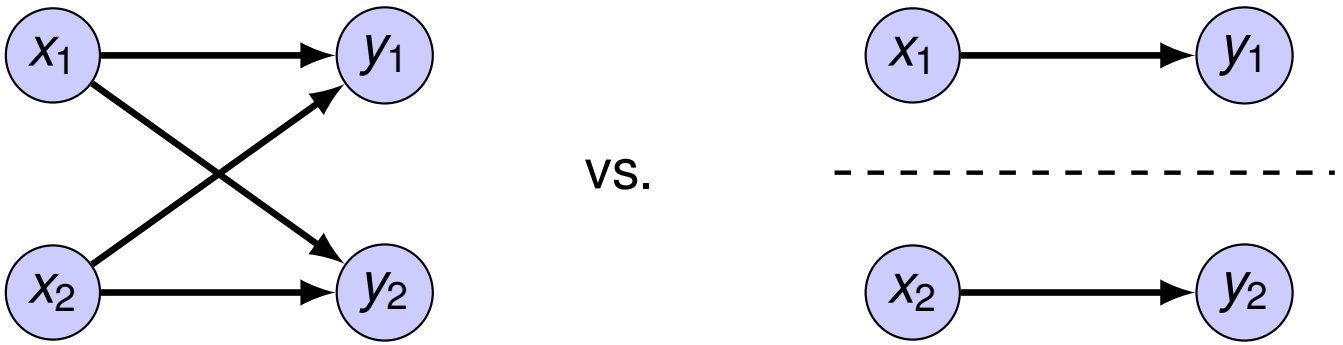
Synergy is associated with high-level cognitive function.



(Luppi *et al.*, 2020a)

INTEGRATED INFORMATION THEORY

- Integrated information measures (Φ) compare a system with a "disconnected" version of itself.



With PID we can "zoom in" into the constituents of Φ:

$$\Phi = \text{Synergy} + \text{Transfer} - \text{Redundancy}$$

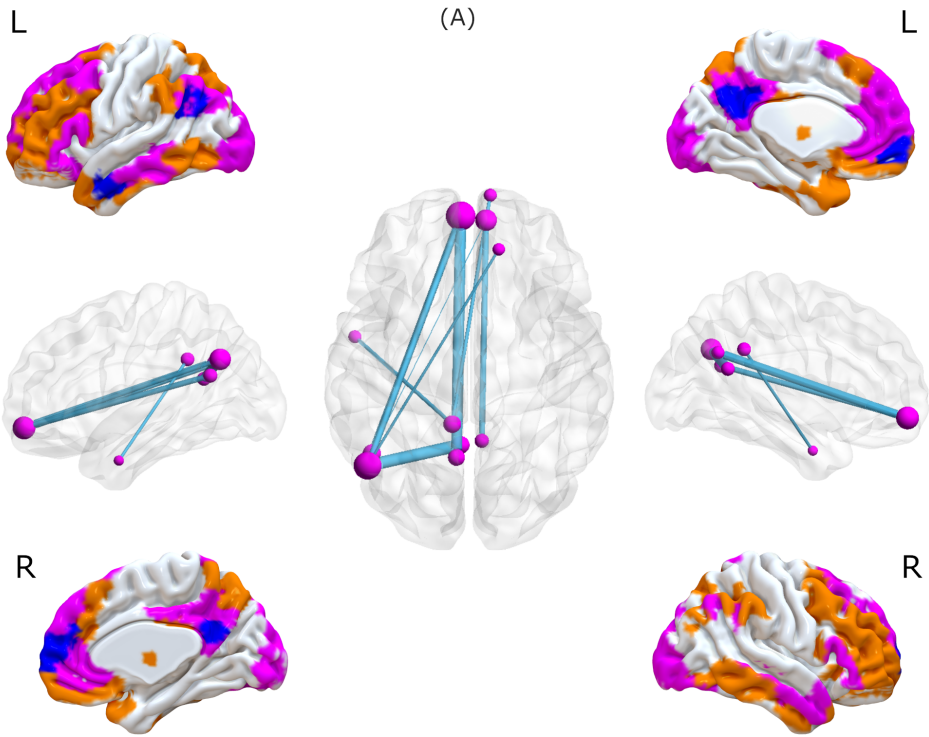
- We can formulate a 'revised Φ': $\Phi^R = \text{Synergy} + \text{Transfer}$

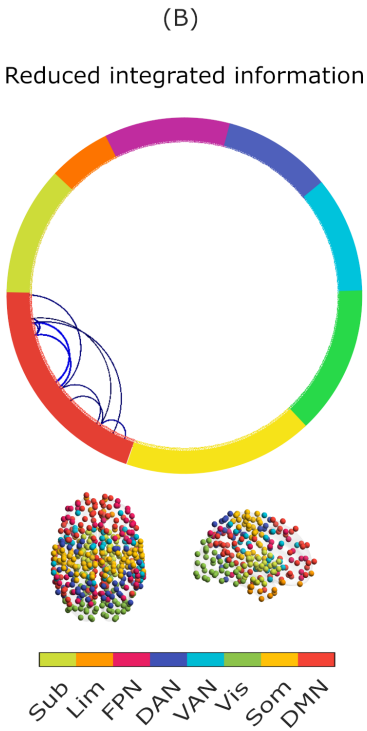
(Mediano *et al.*, 2019)

SYNERGY AND CONSCIOUSNESS

Φ^R, but not normal Φ, decreases in the DMN consistently under propofol anaesthesia and DoC.

- **Bonus**: new statistical test for composite hypotheses across datasets.





(Luppi *et al.*, 2020b)

WRAP-UP

WRAP-UP

- ✓ New tools for LZ analysis: more efficient, versatile, and nuanced.
- ✓ PID reveals “what kind” of information is being processed, links synergy with high-level cognition.
- ✓ New insights on IIT and causal emergence.
- ? Many questions open: extensions, algorithms, applications, and more.

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Thank you for listening!

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