

# Synergy as a common denominator of music and the brain

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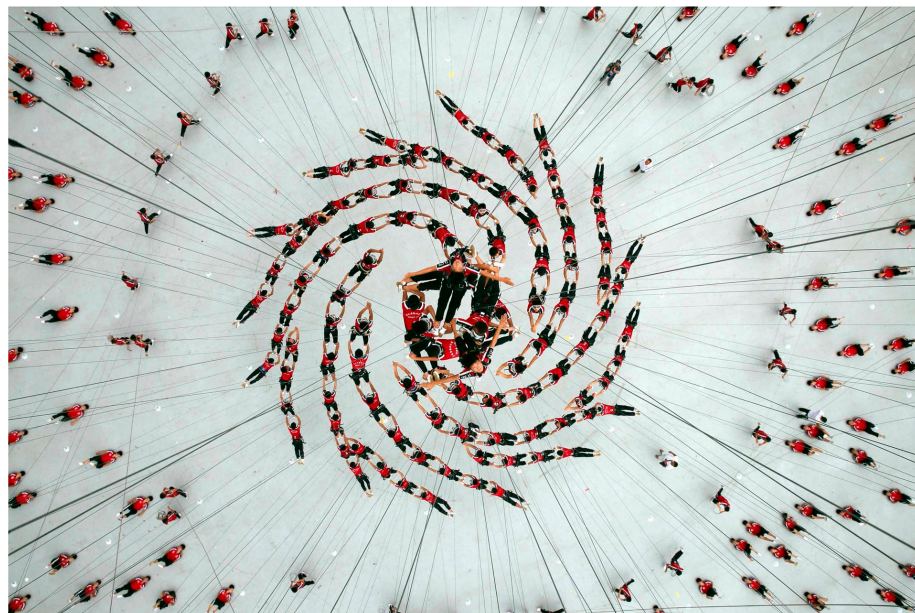
*Centre for Eudaimonia and Human Flourishing, University of Oxford*



# Synergy: when the whole is more than the sum of the parts...



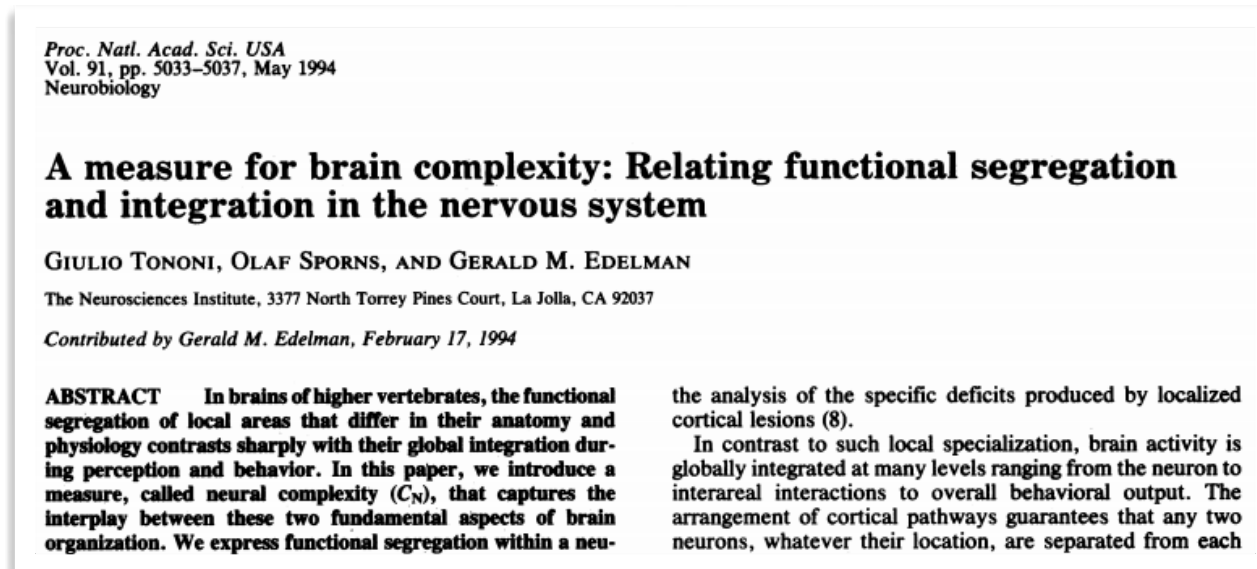
# Synergy: when the whole is more than the sum of the parts...



# Seminal thoughts about the brain

High brain functions seem to be characterised by the coexistence of two forces:

- *Differentiation (local independency)*: the parts of the brain have differentiated functions
- *Integration (global cohesion)*: these parts are integrated into high-level functions



G. Tononi



O. Sporns

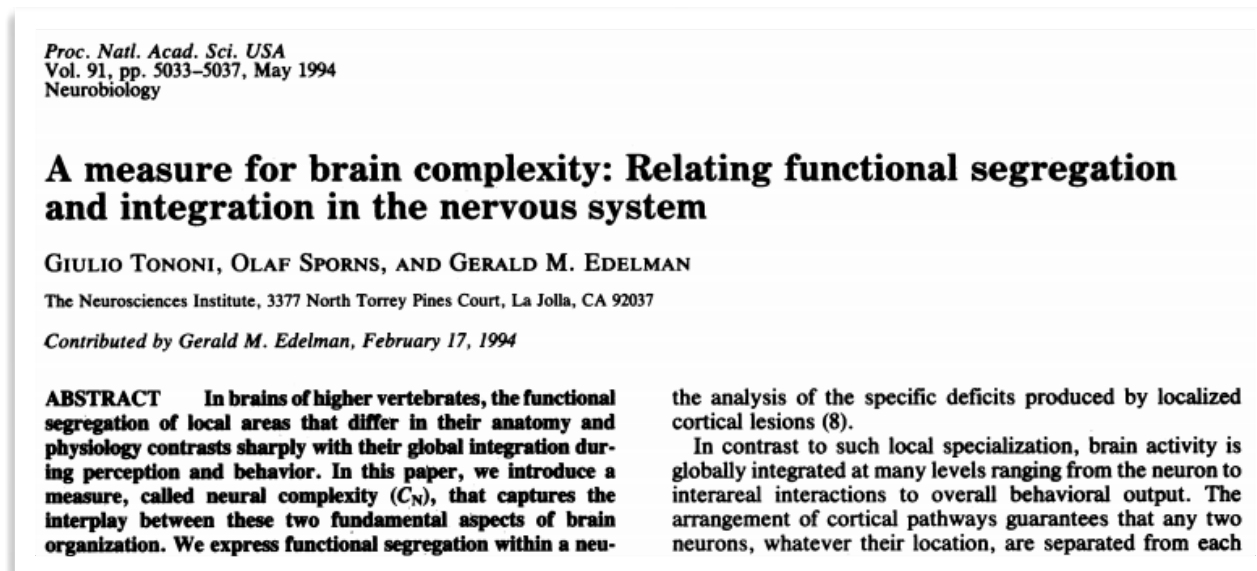


G. Edelman

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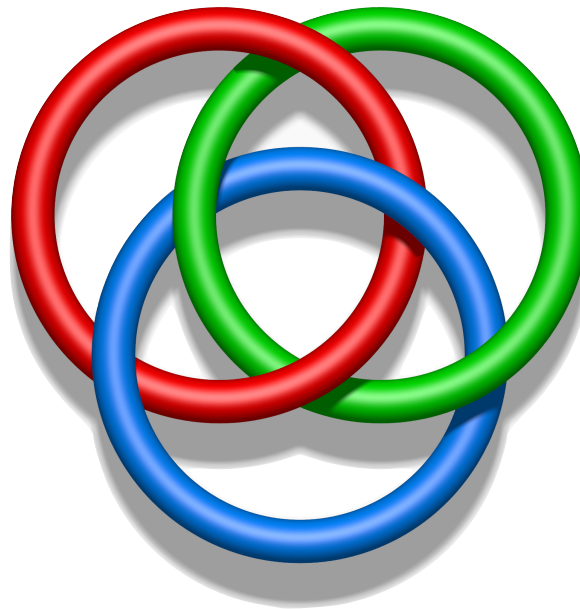
Crucial insight:  
Integration and differentiation are not antithetical,  
but can coexist!

Synergy

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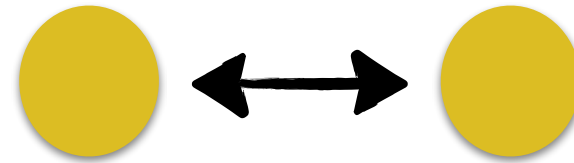
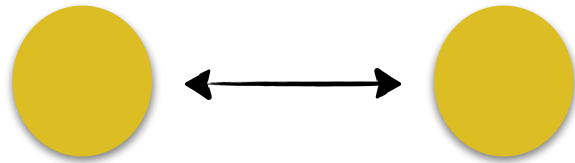
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**Synergy**

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## A key distinction: Synergy vs redundancy

For two variables, interdependency is determined by strength.



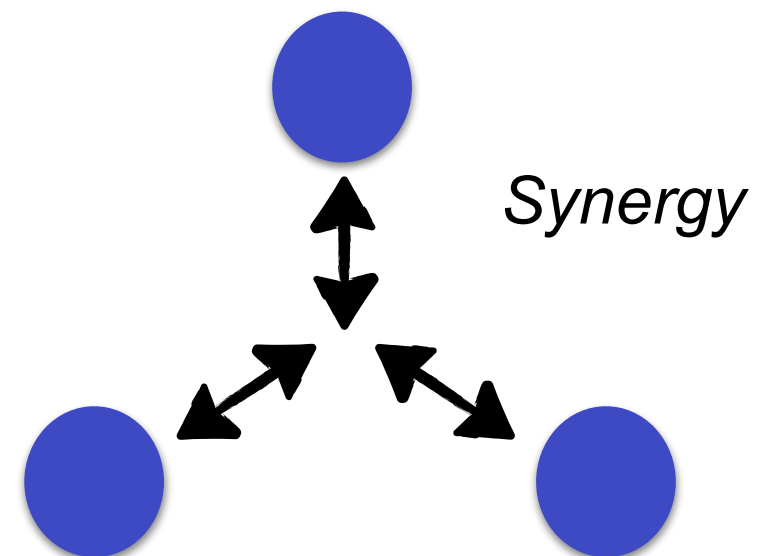
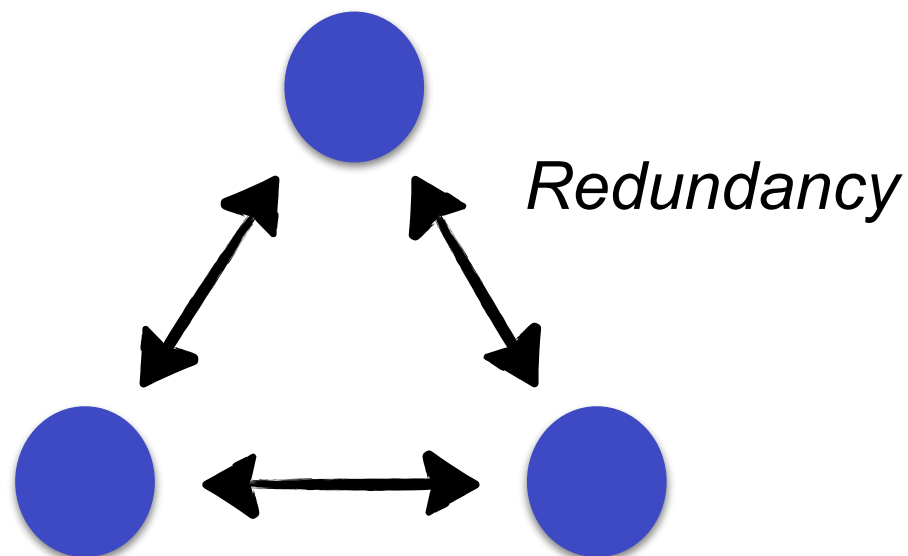
## A key distinction: Synergy vs redundancy

For two variables, interdependency is determined by strength.



For three or more variables, there are qualitatively different “kinds”:

- **Redundancy:** is where each variable has a copy of some data — simple extension of the conventional notion of dependency
- **Synergy:** local independency coexisting with collective structures



# Measuring synergy via the O-information

*O-information*: redundancy minus synergy in systems of all sizes!

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PHYSICAL REVIEW E **100**, 032305 (2019)

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## Quantifying high-order interdependencies via multivariate extensions of the mutual information

Fernando E. Rosas,<sup>1,2,\*</sup> Pedro A. M. Mediano,<sup>3</sup> Michael Gastpar,<sup>4</sup> and Henrik J. Jensen<sup>1,5</sup>

<sup>1</sup>*Centre of Complexity Science and Department of Mathematics, Imperial College London, London SW7 2AZ, England, United Kingdom*

<sup>2</sup>*Department of Electrical and Electronic Engineering, Imperial College London, London SW7 2AZ, England, United Kingdom*

<sup>3</sup>*Department of Computing, Imperial College London, London SW7 2AZ, England, United Kingdom*

<sup>4</sup>*School of Computer and Communication Sciences, École polytechnique fédérale de Lausanne (EPFL), Lausanne 1015, Switzerland*

<sup>5</sup>*Institute of Innovative Research, Tokyo Institute of Technology, Yokohama 226-8502, Japan*



(Received 31 December 2018; published 13 September 2019)

This paper introduces a model-agnostic approach to study statistical synergy, a form of emergence in which patterns at large scales are not traceable from lower scales. Our framework leverages various multivariate extensions of Shannon's mutual information, and introduces the *O-information* as a metric that is capable of characterizing synergy- and redundancy-dominated systems. The *O-information* is a symmetric quantity, and can assess intrinsic properties of a system without dividing its parts into “predictors” and “targets.” We develop key analytical properties of the *O-information*, and study how it relates to other metrics of high-order interactions from the statistical mechanics and neuroscience literature. Finally, as a proof of concept, we present an exploration on the relevance of statistical synergy in Baroque music scores.

## Measuring synergy via the O-information

*O-information*: redundancy minus synergy in systems of all sizes!

Example:

$$X_1 = X_2 = \dots = X_n$$

$$\Omega(\mathbf{X}^n) = n - 1 > 0$$

**redundancy!**

$$X_n = X_1 \oplus X_2 \oplus \dots \oplus X_{n-1}$$

$$\Omega(\mathbf{X}^n) = -(n - 1) < 0$$

**synergy!**



F. Rosas, P.A. M. Mediano, M. Gastpar, and H. J. Jensen. "Quantifying High-order Interdependencies via Multivariate Extensions of the Mutual Information," *Physical Review E* 100, no. 3 (2019): 032305.

## Case study on baroque music scores

Data analysis over music scores from the Baroque period (*Python, Music21 package*)

i) chorales for four voices by **J.S. Bach** (1685–1750)



Sheet music for a four-voice chorale by J.S. Bach, featuring Soprano, Alto, Tenor, and Bass parts. The lyrics are: "Wer hat dich so ge - schla - gen, mein Heil, und dich mit".

The music is written in G major (one sharp) and common time (C). The Soprano and Alto parts are in treble clef, while the Tenor and Bass parts are in bass clef. The Tenor part has an octave sign (8) below the first measure.

The lyrics are: "Wer hat dich so ge - schla - gen, mein Heil, und dich mit".

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Data analysis over music scores from the Baroque period (*Python, Music21 package*)

i) chorales for four voices by **J.S. Bach** (1685–1750)  
(43k four-note chords)



ii) Op. 1, 3, 4, 5 and 6 of **A. Corelli** (1653–1713)  
(80k four-note chords)

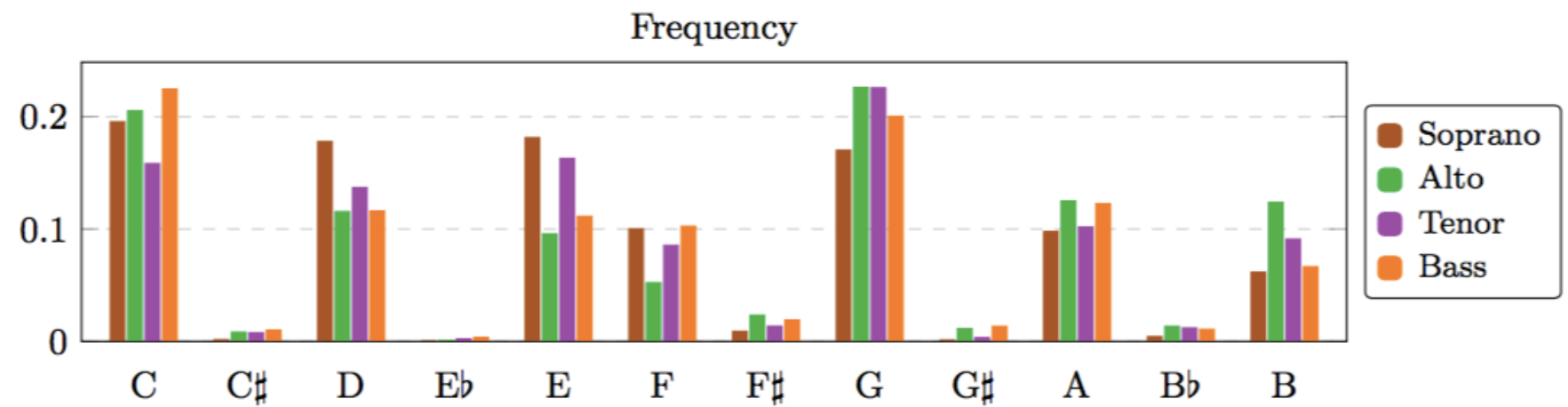


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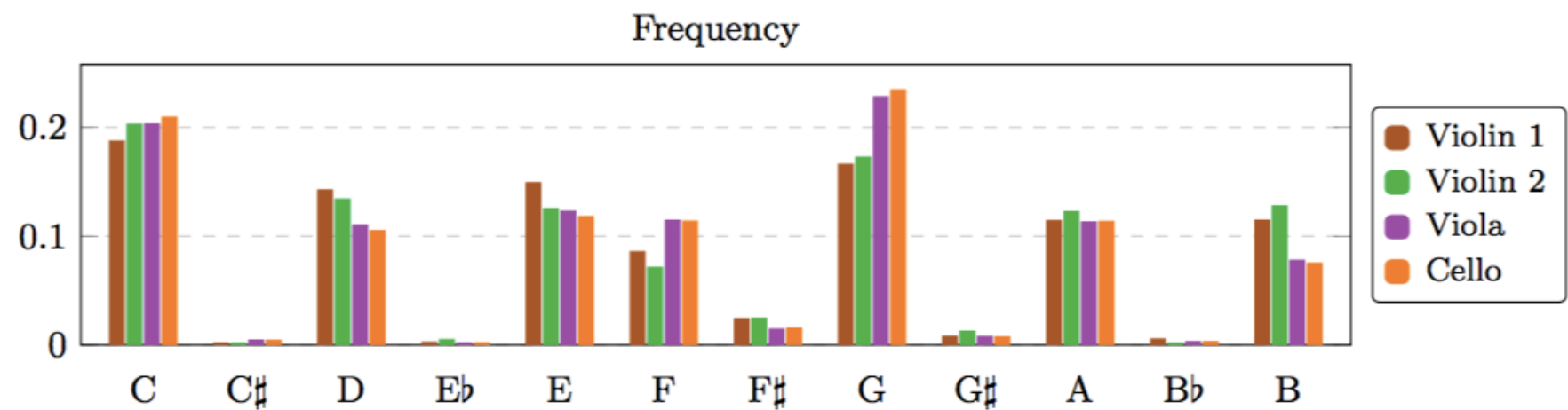
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### Bach's chorales

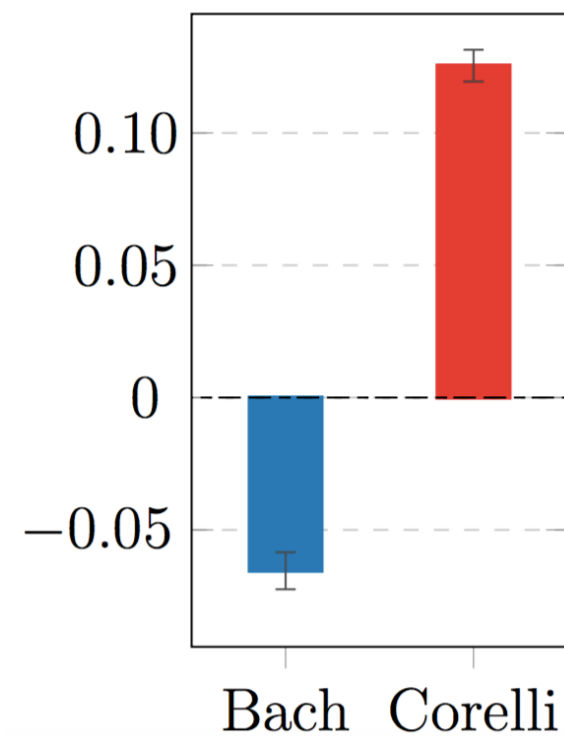


### Corelli's op. 1,3-6



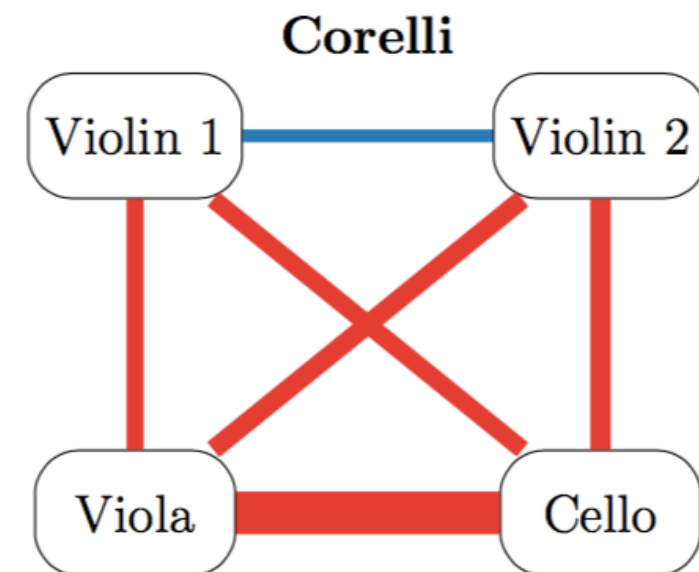
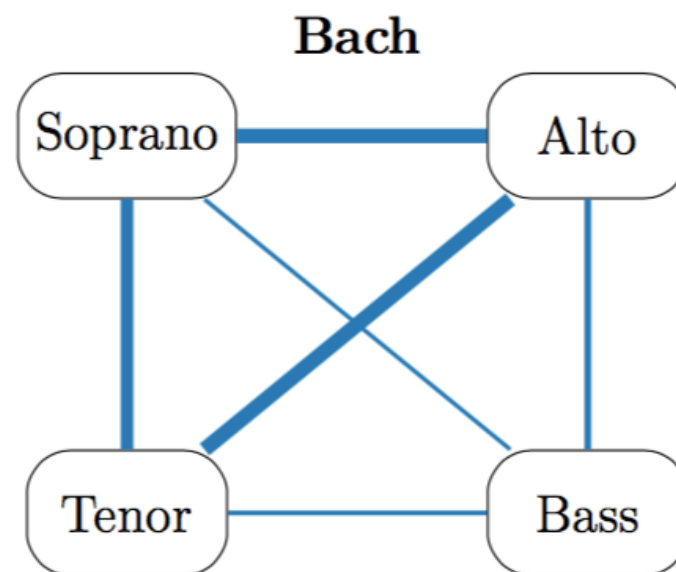
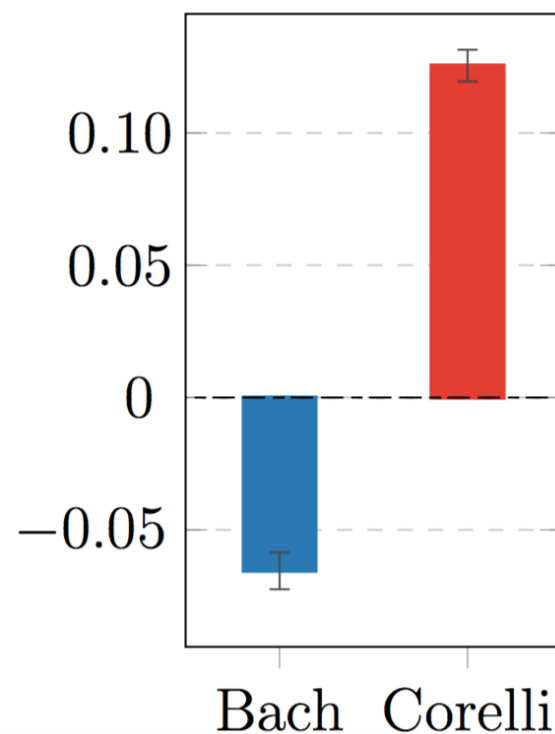
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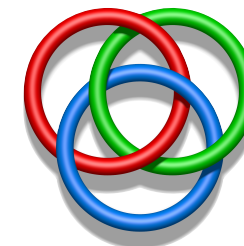


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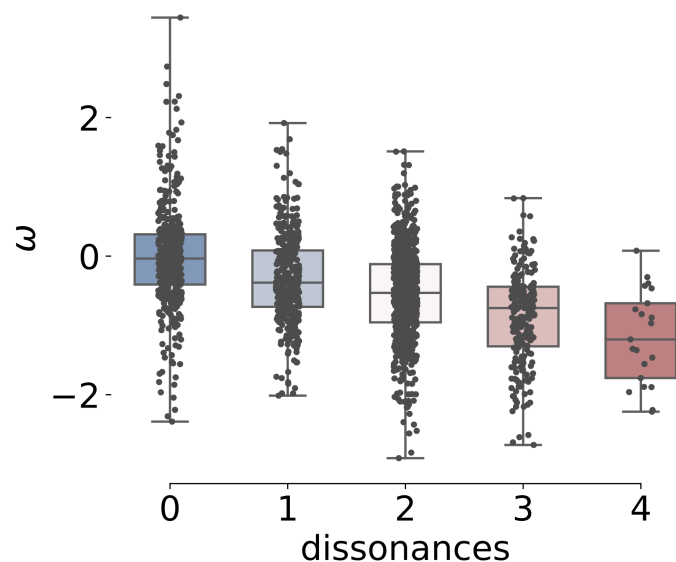
Synergy allows for **local autonomy**  
to coexist with **global cohesion**



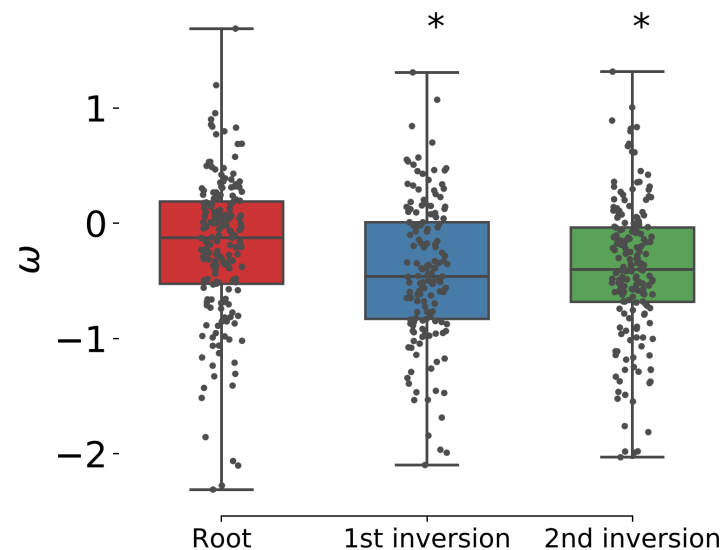
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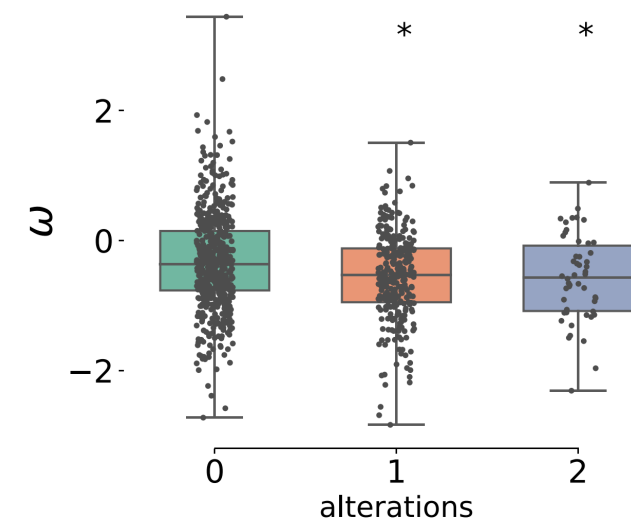
*Synergy grows with  
the number of dissonances  
within a chord*



*Synergy grows with  
the instability of the chord*



*Synergy grows with  
how far a chord is from the  
tonal centre*



Scagliarini, T., Marinazzo, D., Guo, Y., Stramaglia, S., & Rosas, F. E. (2022). Quantifying high-order interdependencies on individual patterns via the local O-information: theory and applications to music analysis. *Physical Review Research*, 4(1), 013184.

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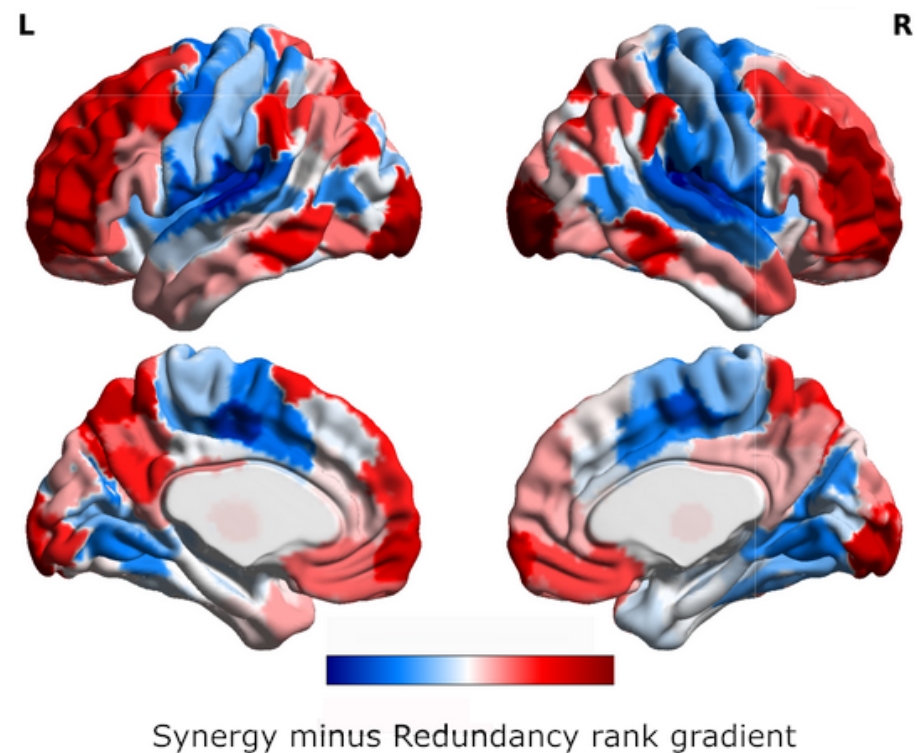
**What if we measure synergy in the human brain?**



# Synergy in human fMRI data

Study of resting state data from N=100 human subjects.

- ♦ **Red** regions are involved into more synergistic dynamics
- ♦ **Blue** regions are involved into more redundant dynamics



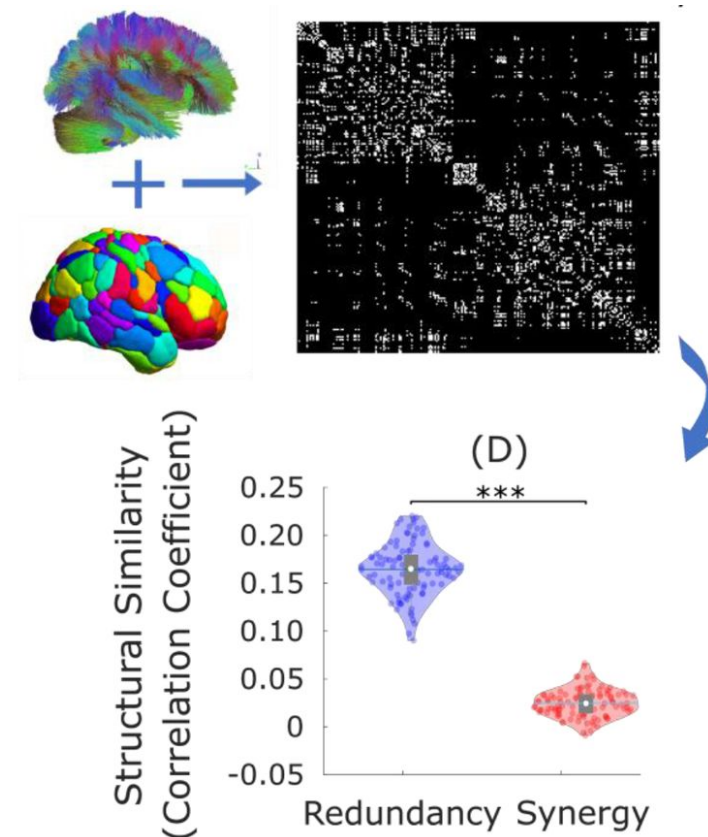
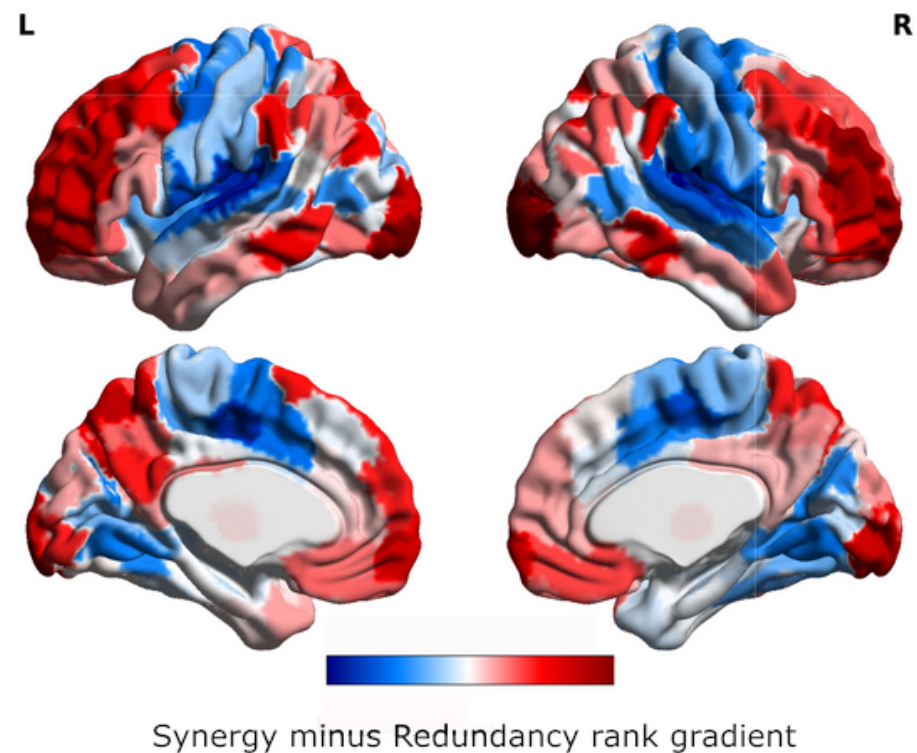
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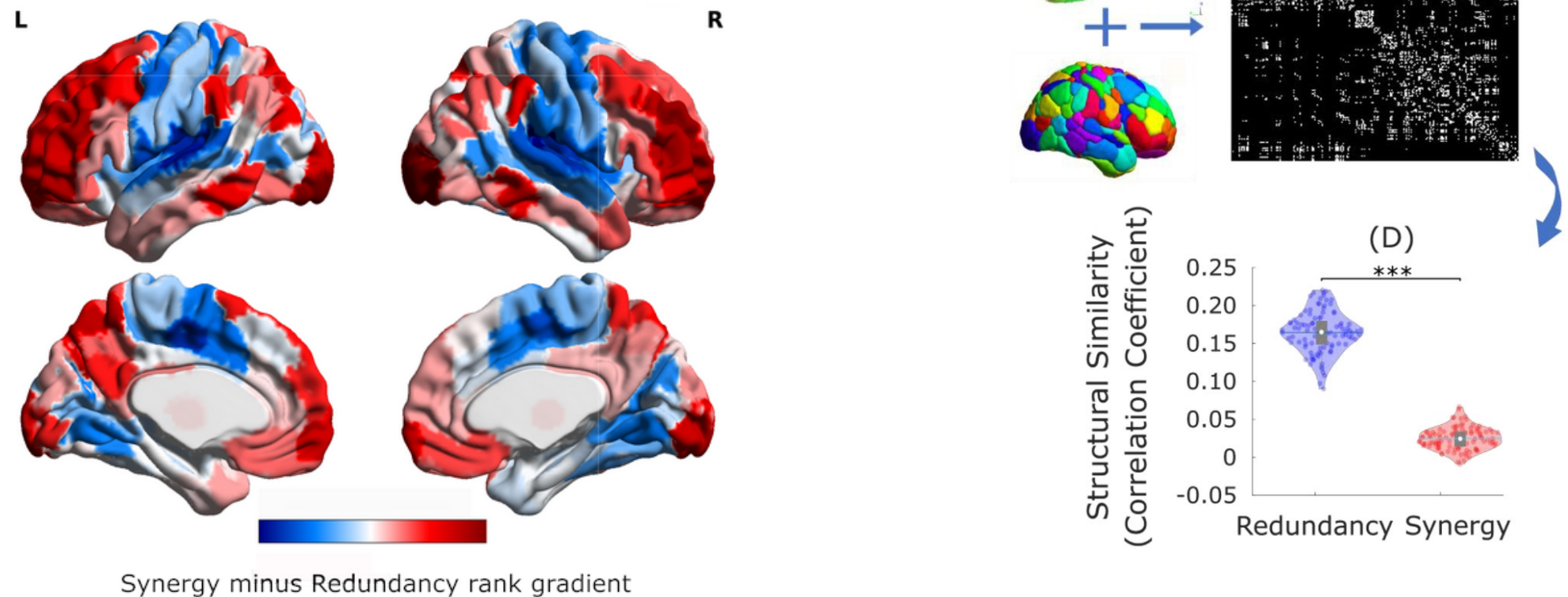
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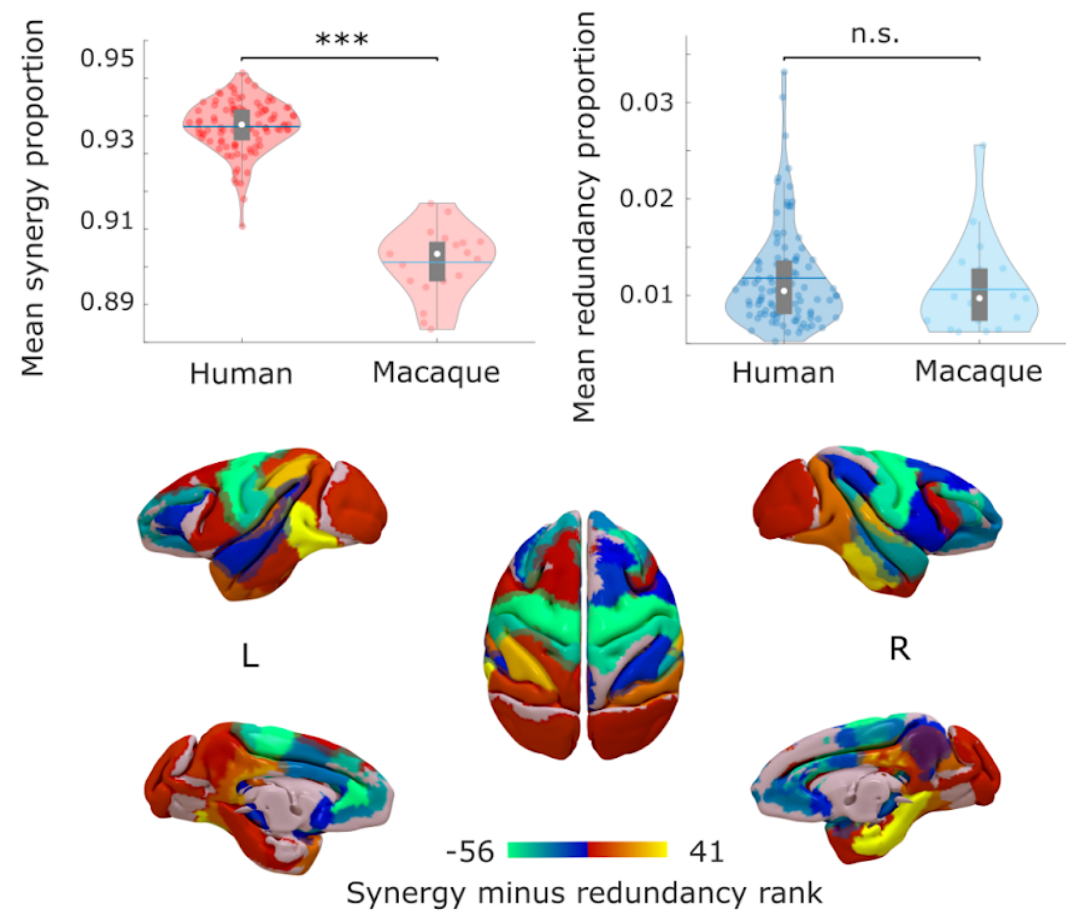
**Redundancy is associated with I/O systems**  
**Synergy seems to enable global integration**

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# Synergy in human fMRI data

Comparing neural dynamics of humans and macaques.

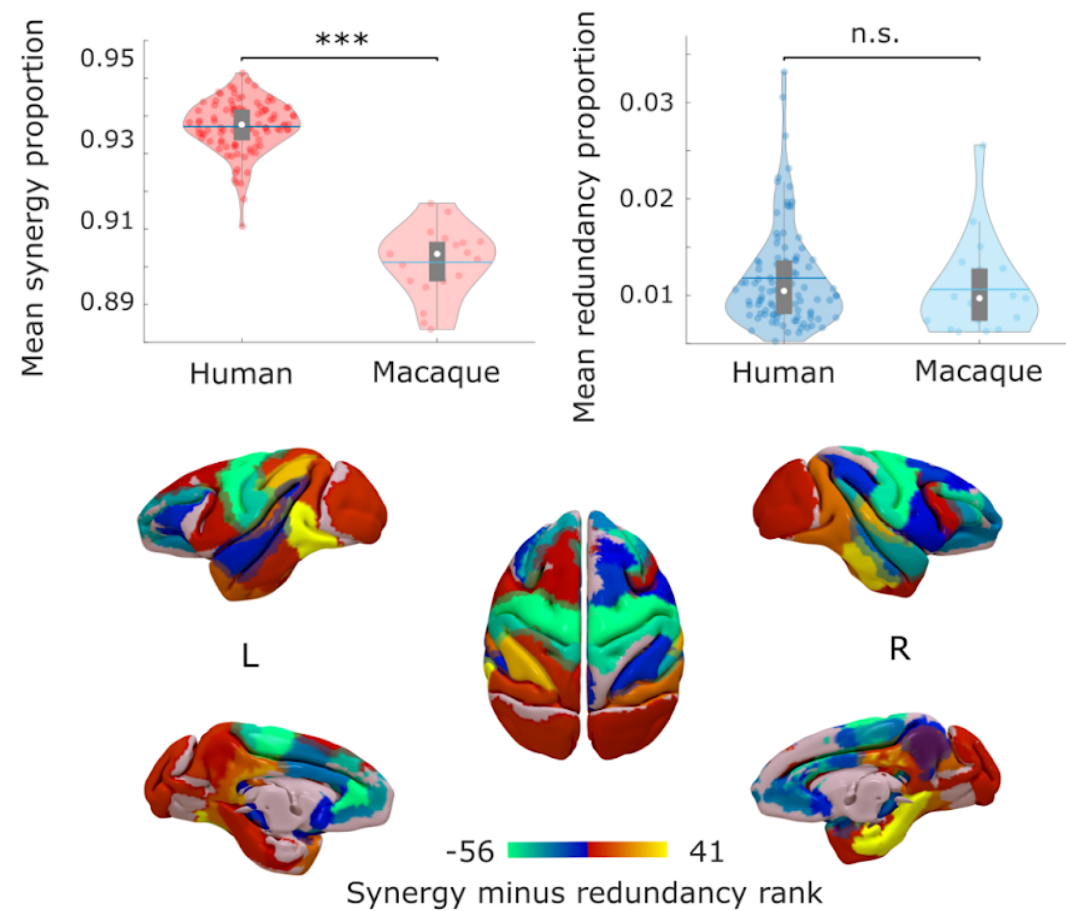


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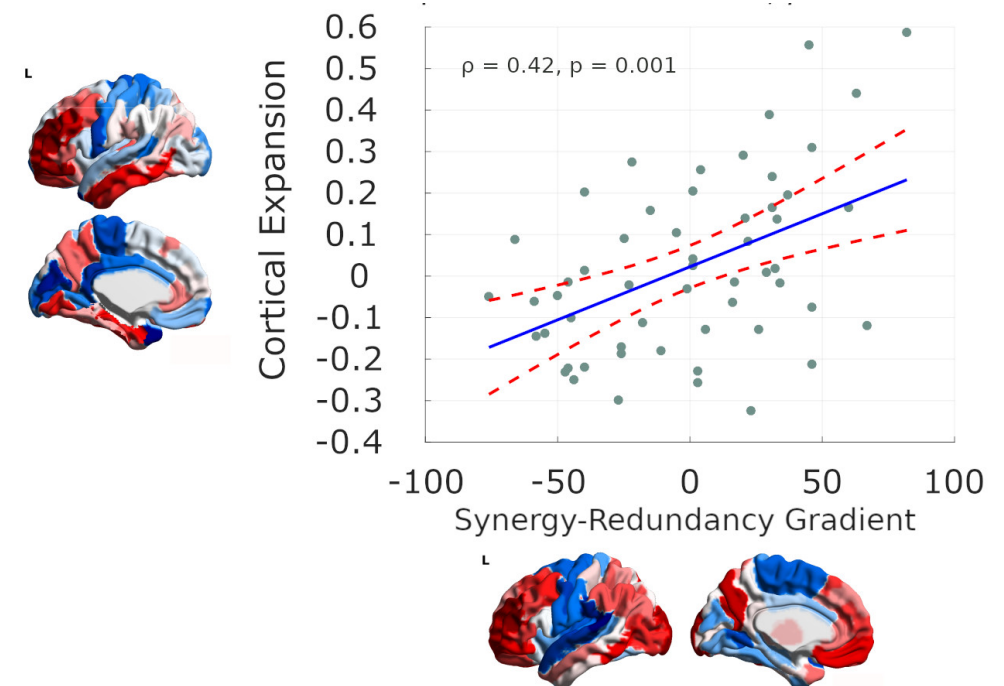
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# Synergy in human fMRI data

Comparing neural dynamics of humans and macaques.



*Chimp-to-human cortical expansion*

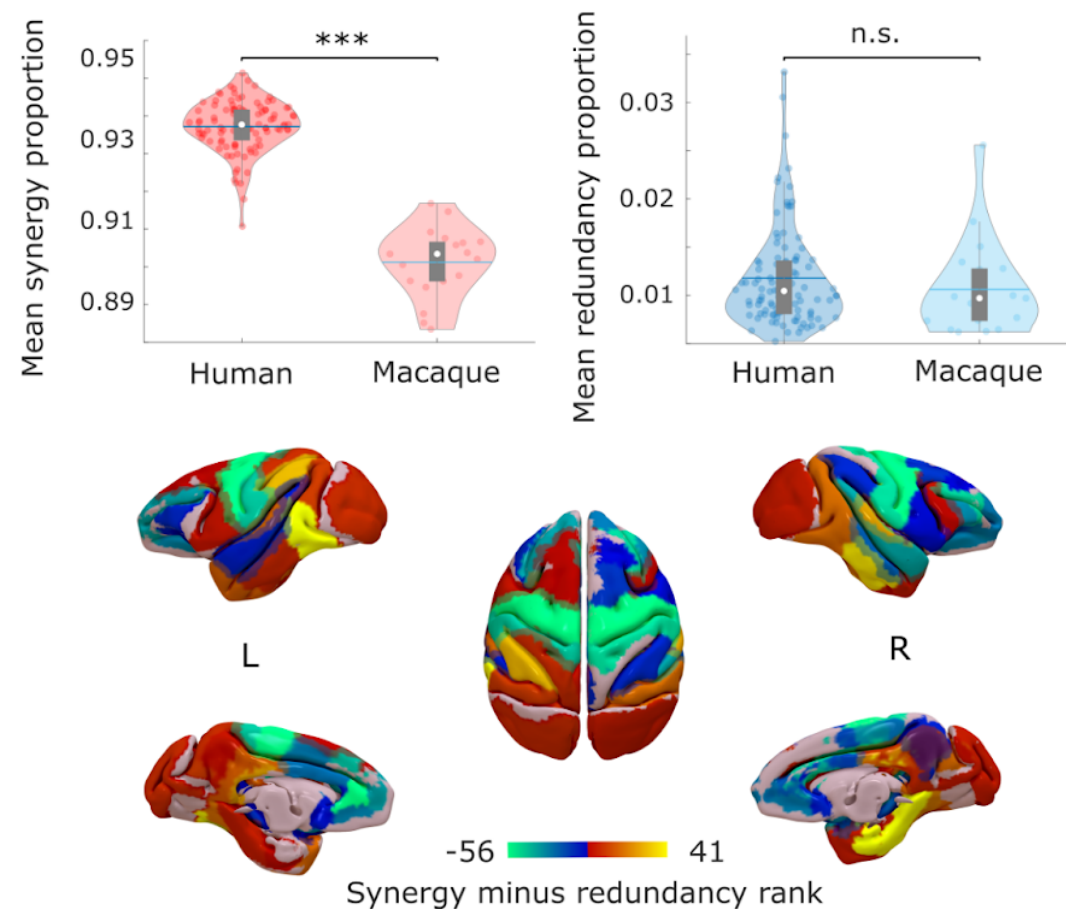


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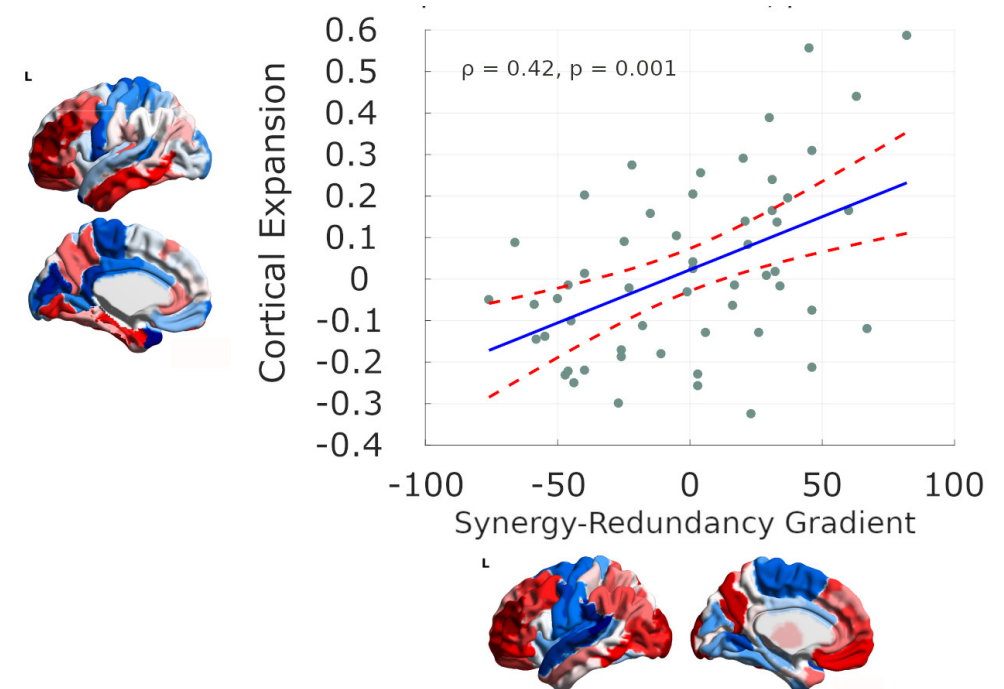
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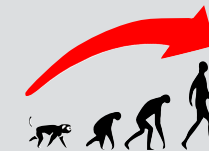
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*Chimp-to-human cortical expansion*



Synergistic neural circuits seem to have been  
**uniquely favoured by evolution**



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## Ideas to take home

- Synergy takes place when the whole is more than the sum of the parts. This can be quantified from experimental data.

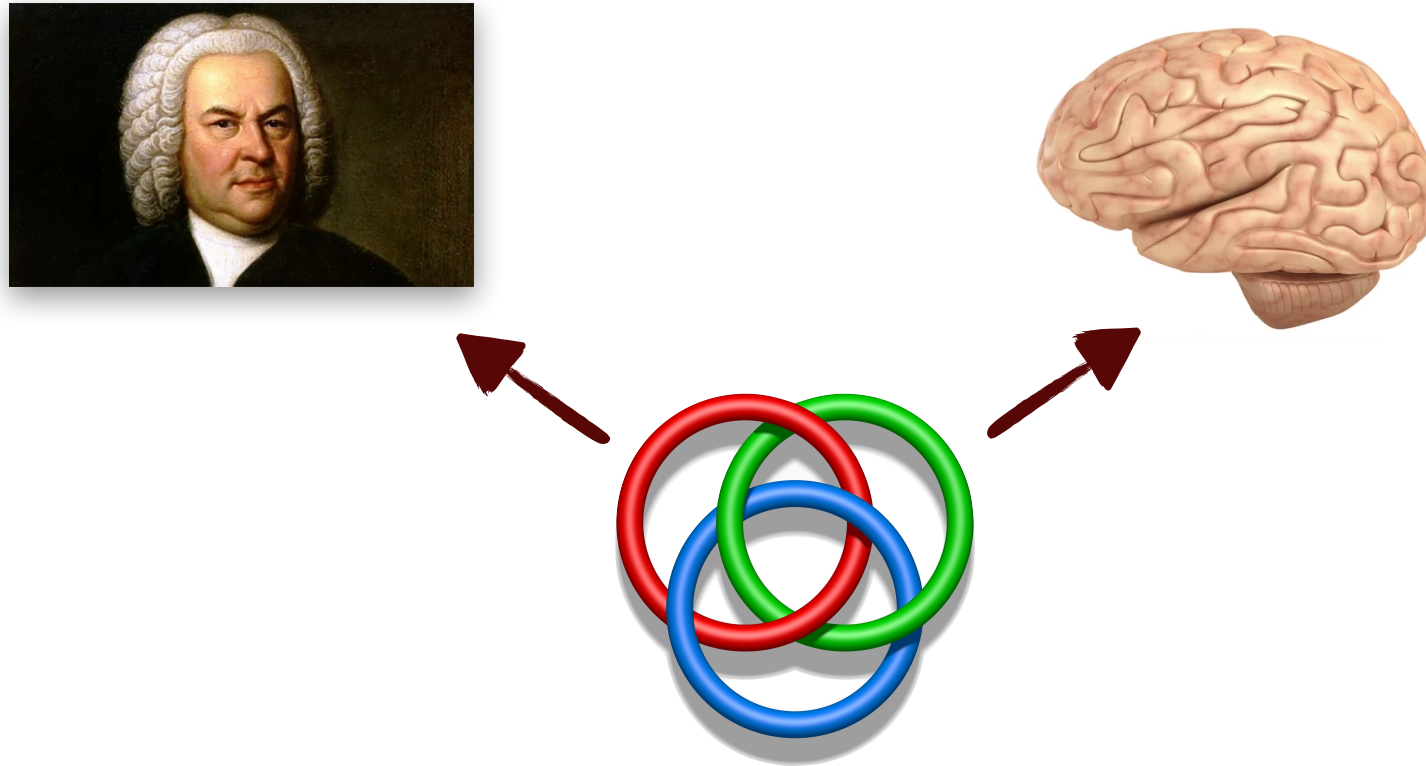
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- In music, synergy is what allows for local autonomy of parts to coexist with global cohesion of the whole.
- In the brain, synergy is an important for integration of information, differentiating humans from macaques.



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*Thank you!*

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**Imperial College**  
**London**

