Complexity Science

Imperial College London

GUILD HALL SCHOOL

Neural markers of shared conscious experiences in classical music improvisation

Alberto Liardi
a.liardi@imperial.ac.uk

Complexity Science Symposium 2026

In search of neural correlates

Aim

- Investigate neural indicators of shared experiences during improvisational states
- Detect neural differences between ***letgo*** and ***strict*** modes
- Explore neural dynamics and (inter-)brain communication

Experiments

- Artists performing music pieces in ***letgo*** and ***strict*** versions
- EEG signal from musicians during musical performance

Methods

- Analysis of signal complexity
- Exploration of brain network topology

Datasets

Duo – Beethoven & Schumann

- Piano
- Cello

Datasets

Duo – Beethoven & Schumann

- Piano
- Cello


Trio – Schubert

- Flute
- Piano
- Singer



frontiers in Psychology

The Improvisational State of Mind: A Multidisciplinary Study of an Improvisatory Approach to Classical Music Repertoire Performance

David Dolan[1], Henrik J. Jensen[2,3], Pedro A. M. Mediano[4], Miguel Molina-Solana[4,5], Hardik Rajpal[2], Fernando Rosas[2,6] and John A. Sloboda[1]*

Datasets

Duo – Beethoven & Schumann

- Piano
- Cello

Trio – Schubert

- Flute
- Piano
- Singer

Trio – Ravel & Improvised

- Flute
- Harp
- Viola

frontiers in Psychology

The Improvisational State of Mind: A Multidisciplinary Study of an Improvisatory Approach to Classical Music Repertoire Performance

*David Dolan[1], Henrik J. Jensen[2,3], Pedro A. M. Mediano[4], Miguel Molina-Solana[4,5], Hardik Rajpal[2], Fernando Rosas[2,6] and John A. Sloboda[1]**

The improvisatory approach to classical music performance: An empirical investigation into its characteristics and impact

David Dolan[1], John Sloboda[1], Henrik Jeldtoft Jensen[2], Björn Crüts[3] and Eugene Feygelson[4]

MPR

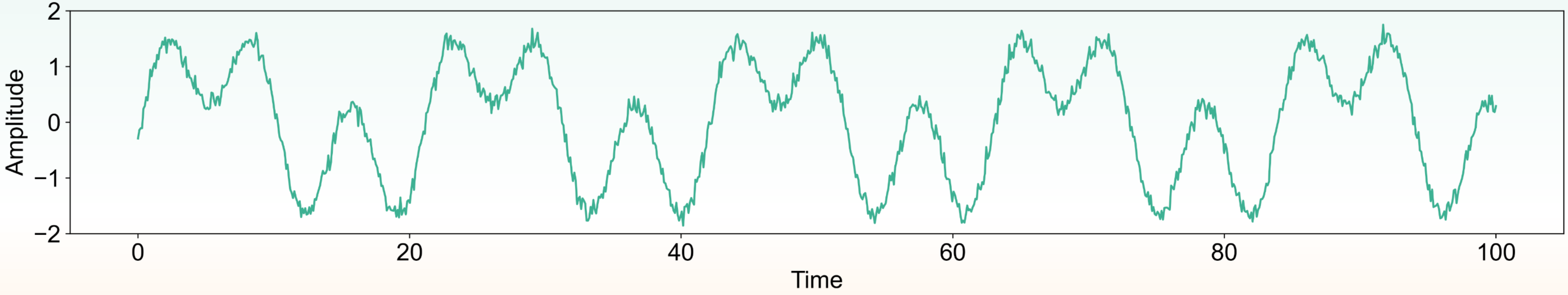
Music Performance Research

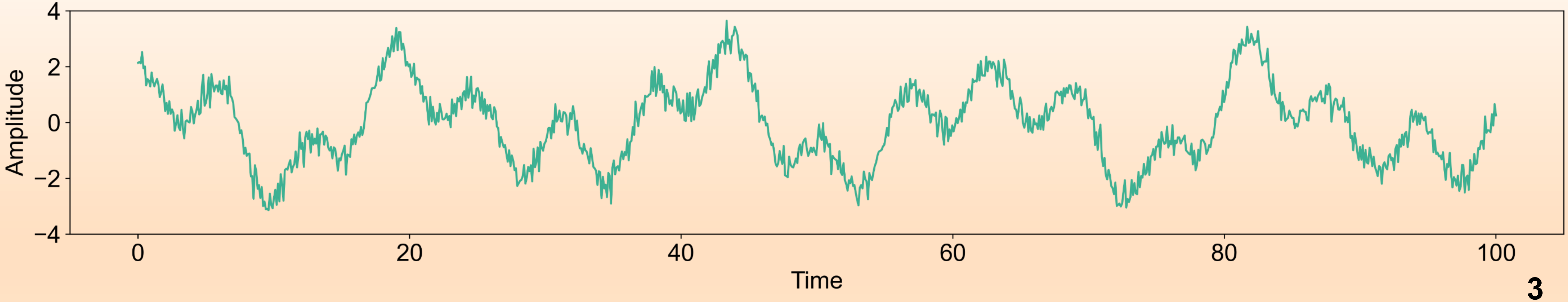
Intermezzo #1 – Complexity and CSER

Signal complexity: Measure of the dynamical richness of a signal

Intermezzo #1 – Complexity and CSER

Signal complexity: Measure of the dynamical richness of a signal

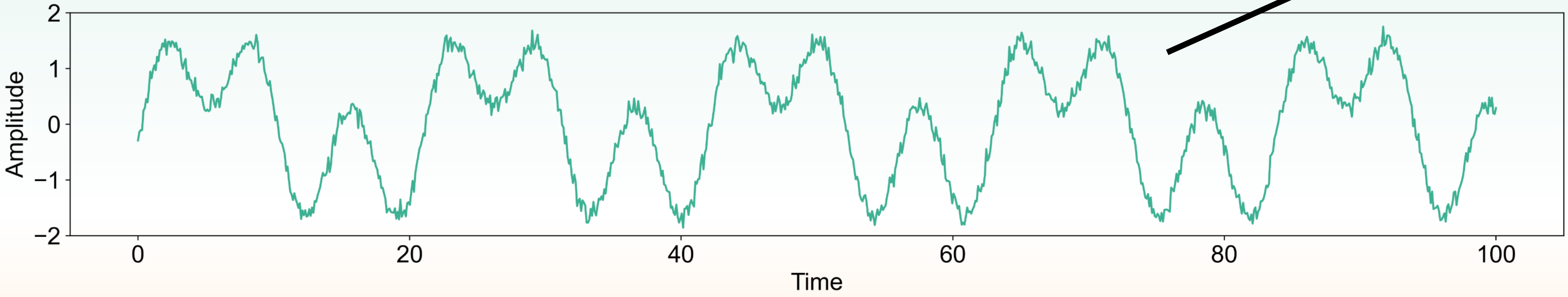




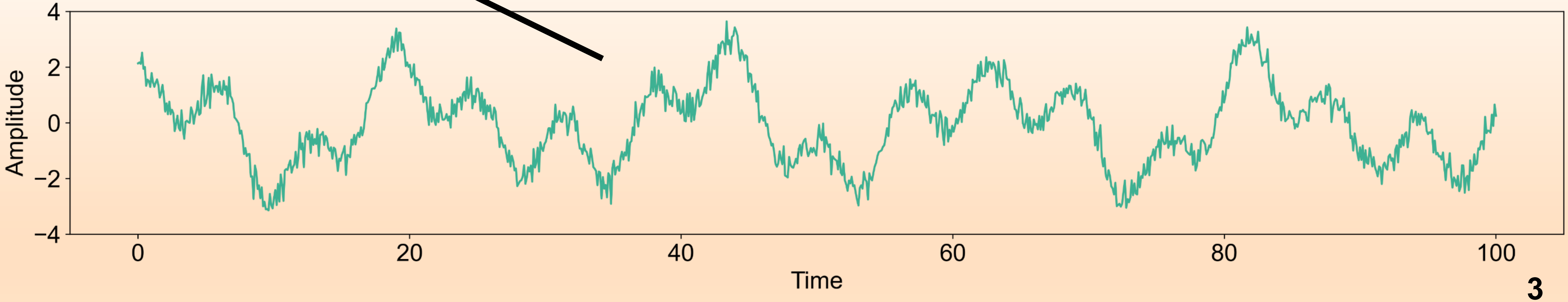
Intermezzo #1 – Complexity and CSER

Signal complexity: Measure of the dynamical richness of a signal

Low Complexity



High Complexity



Intermezzo #1 – Complexity and CSER

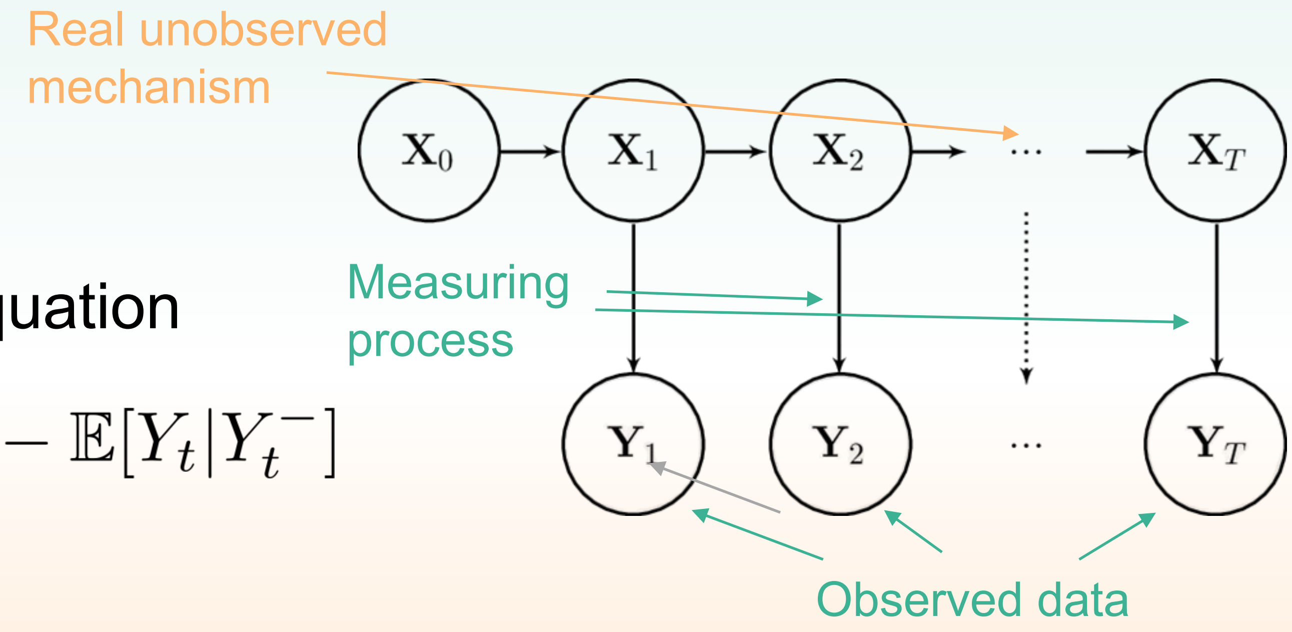
Signal complexity: Measure of the dynamical richness of a signal

State-space models

$$X_{t+1} = AX_t + K\epsilon_t \quad \text{State Equation}$$

$$Y_t = CX_t + \epsilon_t \quad \text{Observation Equation}$$

- ϵ_t is the *innovation* at time t: $\epsilon_t \equiv Y_t - \mathbb{E}[Y_t | Y_t^-]$



Intermezzo #1 – Complexity and CSER

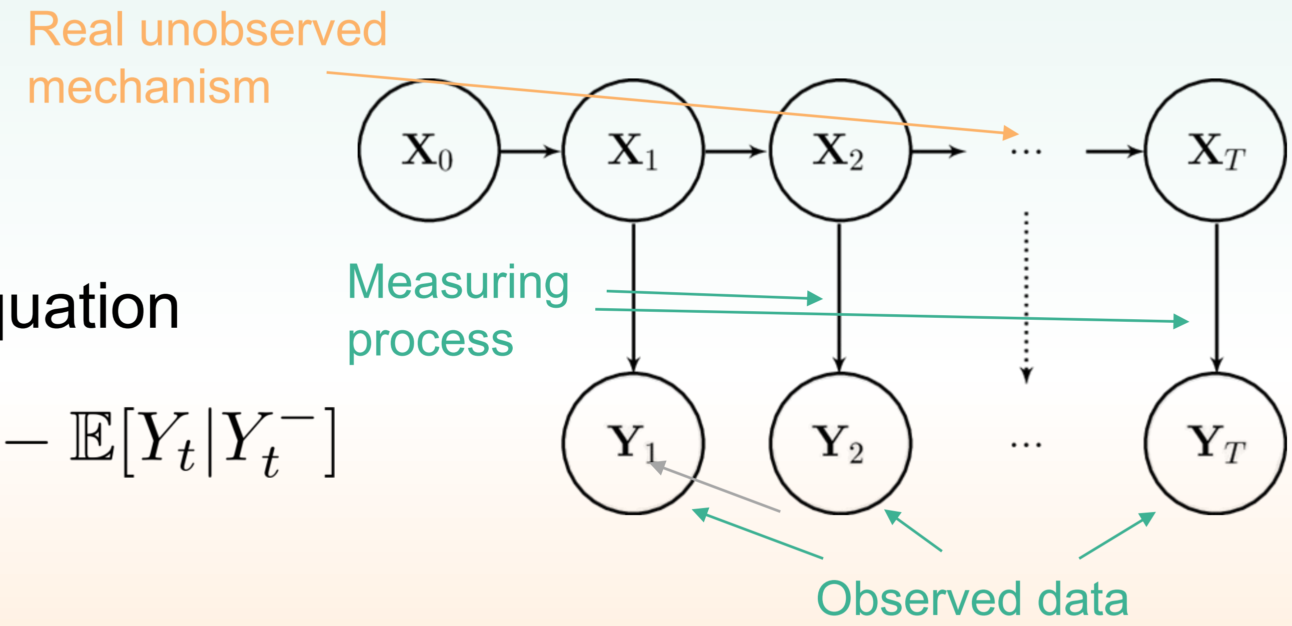
Signal complexity: Measure of the dynamical richness of a signal

State-space models

$$X_{t+1} = AX_t + K\epsilon_t \quad \text{State Equation}$$

$$Y_t = CX_t + \epsilon_t \quad \text{Observation Equation}$$

- ϵ_t is the *innovation* at time t: $\epsilon_t \equiv Y_t - \mathbb{E}[Y_t | Y_t^-]$



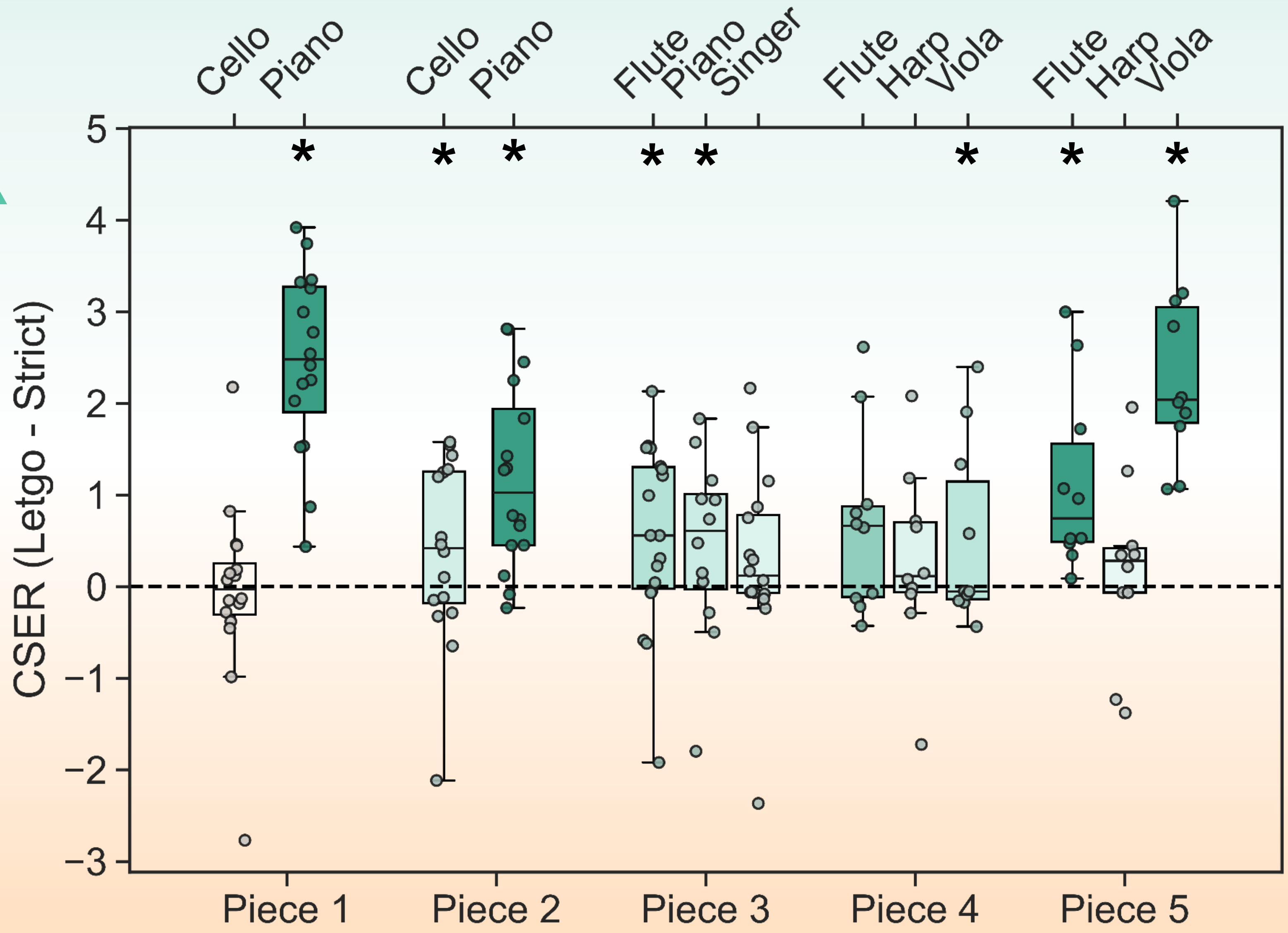
Complexity via State-space Entropy Rate (CSER)

- Assume Gaussian noise: $\epsilon_t \sim \mathcal{N}(0, V)$
- Define: $\mathrm{CSER} = \frac{1}{2} \log |V|$

Mediano, Pedro AM, et al. *eLife* (2023): 10.7554 88683.1

Results – Complexity

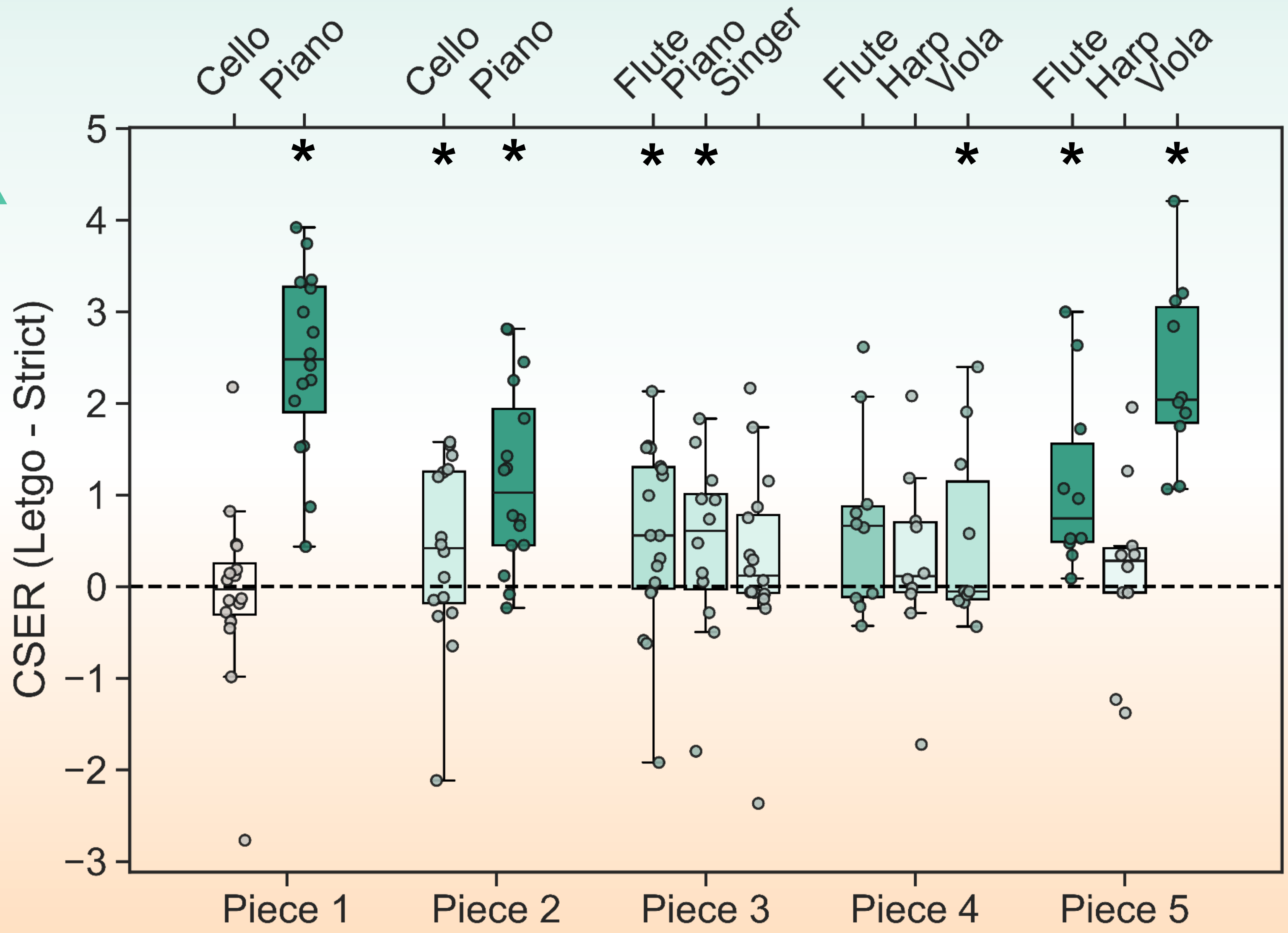
Higher complexity in letgo



Higher complexity in strict

Results – Complexity

Higher complexity in letgo

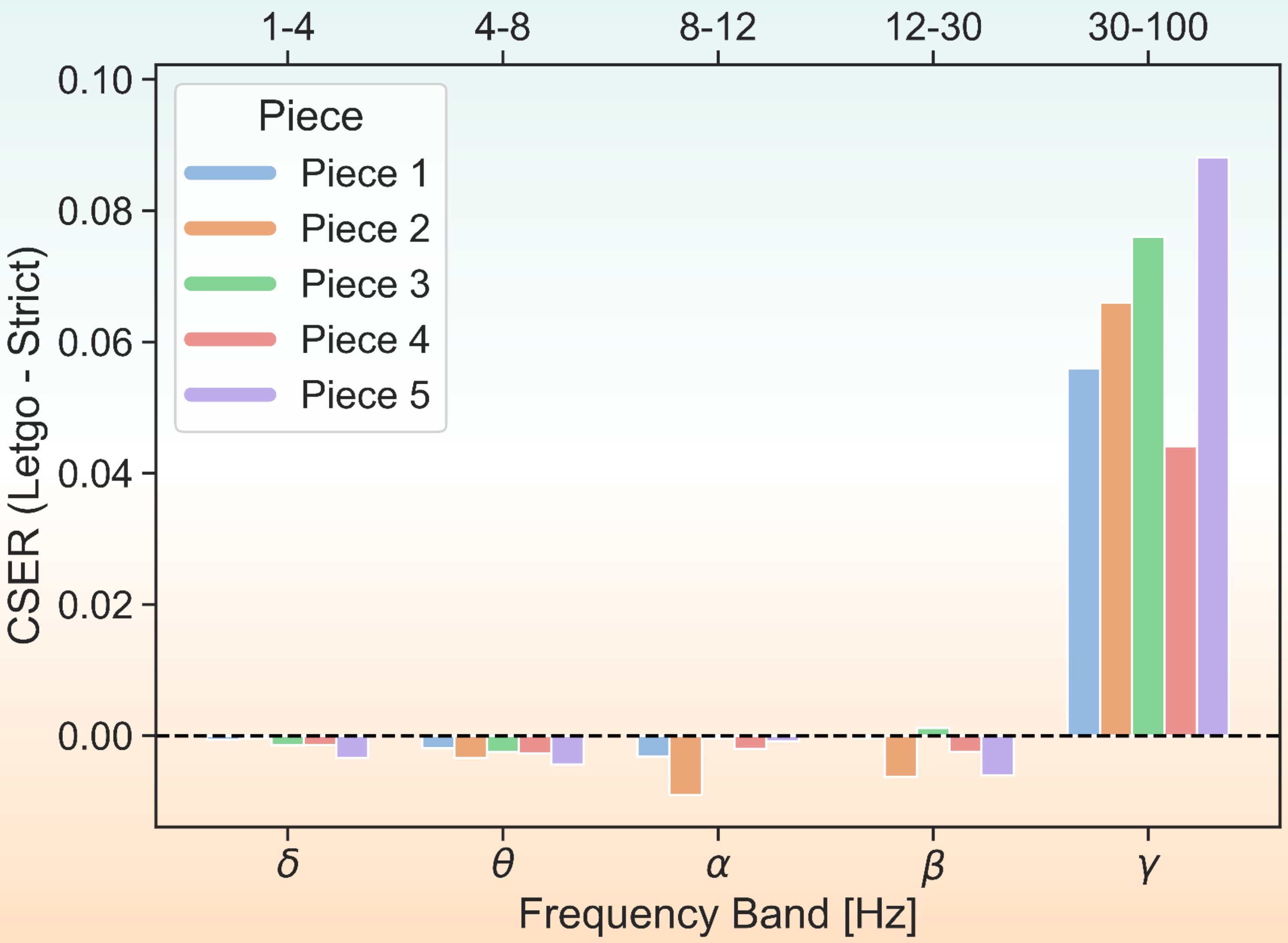


Higher complexity in strict

- Letgo performances have higher neural signal diversity and richer dynamics

Results – Complexity

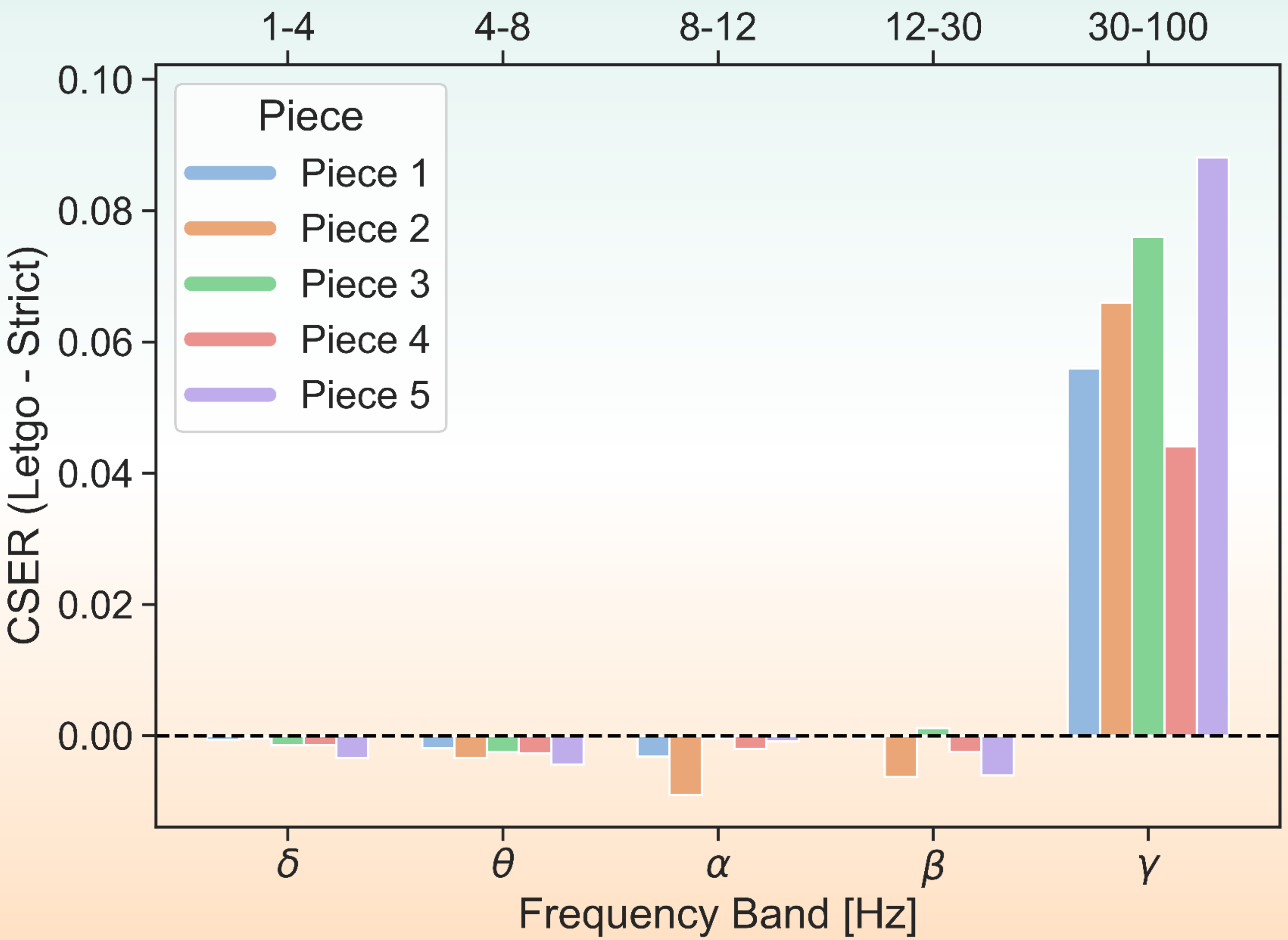
Higher letgo



Higher strict

Results – Complexity

Higher letgo



Higher strict

- Indicators of heightened awareness and cognitive engagement during letgo

Intermezzo #2 – Communication and Networks

How do brains communicate with each other?

Intermezzo #2 – Communication and Networks

How do brains communicate with each other?

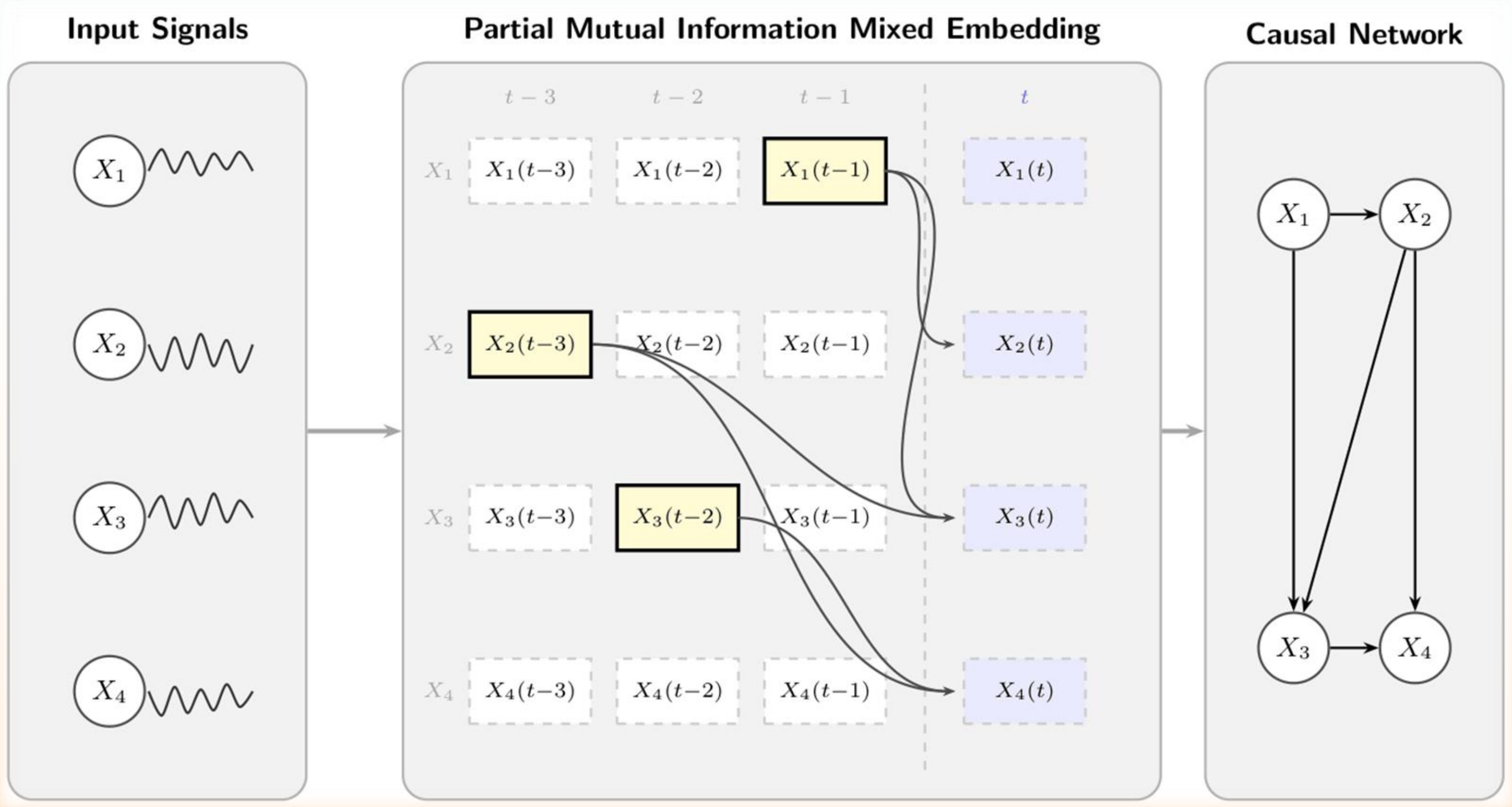
Use **Partial Mutual Information Mixed Embedding (pMIME)** to construct networks of information flow

Kugiumtzis, Dimitris. *Physical Review E—Statistical, Nonlinear, and Soft Matter Physics* 87.6 (2013): 062918.

Intermezzo #2 – Communication and Networks

How do brains communicate with each other?

Use **Partial Mutual Information Mixed Embedding (pMIME)** to construct networks of information flow



Kugiumtzis, Dimitris. *Physical Review E—Statistical, Nonlinear, and Soft Matter Physics* 87.6 (2013): 062918.

Intermezzo #2 – Communication and Networks

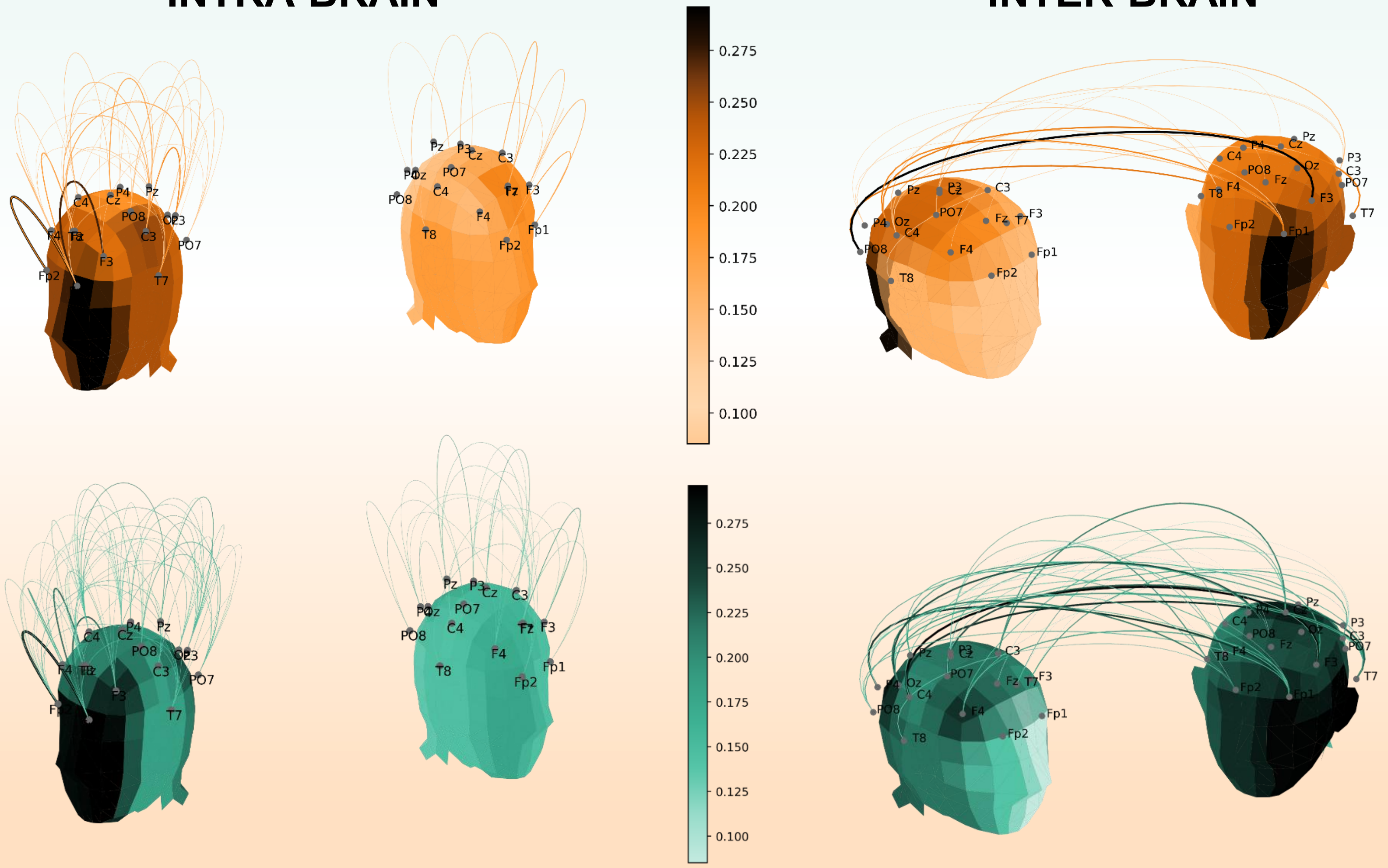
How are brains communicating with each other?

Duo

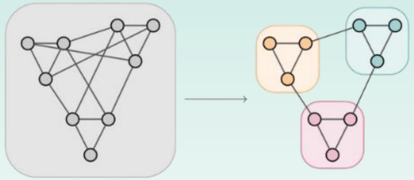
INTRA-BRAIN **INTER-BRAIN**

STRICT

LET-GO

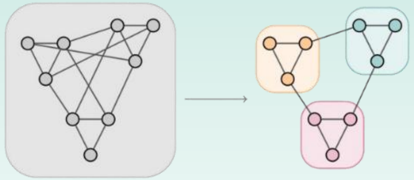


Results – Clusters

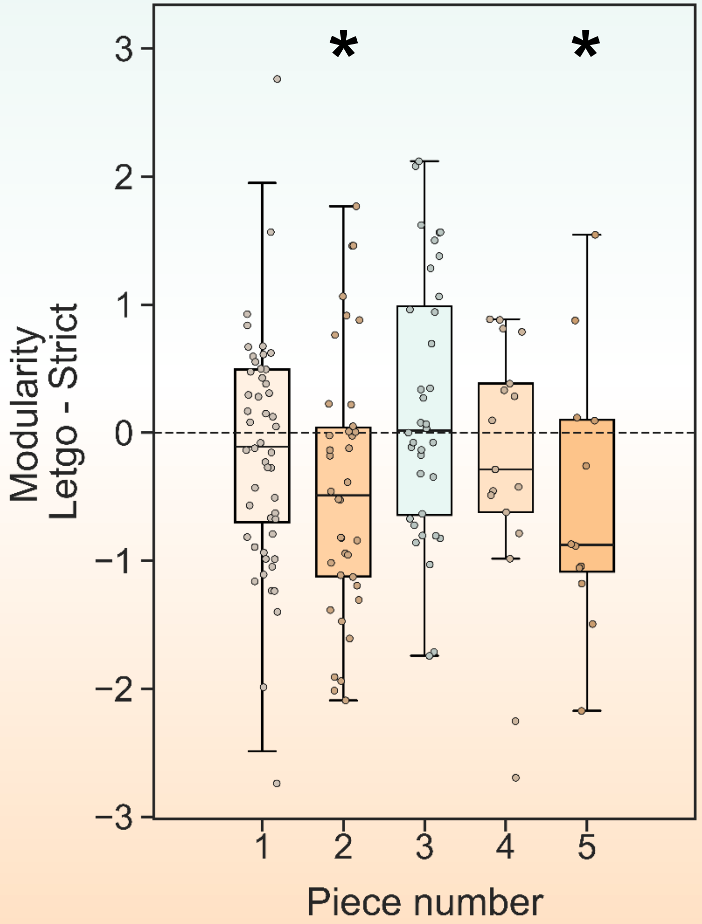


Community detection to identify clusters of increased interdependence

Results – Clusters

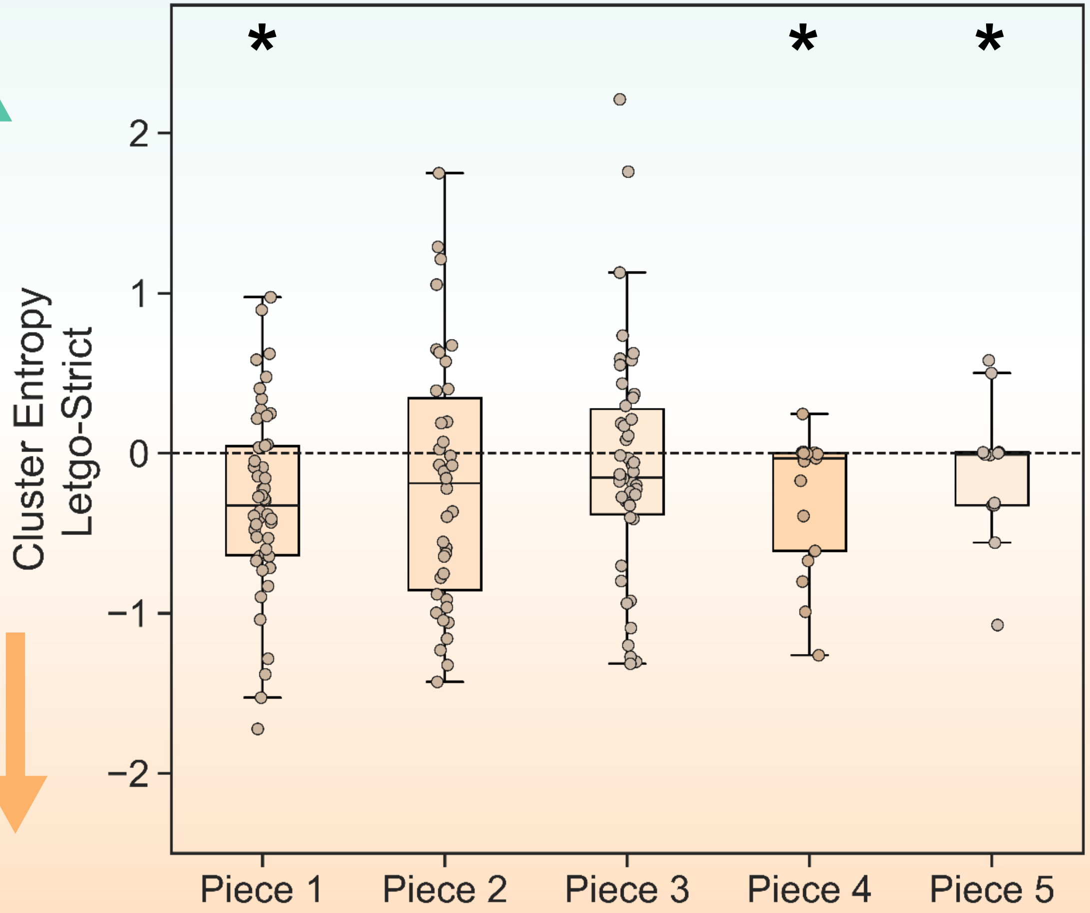


Community detection to identify clusters of increased interdependence

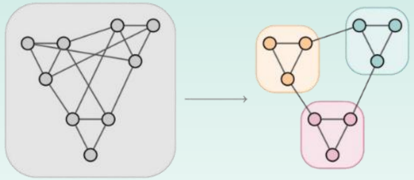


More modular in letgo

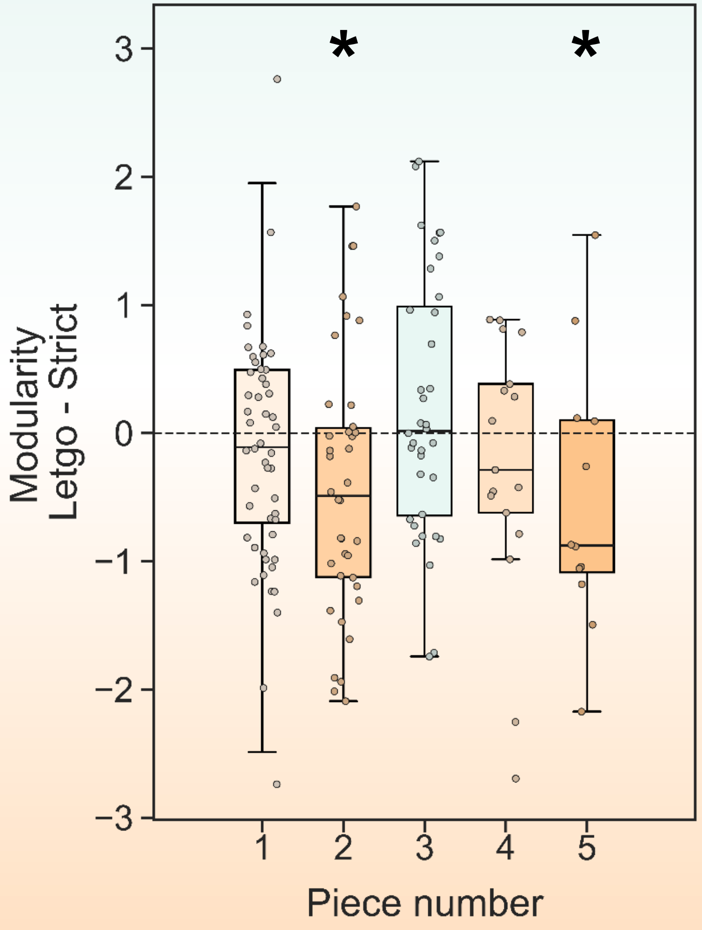
More modular in strict



Results – Clusters

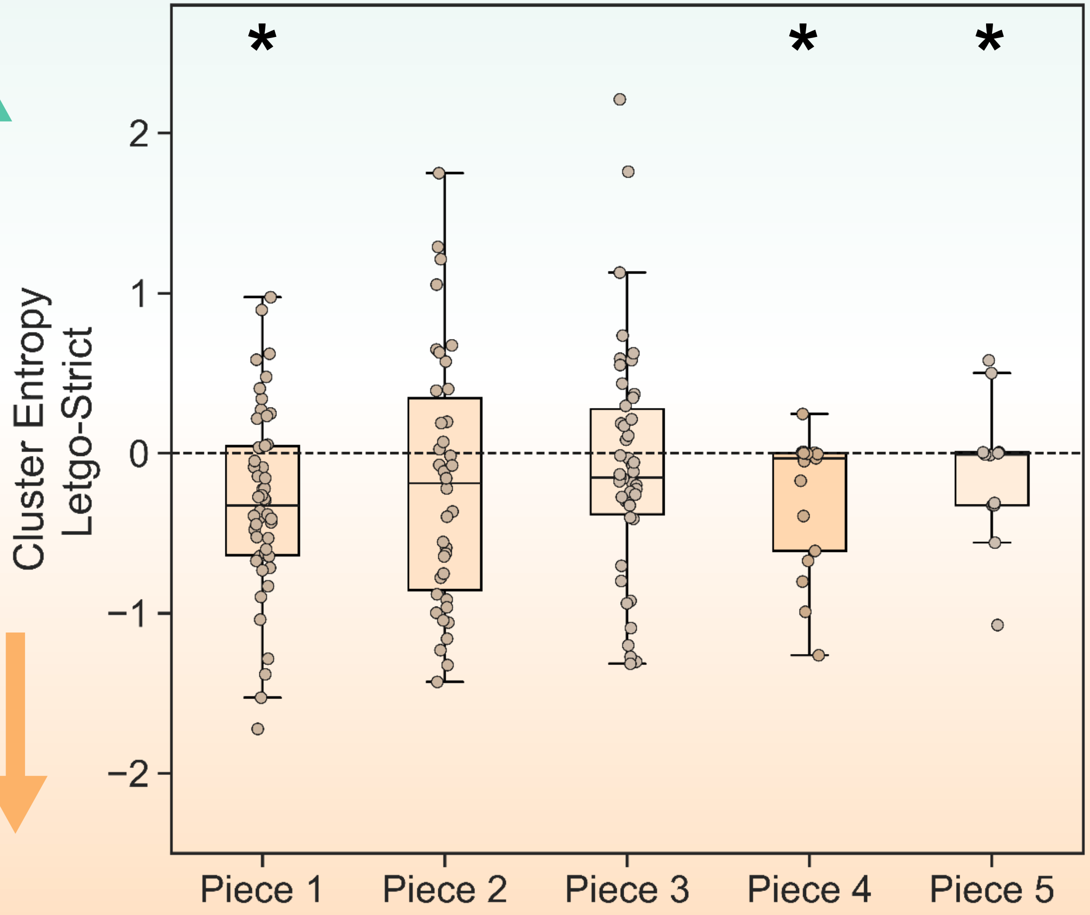


Community detection to identify clusters of increased interdependence



More modular in letgo

More modular in strict



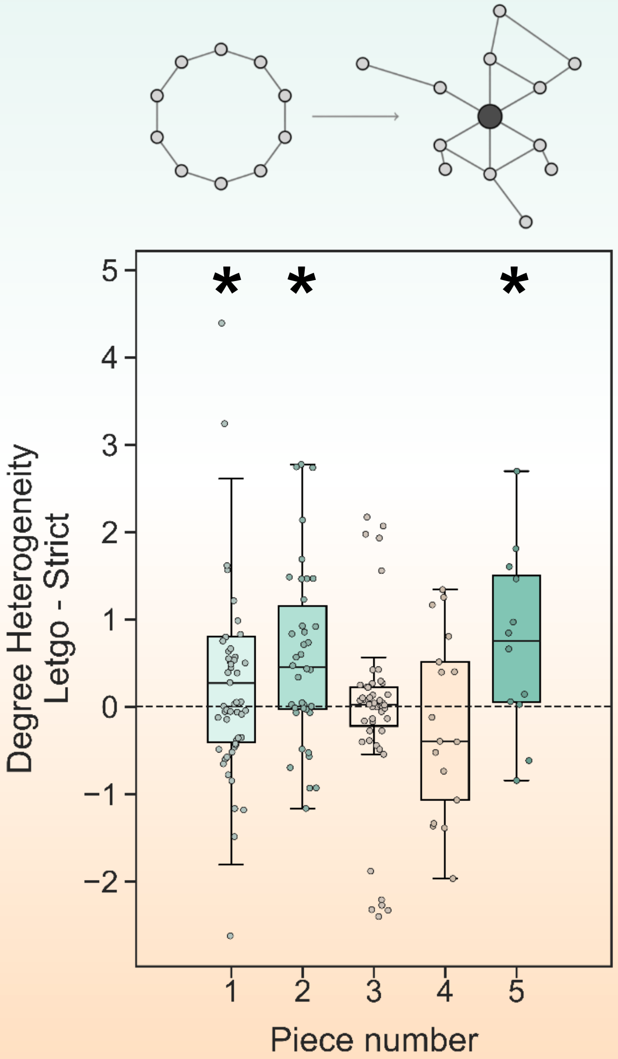
- Increased regional segregation in strict modes

Results – Network topology

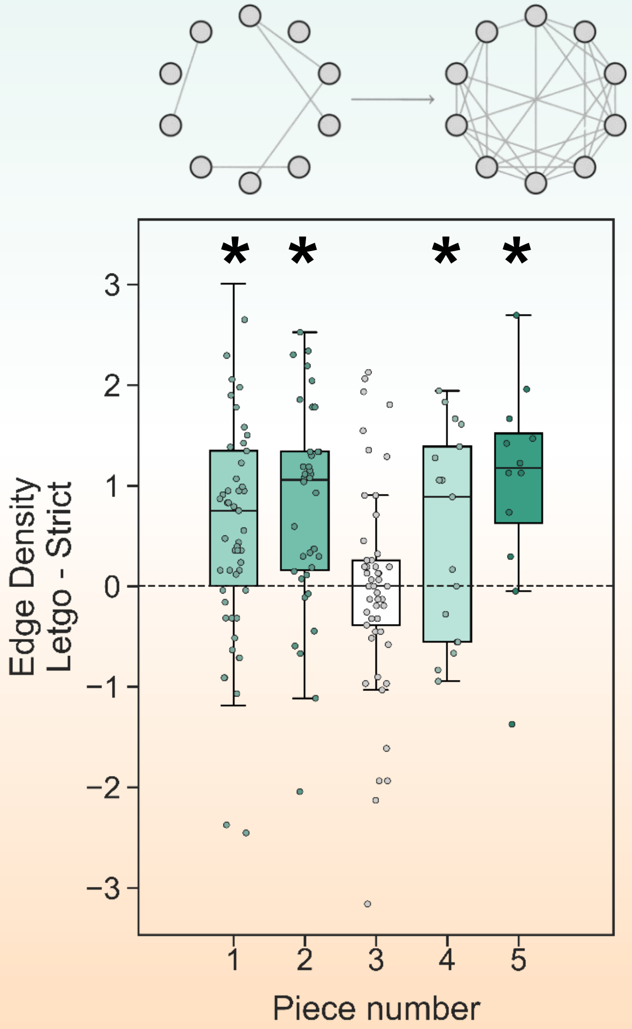
Network topology to explore brain connectivity and organisation

Results – Network topology

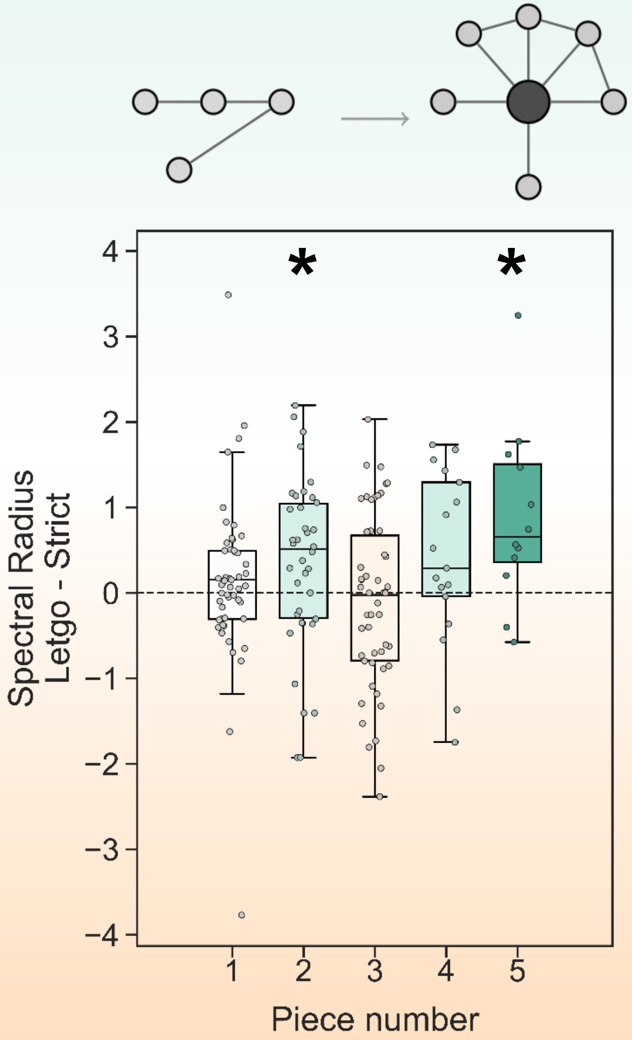
Degree heterogeneity



Edge density



Spectral Radius

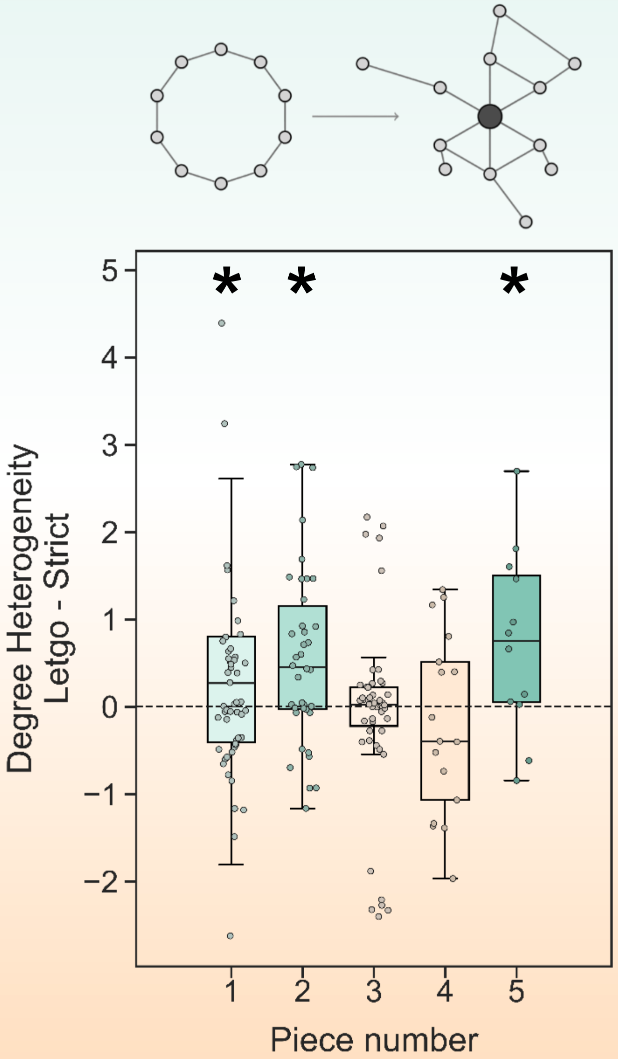


Higher
letgo

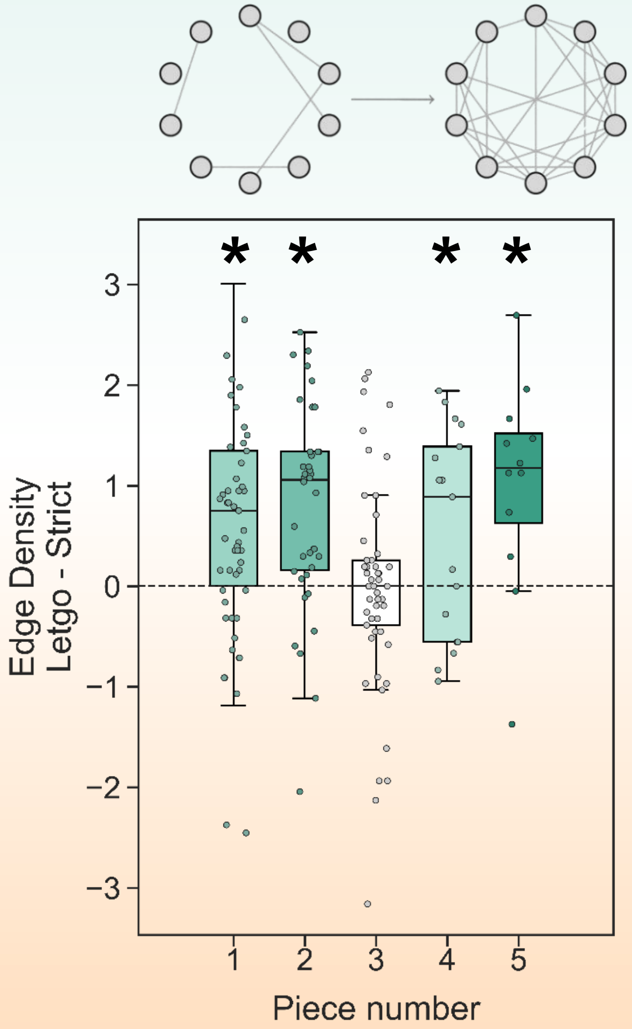
Higher
strict

Results – Network topology

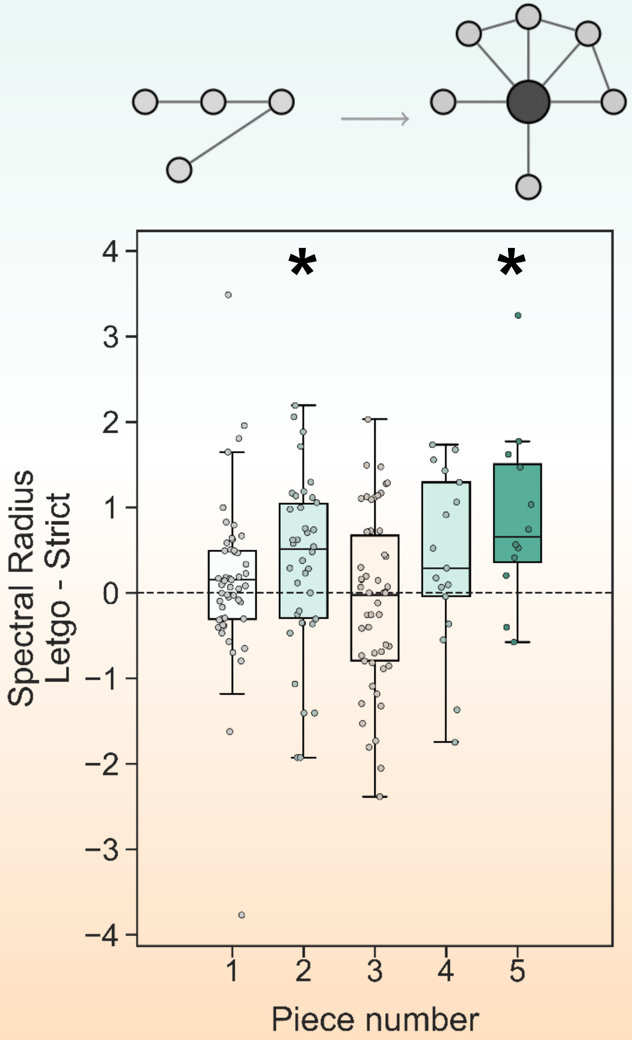
Degree heterogeneity



Edge density



Spectral Radius



Higher letgo

Higher strict

- Increased connectivity and more integrated organisation in letgo

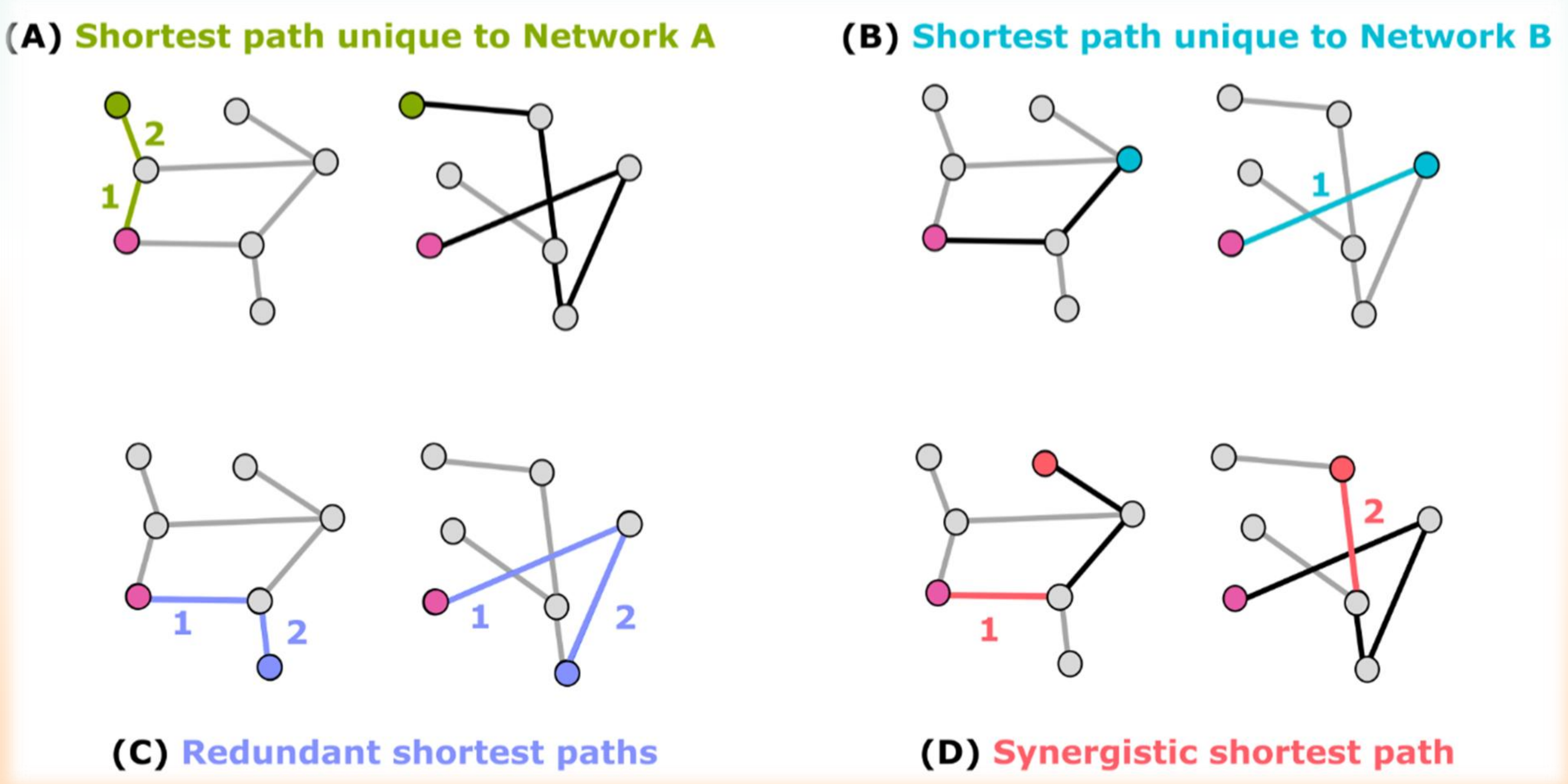
Results – Communication efficiency

Partial Network Decomposition to analyse shortest paths across multilayer networks

Luppi, Andrea I., et al. *arXiv preprint* arXiv:2306.01645 (2023).

Results – Communication efficiency

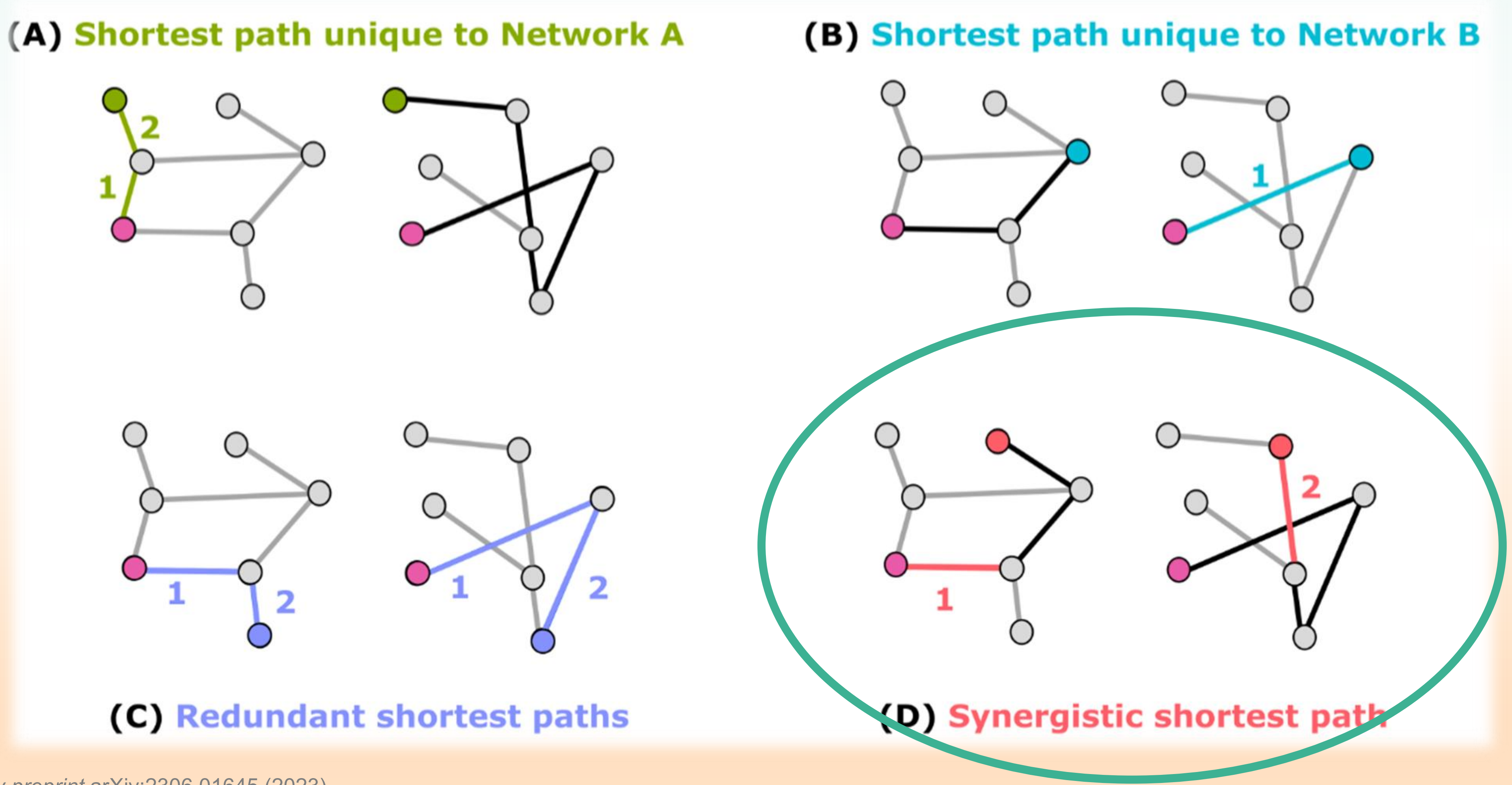
Partial Network Decomposition to analyse shortest paths across multilayer networks



Luppi, Andrea I., et al. *arXiv preprint* arXiv:2306.01645 (2023).

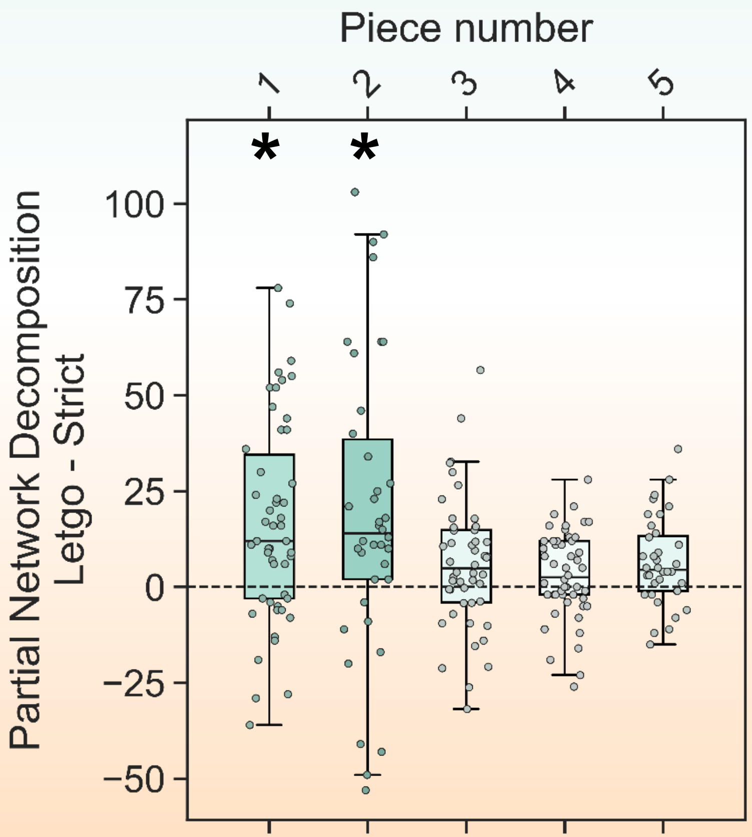
Results – Communication efficiency

Partial Network Decomposition to analyse shortest paths across multilayer networks



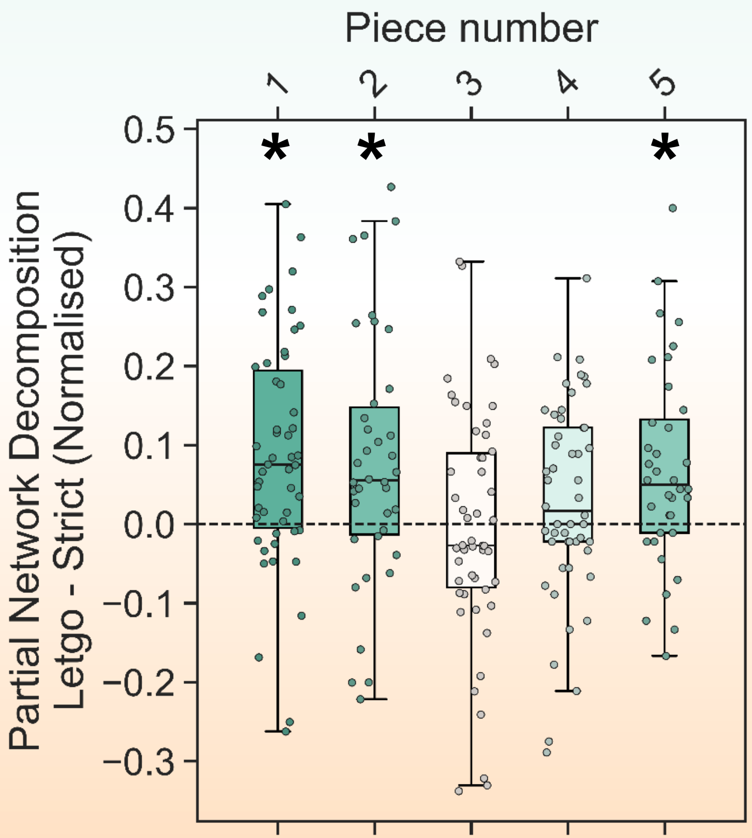
Results – Communication efficiency

Partial Network Decomposition to analyse shortest paths across multilayer networks



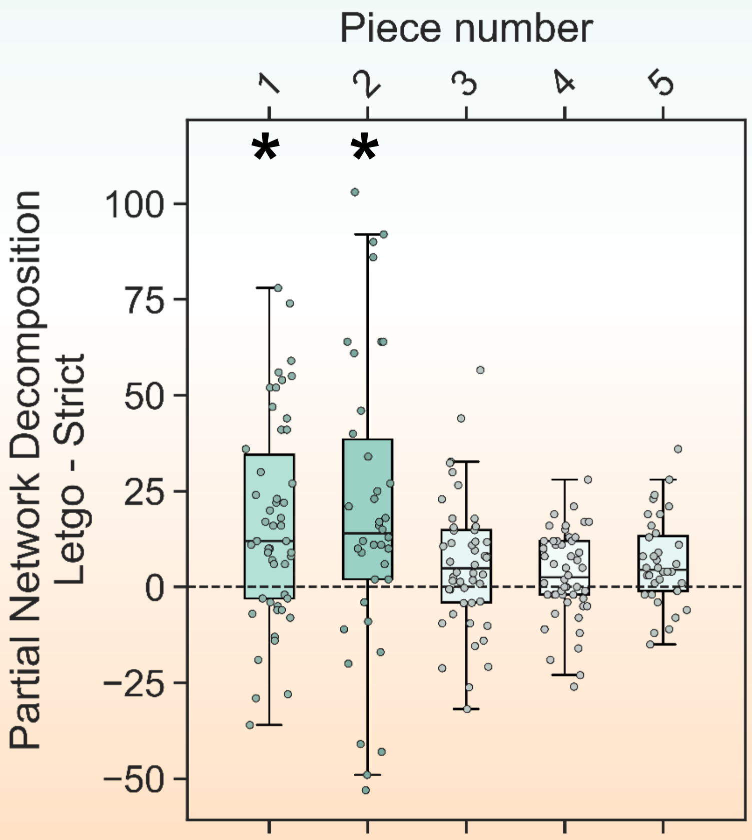
More synergy in letgo

More synergy in strict



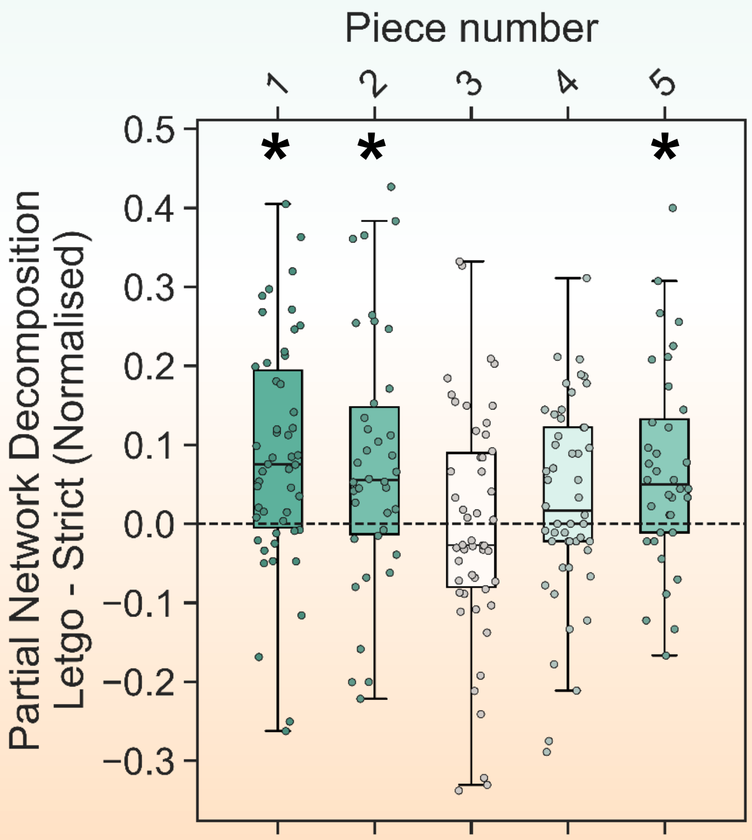
Results – Communication efficiency

Partial Network Decomposition to analyse shortest paths across multilayer networks



More synergy in letgo

More synergy in strict



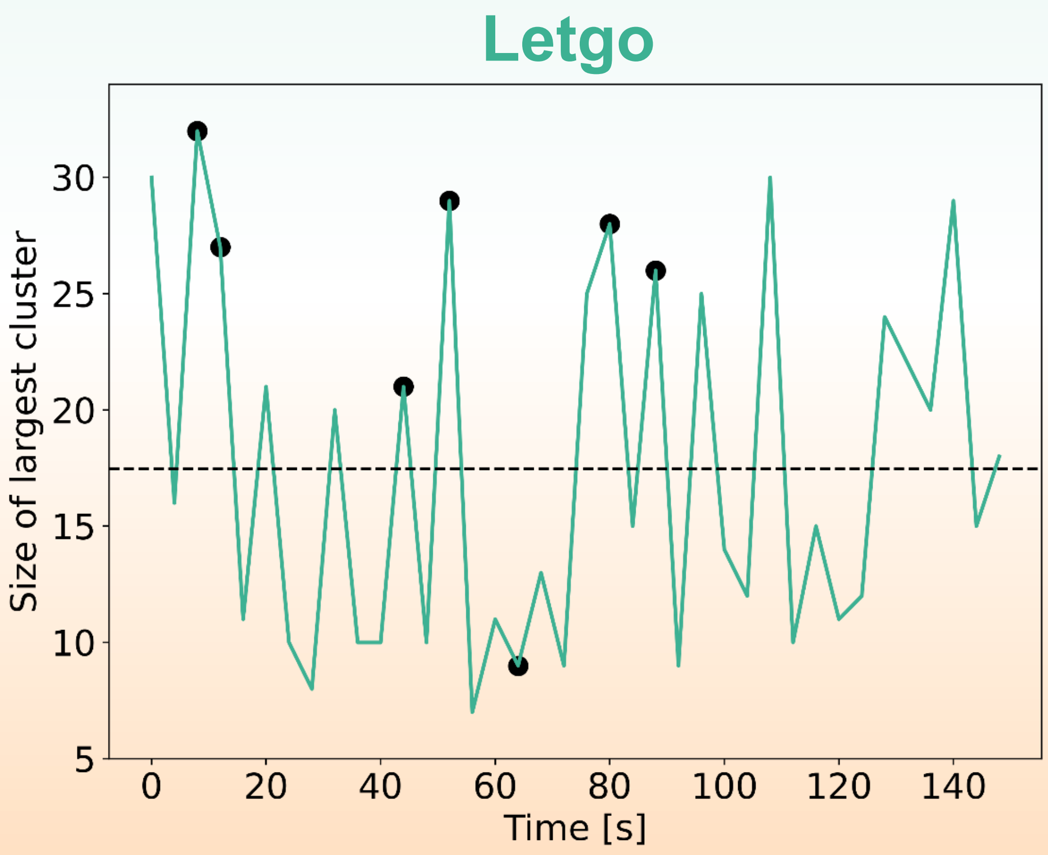
- Letgo states enhance synergistic information transmission

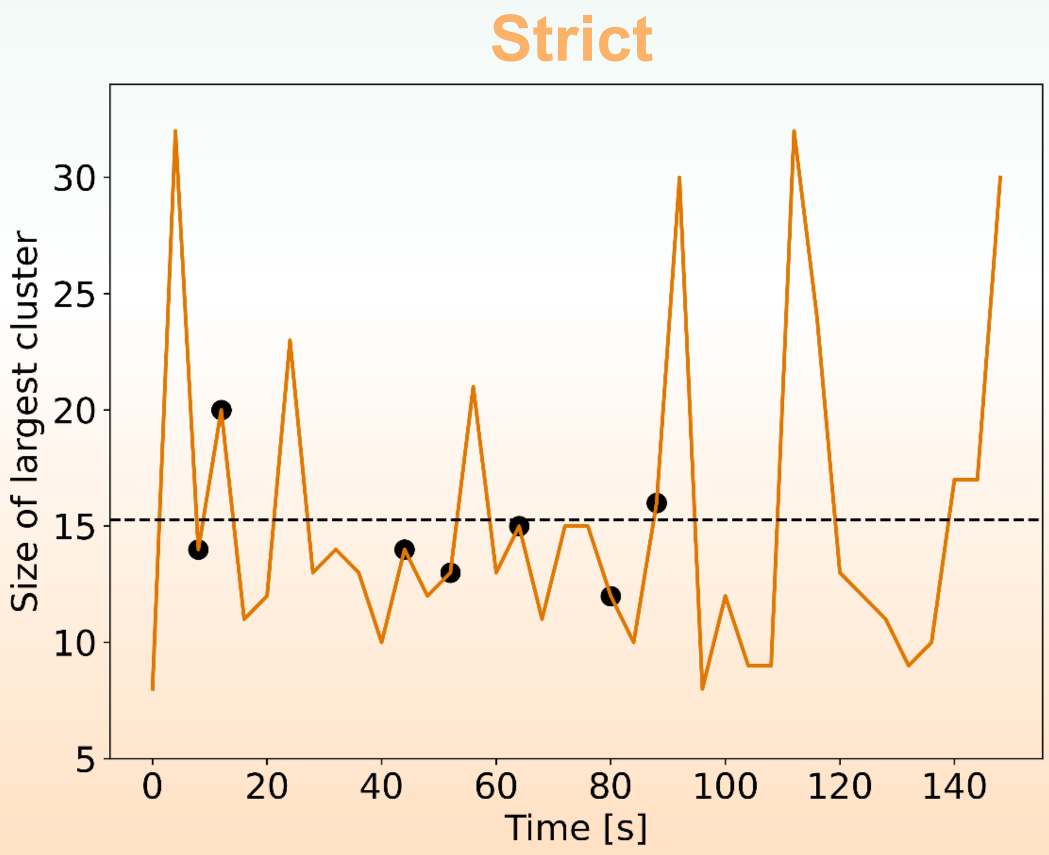
Bonus – Subjective experience

Moments of togetherness: occasions in which the musicians felt a particularly heightened shared musical experience

Bonus – Subjective experience

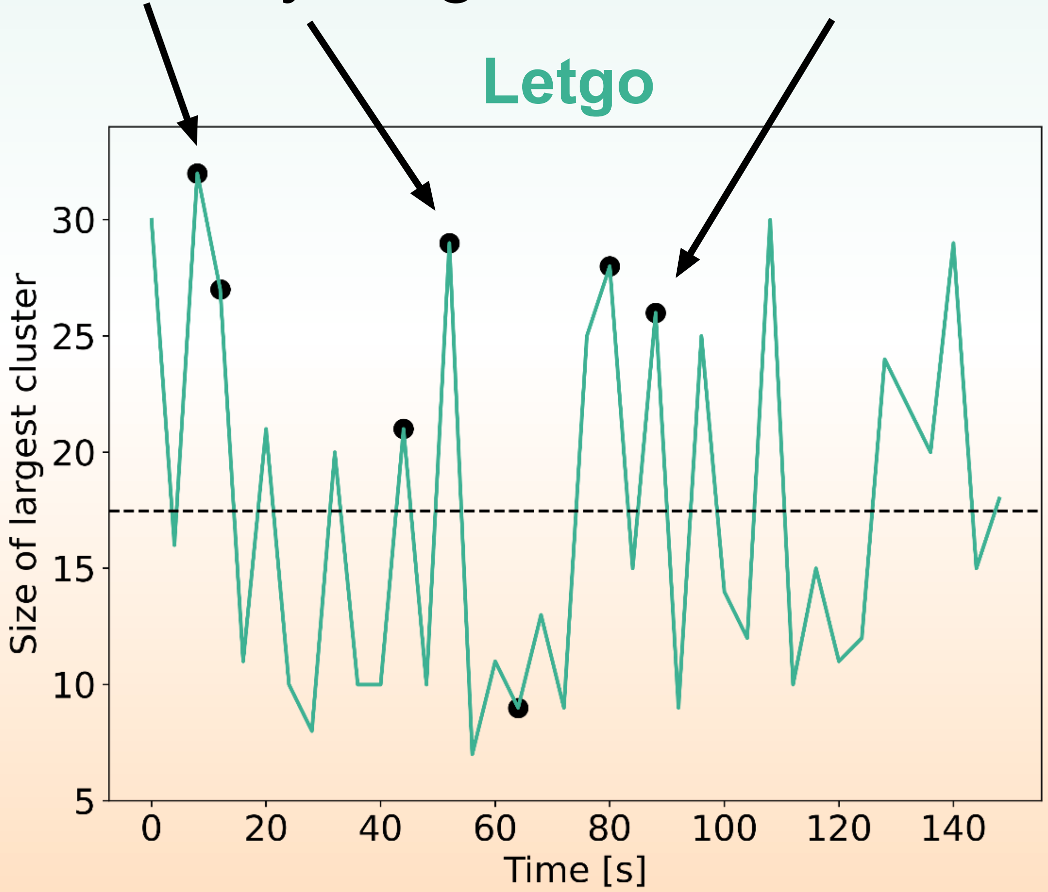
Moments of togetherness: occasions in which the musicians felt a particularly heightened shared musical experience

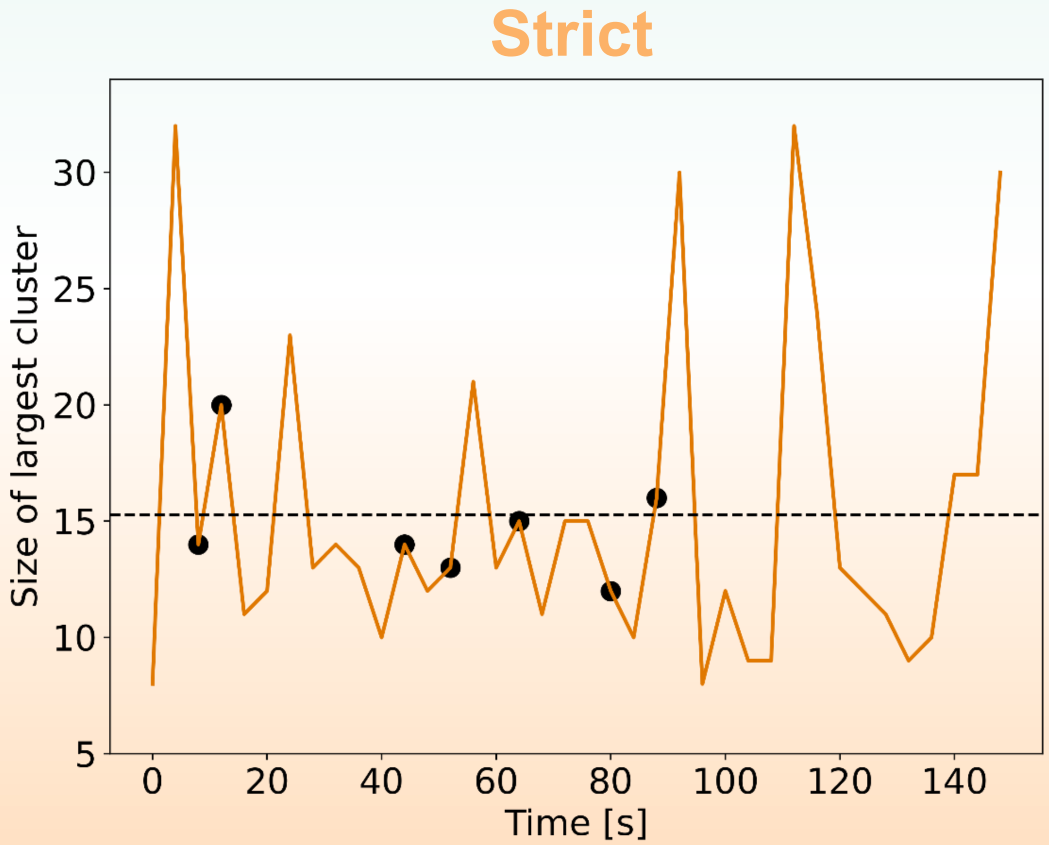




Bonus – Subjective experience

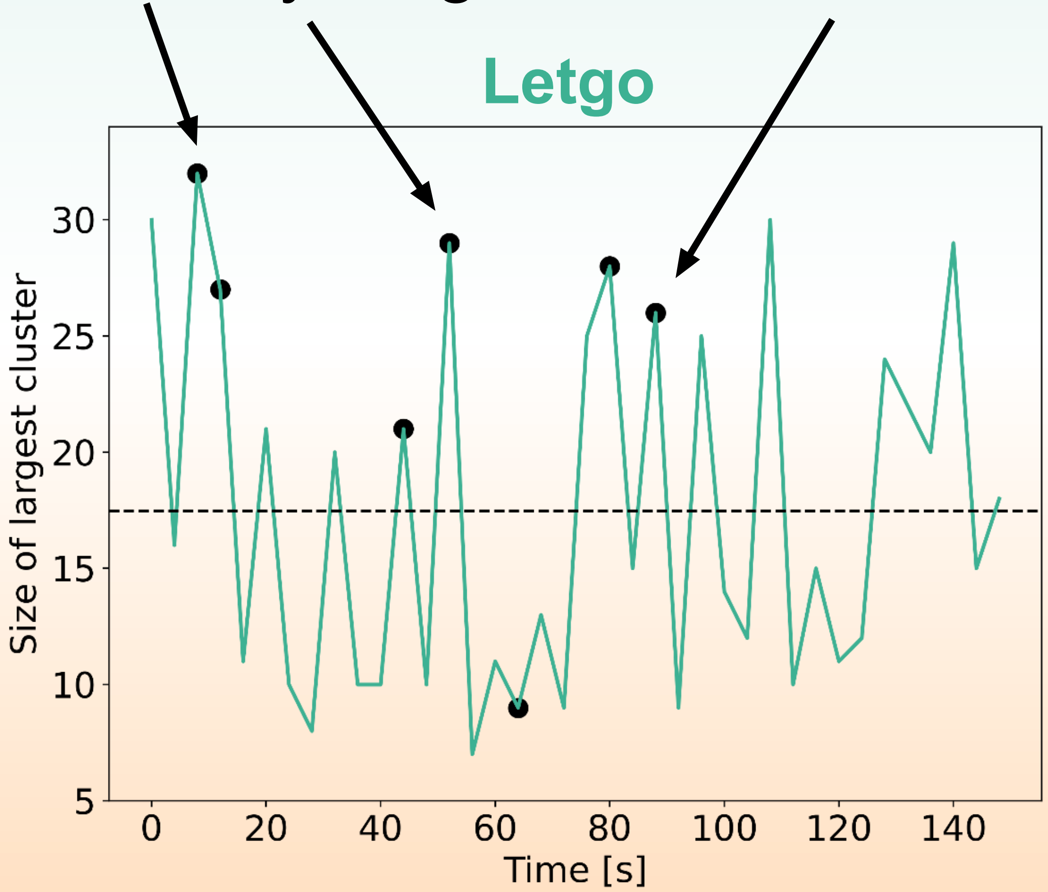
Moments of togetherness: occasions in which the musicians felt a particularly heightened shared musical experience

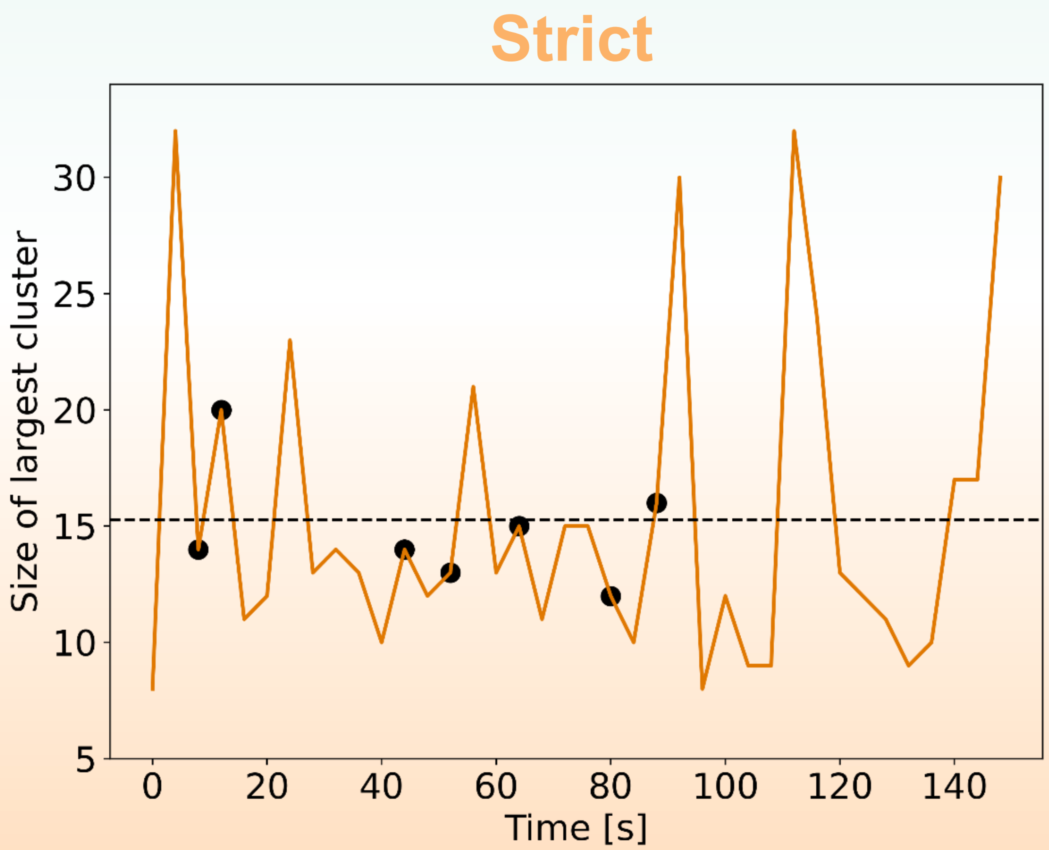




Bonus – Subjective experience

Moments of togetherness: occasions in which the musicians felt a particularly heightened shared musical experience





- Agreement between clustering structure and subjective experience

Conclusions

Takeaway messages

- Richer dynamical activity during *letgo* performances (complexity)
- Increased brain cooperation during improvisational performances (community structure, connectivity synergistic paths)
- Correspondence between community structures and subjective experience (moments of togetherness)

Acknowledgments

Madalina Sas

Hardik Rajpal

Fernando Rosas

Pedro Mediano

Acknowledgments

Madalina Sas

Hardik Rajpal

Henrik Jensen

Fernando Rosas

Pedro Mediano