



Network Science Institute
at Northeastern University

N Northeastern University
London



Introduction to HOI-BrainMod: Workshop on Brain Modeling and High-Order Interactions

Marilyn Gatica

Fellow at the Institute for Advanced Study (IAS)
Postdoctoral Research Assistant, Network Science Institute, Northeastern University London

Meet the Speakers

Marilyn Gatica



Higher-order
Whole-brain modelling
Computational neuroscience
Neuromodulation

Carlos Coronel



Aging
Dementia
Biophysical modeling of chemical neuromodulation
Computational neuroscience

Ruben Herzog



Functional brain organization
Computational neuroscience
Brain health
Non-ordinary states of consciousness

Matteo Neri



Interactions within complex systems
Mechanisms and emergent properties
Theoretical methods
Cognitive neuroscience

Programme

Workshop (07/05)	
08:30 – 09:00	Coffee
09:00 – 09:30	Workshop Overview (Marilyn)
09:30 – 10:30	Whole-brain modelling (Carlos)
10:30 – 11:00	Coffee break
11:00 – 12:30	Tutorials whole-brain models (Carlos, Marilyn)
12:30 – 13:30	Lunch
13:30 – 14:15	High-order fundaments (Matteo)
14:15 – 15:00	Tutorial HOI (Matteo)
15:00 – 15:30	Coffee break
15:30 – 16:15	High-order applications (Ruben)
16:15 – 17:00	Tutorial THOI (Ruben)

HOUSE RULES



Coffee break
and lunch
kindly
provided by IAS



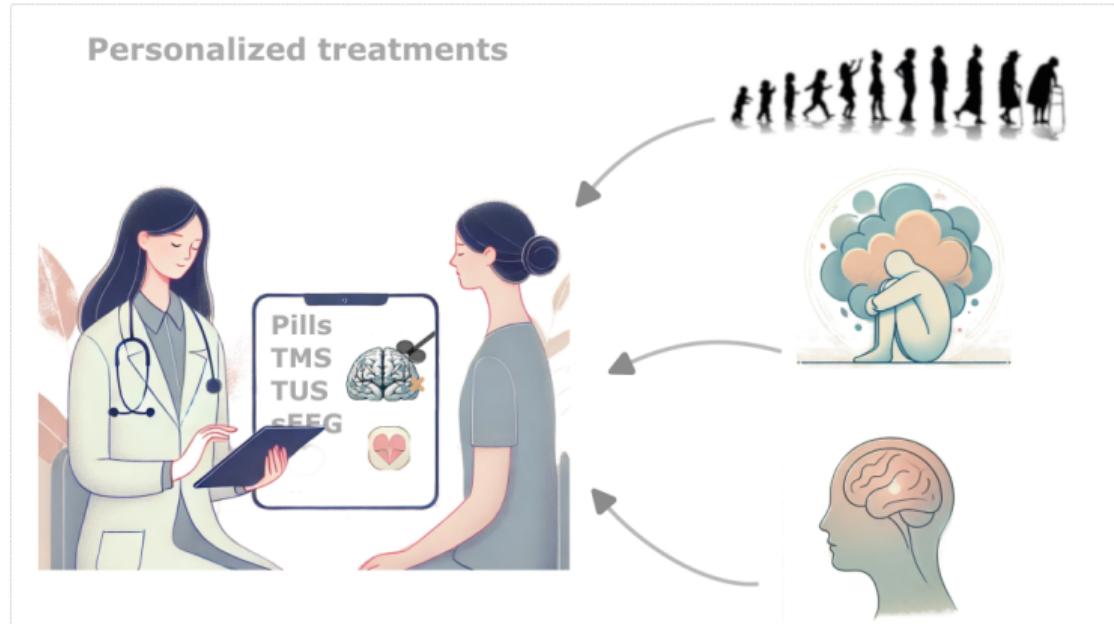
For the break/lunch
break, you can go and
sit outside by the canal,
but please return
plates/cutlery



Internet: Eduroam or ask
Merel for a daily internet code

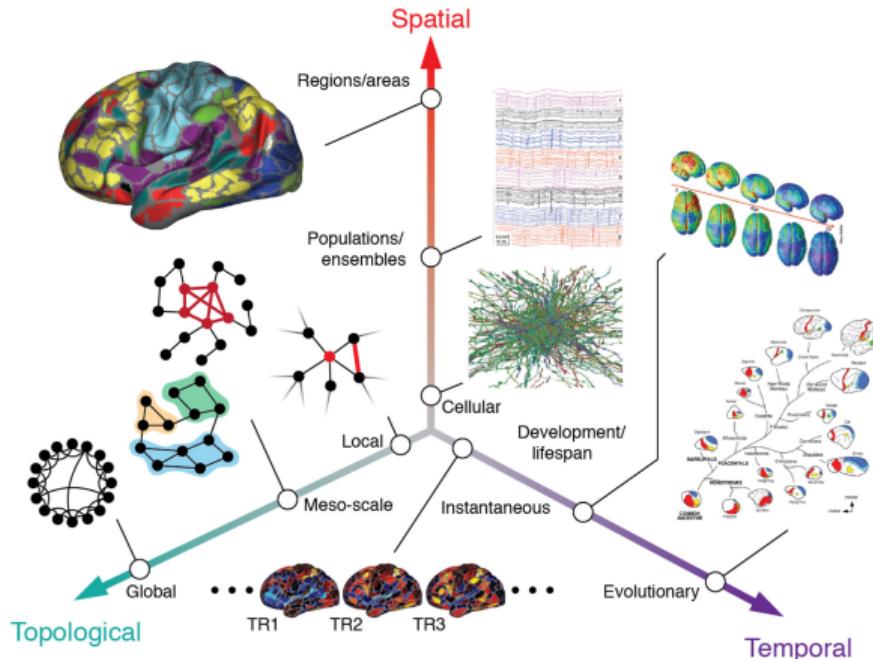


Have fun!



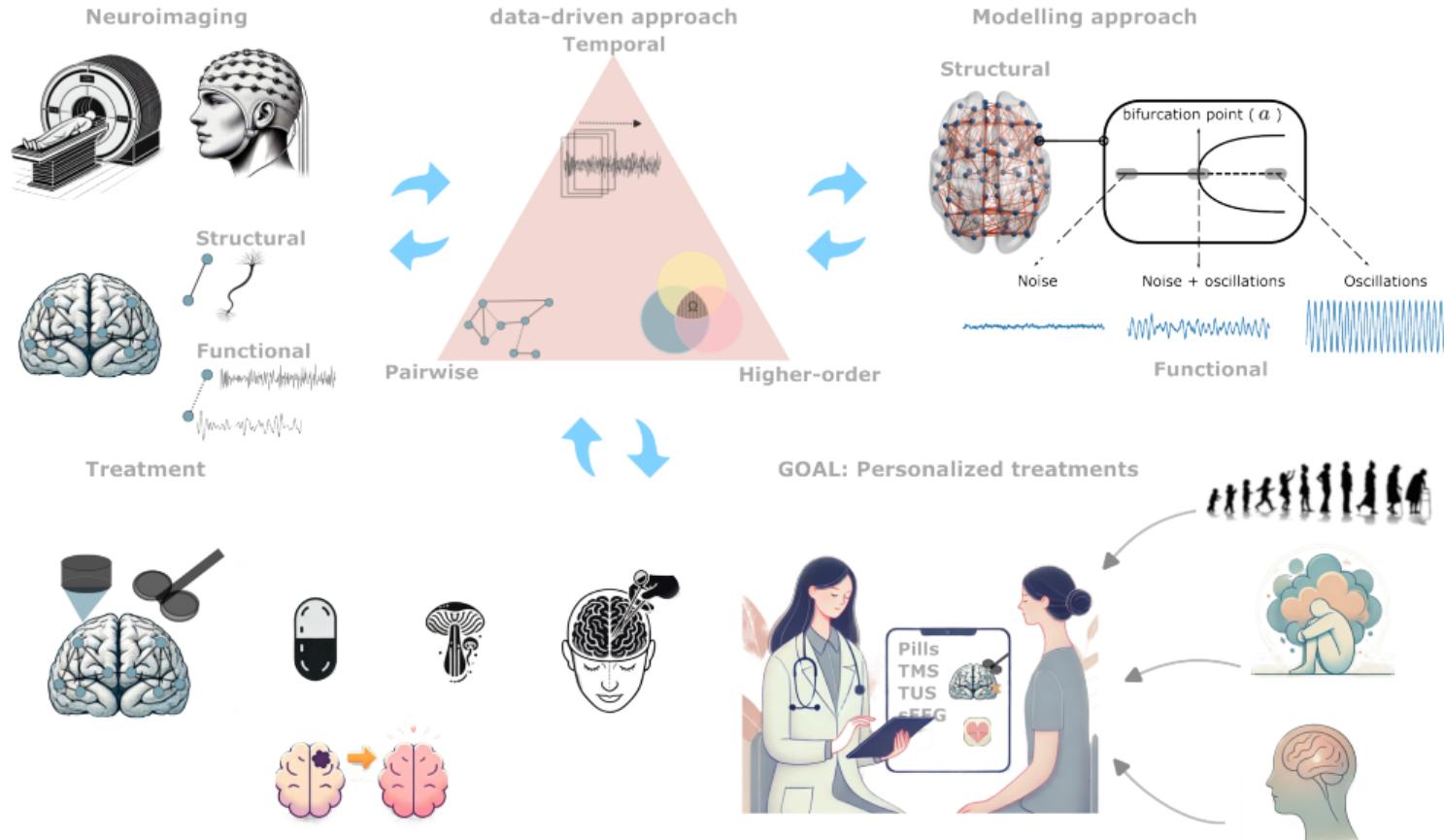
Challenges

How do we move forward toward our goal, given the complexity across multiple scales?

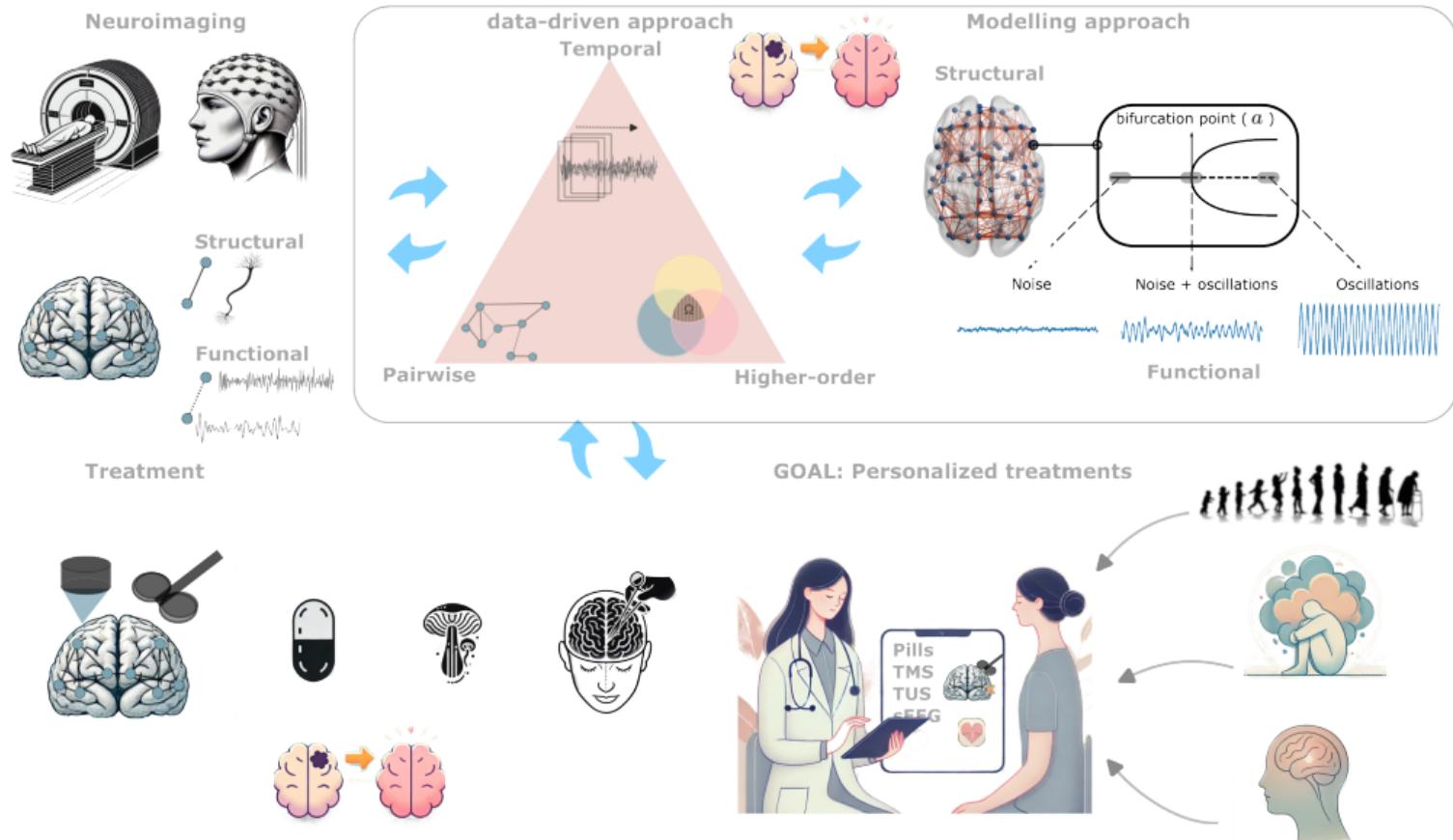


Betzel and Bassett, 2017, Neuroimage

Motivation



Motivation



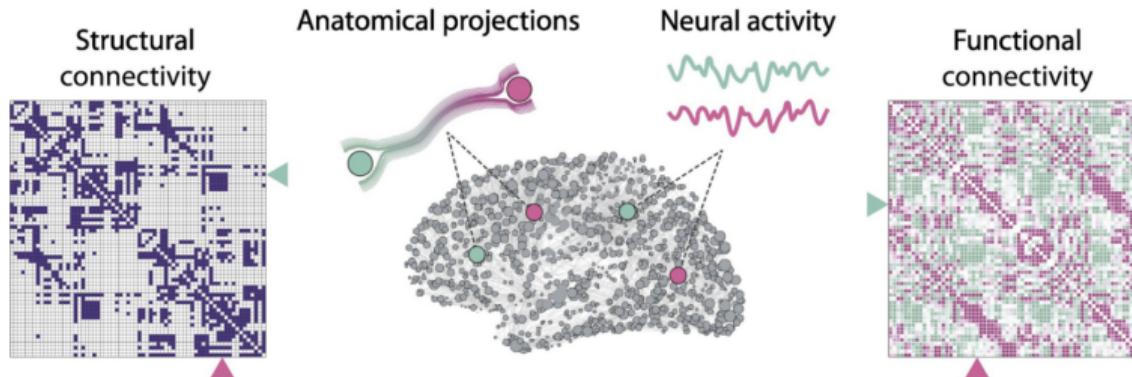
HOI-BrainMod



Workshop on Brain Modeling and High-Order Interactions

- Our main goal is to advance into **personalized treatments**.
- **Mechanistic models** are essential (morning).
- **New methodologies** and biomarkers are needed (afternoon).

Functional and structural connectivity



Suarez, et al 2020, Trends in Cognitive sciences

Higher-order interactions

order 3



order 4

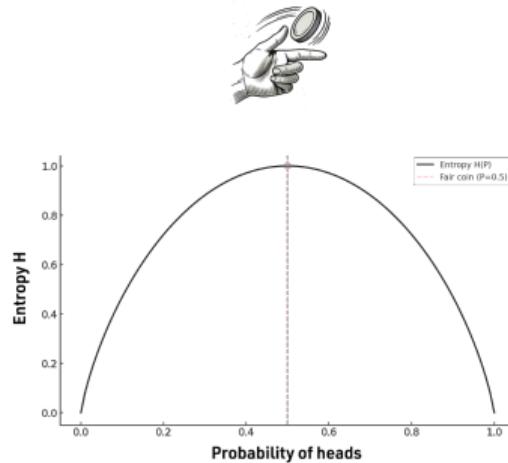


order 5



...

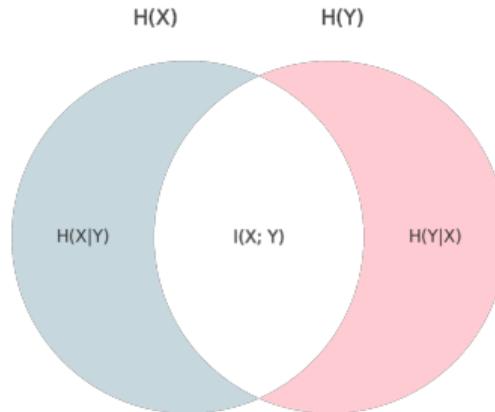
Entropy ($n = 1$)



$$H(X) = - \sum_{x \in \mathcal{X}} P(x) \log_2 P(x)$$

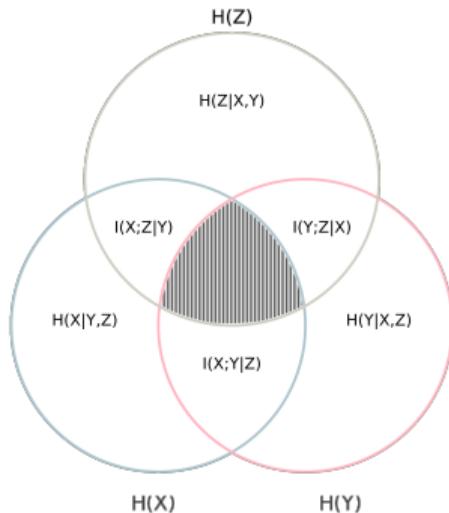
$$h(X) = - \int_X f(x) \log_2 f(x) dx$$

Mutual Information ($n = 2$)



$$\begin{aligned} I(X; Y) &\equiv H(X) - H(X | Y) \\ &\equiv H(Y) - H(Y | X) \\ &\equiv H(X) + H(Y) - H(X, Y) \\ &\equiv H(X, Y) - H(X | Y) - H(Y | X) \end{aligned}$$

Interaction Information ($n=3$)



$$I(X; Y; Z) = I(X; Y) - I(X; Y | Z)$$

$I(X; Y; Z) > 0$ Redundancy

$I(X; Y; Z) < 0$ Synergy

High-order interactions ($n \geq 3$)

order 3



order 4



order 5



⋮ ⋮ ⋮

0-Information ($n \geq 3$)

$$\Omega(X^n) := (n - 2)H(X^n) + \sum_{j=1}^n [H(X_j) - H(X_{-j}^n)]$$

$\Omega(X^n) > 0$ redundancy-dominated

$\Omega(X^n) < 0$ synergy-dominated

Rosas, Mediano, et. al, 2019, Phys Rev X

Note:

Redundancy and synergy can also be computed between pairs of regions.

Note:

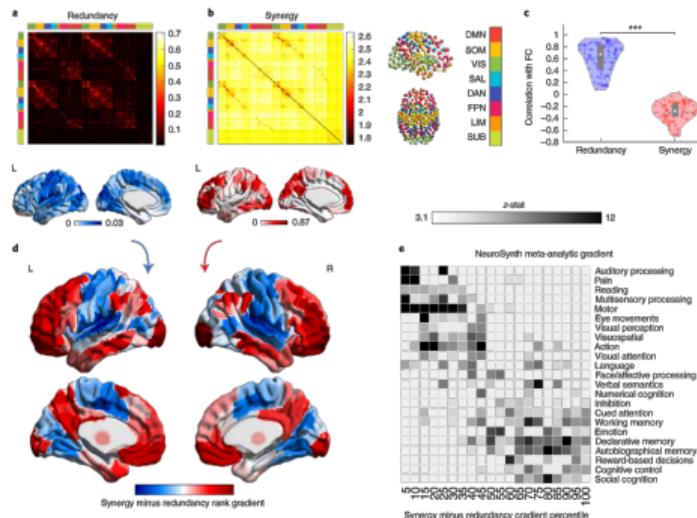
Redundancy and synergy can also be computed between pairs of regions.

Article | Published: 26 May 2022

A synergistic core for human brain evolution and cognition

Andrea I. Luppì , Pedro A. M. Mediano, Fernando E. Rosas, Negin Holland, Tim D. Fryer, John T. O'Brien, James B. Rowe, David K. Menon, Daniel Bor & Emmanuel A. Stamatakis

Nature Neuroscience 25, 771–782 (2022) | Cite this article

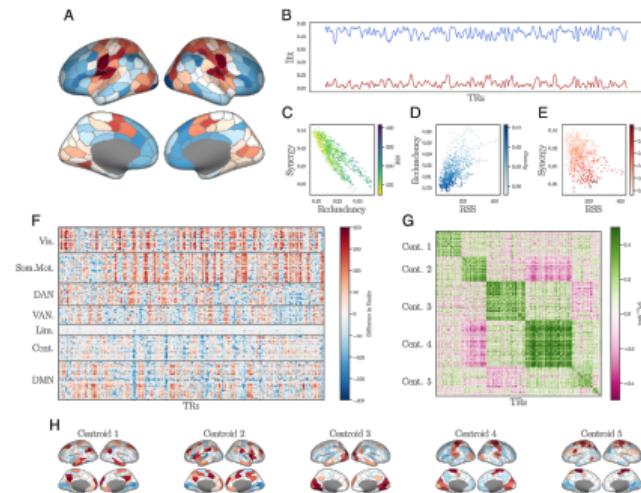


Partial entropy decomposition reveals higher-order information structures in human brain activity

Thomas F. Varley , Maria Pope , Maria Grazia Puccio , and Olaf Sporns Authors Info & Affiliations

Edited by Marcus Raichle, Washington University In St Louis School of Medicine, St. Louis, MO; received January 16, 2023; accepted June 6, 2023

july 19, 2023 | 120 (30) e2300888120 | <https://doi.org/10.1073/pnas.2300888120>





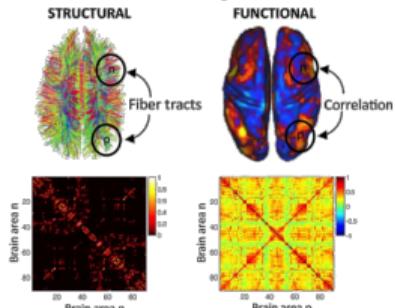


Redundancy

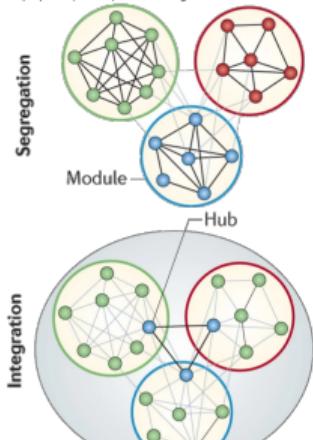


Synergy

Pairwise analysis



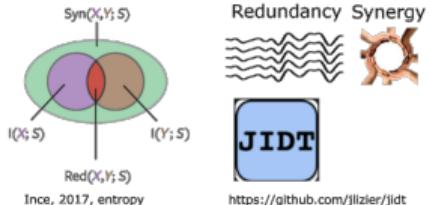
Cabral, et al, 2017, NeuroImage
 Deco, et al, 2015, Nature Reviews Neuroscience
 Rubinov, Sporns, 2010, NeuroImage



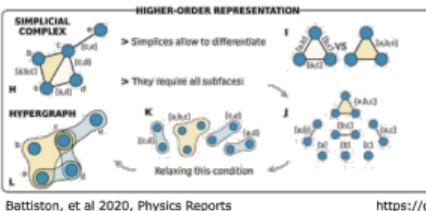
Brain Connectivity Toolbox
brain-connectivity-toolbox.net

High-order analysis

Multivariate Information theory



Topology

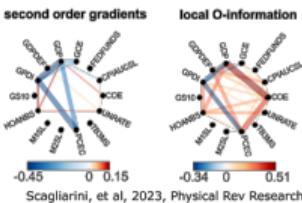


XGI

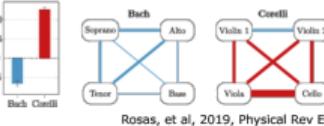
<https://github.com/xgi-org/xgi>

High-order applications

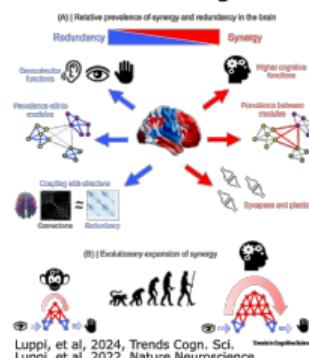
Macroeconomic data



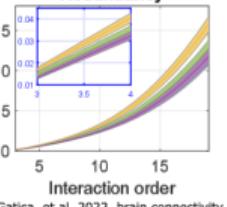
Music



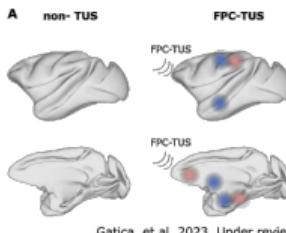
Evolution and cognition



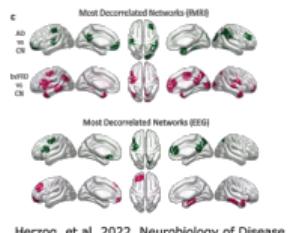
Healthy aging



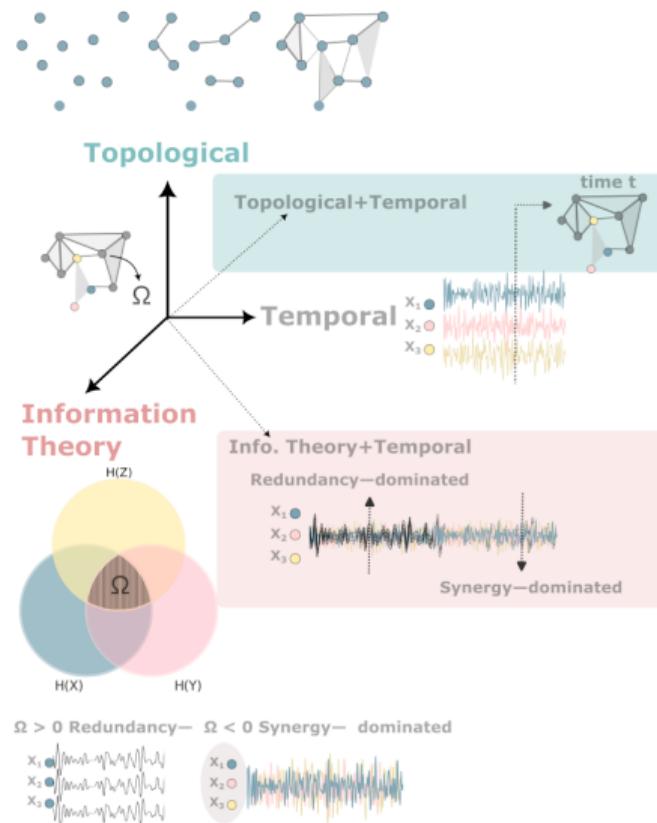
Transcranial ultrasound Stimulation



Neurodegeneration



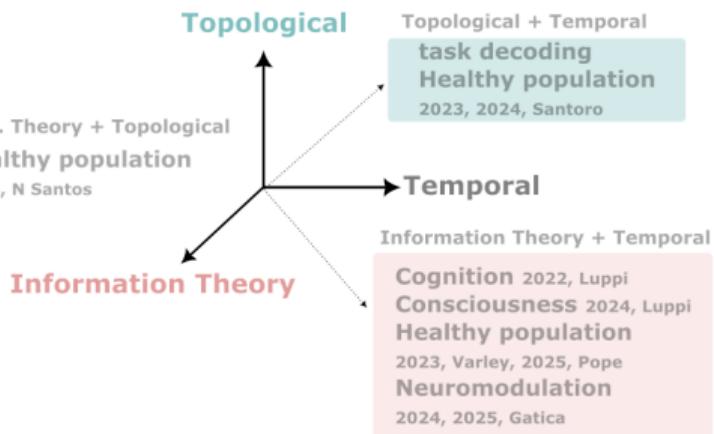
A. Higher-order interdependencies



B. Higher-order in the human brain

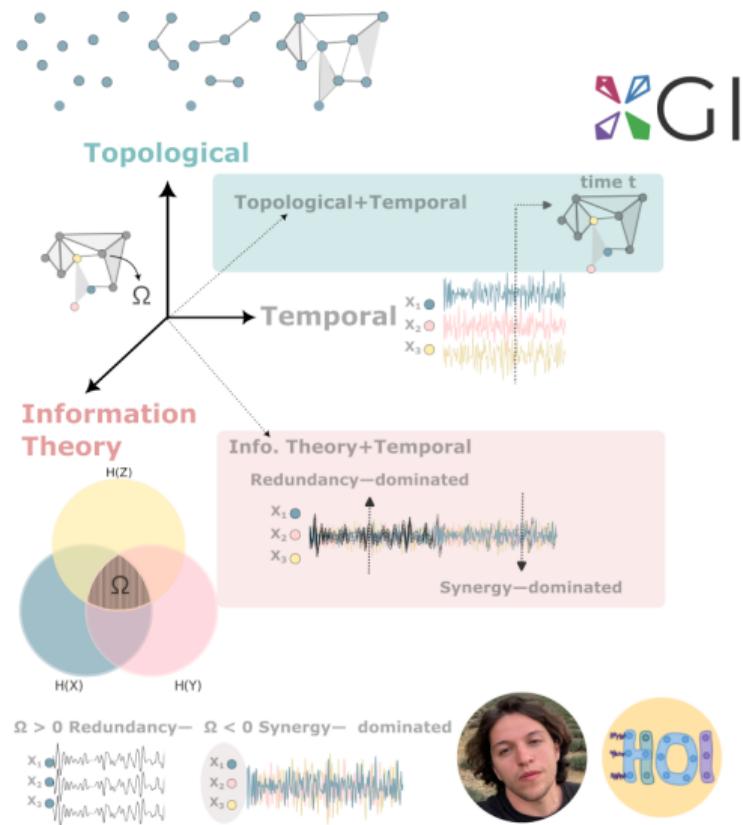


Psychodelics 2013, Petri
Traumatic brain injury 2015, Nielson
Schizophrenia 2020, Stoltz



Healthy aging 2018, Pontes, 2020, 2021, Gatica
Alzheimer and Frontotemporal Dementia 2023, Herzog
Consciousness (ketamine 2022, Herzog, meditation 2024, Kumar)
Schizophrenia 2023, Li
Infants 2024, Varley

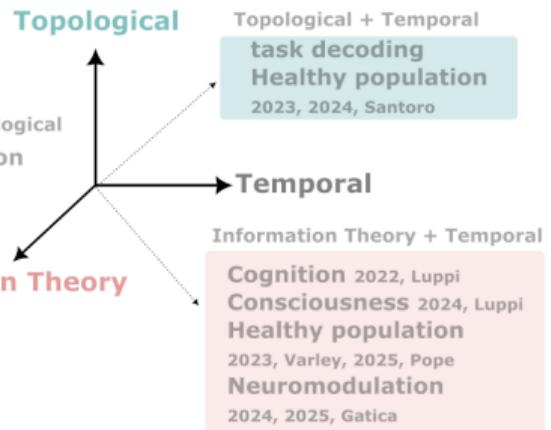
A. Higher-order interdependencies



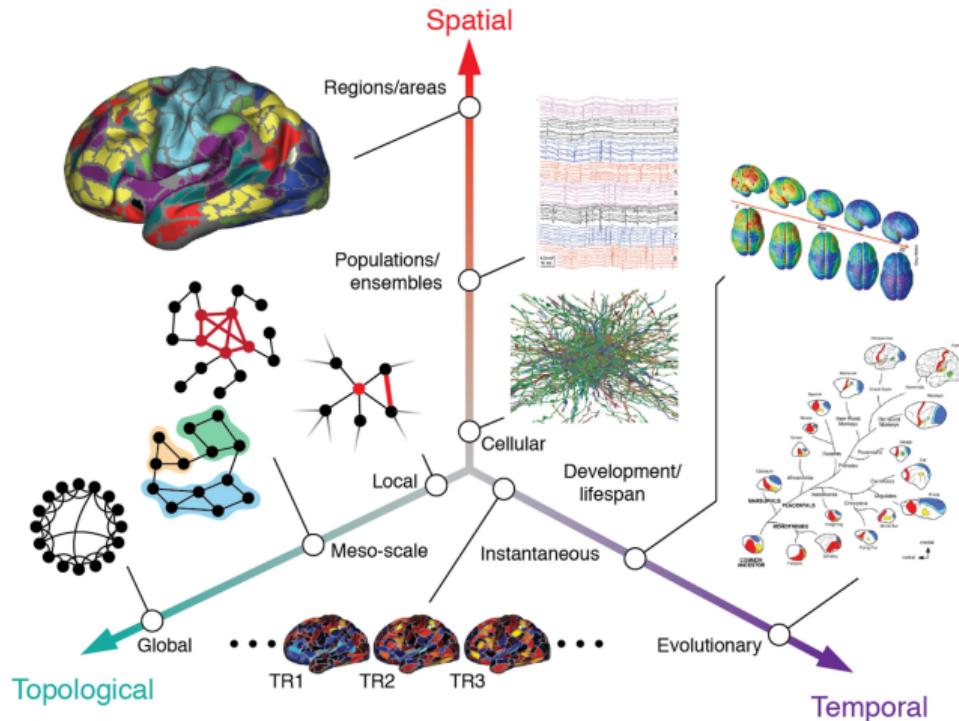
B. Higher-order in the human brain



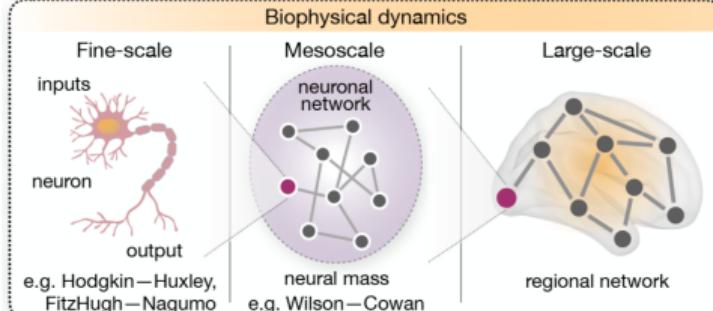
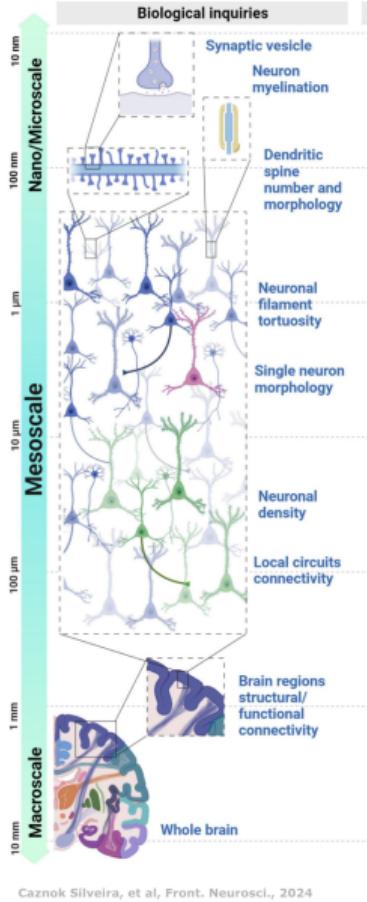
Psychodelics 2013, Petri
Traumatic brain injury 2015, Nielson
Schizophrenia 2020, Stoltz



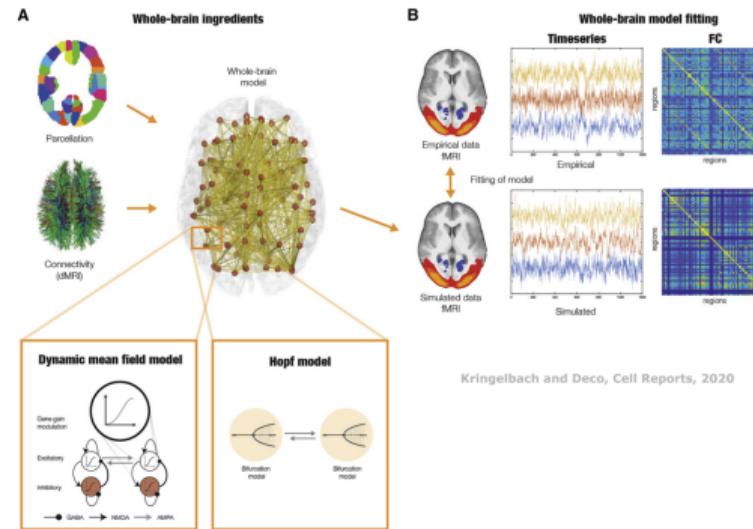
Back to the challenges



Betzel and Bassett, 2017, Neuroimage



Lynn and Bassett, *Nature Reviews Physics*, 2019



Current Biology
Article



THEVIRTUALBRAIN.

Whole-Brain Multimodal Neuroimaging Model Using Serotonin Receptor Maps Explains Non-linear Functional Effects of LSD

Gustavo Deco,^{1,2,3,4,*} Josephine Cruzat,¹ Joana Cabral,^{5,6,7} Gitte M. Knudsen,^{8,9} Robin L. Carhart-Harris,¹⁰ Peter C. Whybrow,¹¹ Nikos K. Logothetis,^{12,13} and Morten L. Kringelbach^{5,6,7,14,15,*}

> *Alzheimers Dement.* 2024 May;20(5):3228-3250. doi: 10.1002/ALZ.13788. Epub 2024 Mar 19.



Viscous dynamics associated with hypoexcitation and structural disintegration in neurodegeneration via generative whole-brain modeling

Carlos Coronel-Oliveros^{1,2,3,4}, Raúl González Gómez^{1,5}, Kamalini Ranasinghe⁶, Agustín Sainz-Ballesteros¹, Agustina Legaz⁷, Sol Fittipaldi^{1,2,3,7,9}, Josephine Cruzat¹, Rubén Herzog¹, Gorsev Yener^{8,9}, Mario Parra¹⁰, David Aguillon¹¹, Francisco Lopera¹¹, Hernando Santamaría-García^{12,13}, Sebastián Moguilner^{1,7}, Vicente Medel^{1,14,15}, Patricio Orio^{4,16}, Robert Whelan^{2,3}, Enzo Tagliazucchi^{1,17}, Pavel Prado^{1,18}, Agustín Ibañez^{1,2,3,7,19}



RESEARCH ARTICLE

Cholinergic neuromodulation of inhibitory interneurons facilitates functional integration in whole-brain models



Carlos Coronel-Oliveros^{1,2}, Rodrigo Cofré³, Patricio Orio^{1,4,*}

The Virtual Brain: a simulator of primate brain network dynamics

Paula Sanz Leon^{1,*} Stuart A. Knock² M. Marmaduke Woodman¹ Lia Domide¹
Jochen Mersmann⁴ Anthony R. McIntosh⁵ Viktor Jirsa^{1,*}



Metastable oscillatory modes emerge from synchronization in the brain spacetime connectome

Joana Cabral¹, Francesca Castaldo, Jakub Vohryzek, Vladimir Litvak, Christian Bick, Renaud Lambiotte, Karl Friston, Morten L. Kringelbach & Gustavo Deco

Communications Physics 5, Article number: 184 (2022) | [Cite this article](#)



Perturbations in dynamical models of whole-brain activity dissociate between the level and stability of consciousness

Yonatan Sanz Perl^{1,2}, Carla Pallavicini^{1,3}, Ignacio Pérez Ipiña, Athena Demertzis, Vincent Bonhomme, Charlotte Martial, Rajanikant Panda, Jitka Annen, Agustín Ibañez, Morten Kringelbach, Gustavo Deco, Helmut Laufs, Jacobo Sitt, Steven Laureys^{1,2}, Enzo Tagliazucchi^{1,3,4}

Published: July 27, 2021 • <https://doi.org/10.1371/journal.pcbi.1009139>



> *Netw Neurosci.* 2024 Dec 10(8):1590-1612. doi: 10.1162/netn_a_00410. eCollection 2024.

Neural mass modeling for the masses: Democratizing access to whole-brain biophysical modeling with FastDMF

Rubén Herzog¹, Pedro A M Mediano^{2,3}, Fernando E Rosas^{4,5,6,7}, Andrea I Luppi^{7,8,9,10}, Yonatan Sanz-Perl^{11,12,13,14}, Enzo Tagliazucchi^{11,15}, Morten L Kringelbach^{7,16,17}, Rodrigo Cofré¹⁸, Gustavo Deco^{14,19}

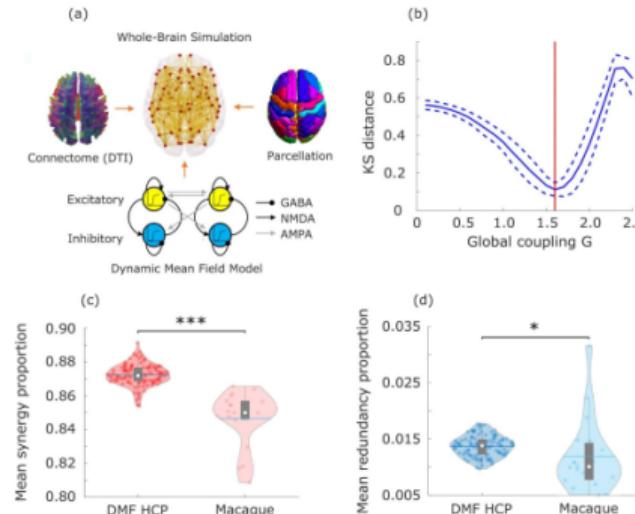


Can whole-brain models reproduce both redundancy and synergy?

A synergistic core for human brain evolution and cognition

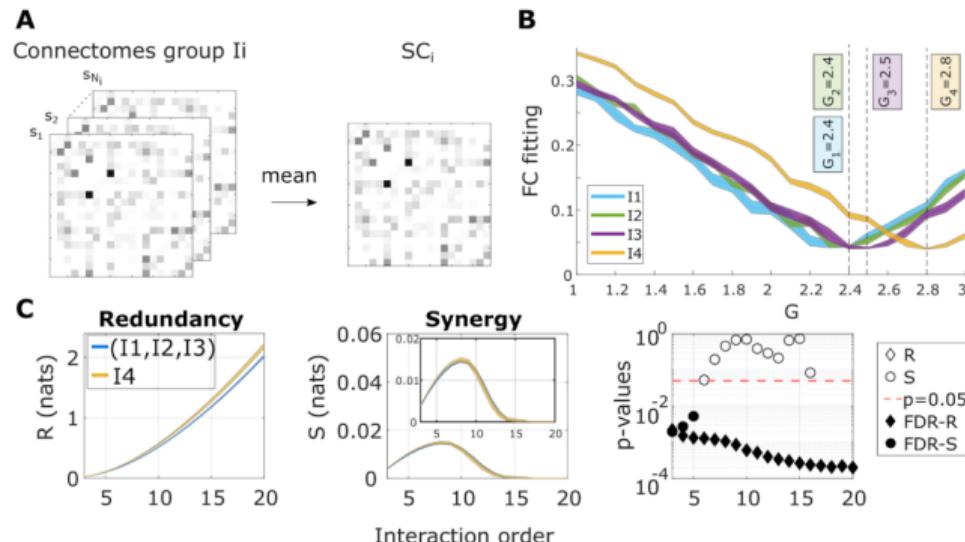
[Andrea I. Luppi](#) , [Pedro A. M. Mediano](#), [Fernando E. Rosas](#), [Negin Holland](#), [Tim D. Fryer](#), [John T. O'Brien](#),
[James B. Rowe](#), [David K. Menon](#), [Daniel Bor](#) & [Emmanuel A. Stamatakis](#)

[Nature Neuroscience](#) **25**, 771–782 (2022) | [Cite this article](#)



High-order functional redundancy in ageing explained via alterations in the connectome in a whole-brain model

Marilyn Gatica, Fernando E. Rosas, Pedro A. M. Mediano, Ibai Diez, Stephan P. Swinnen, Patricio Orio, Rodrigo Cofré  , Jesus M. Cortes  



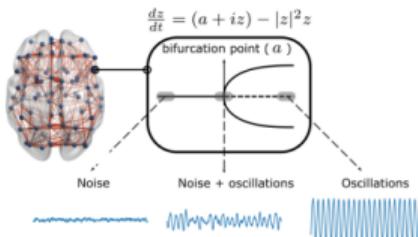
Understanding the high-order network plasticity mechanisms of ultrasound neuromodulation

Marilyn Gatica, Cyril Atkinson-Clement, Carlos Coronel-Oliveros, Mohammad Alkhawashki, Pedro A. M. Mediano, Enzo Tagliazucchi, Fernando E. Rosas, Marcus Kaiser, Giovanni Petri

doi: <https://doi.org/10.1101/2025.01.11.632528>

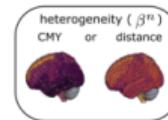
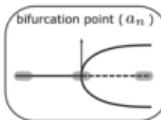
A Whole-brain model

Stuart Landau oscillators (local dynamics)



B Regional heterogeneity and stimulation

bifurcation point (a_n)

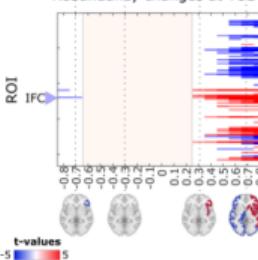


Control: $a_n = \text{bias} + \text{scale } \beta^n$

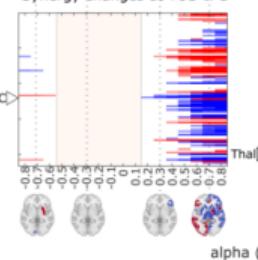
TUS: $a_n = \text{bias} + \text{scale } (\beta^n + \alpha \beta_n^s)$

D Simulated HOI effects after TUS (distance model)

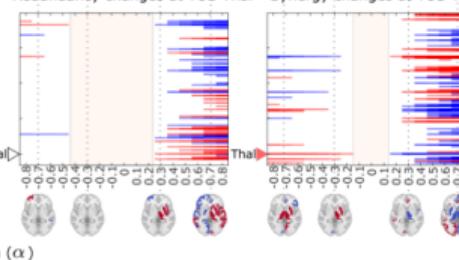
Redundancy changes at TUS-IFC



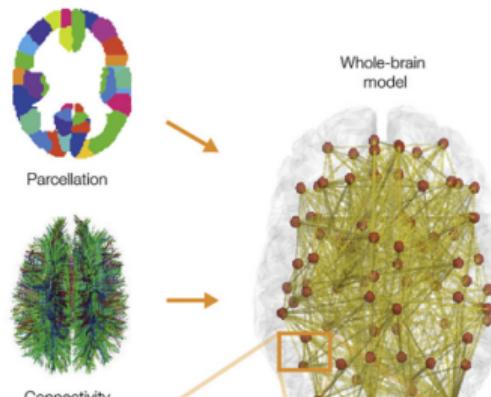
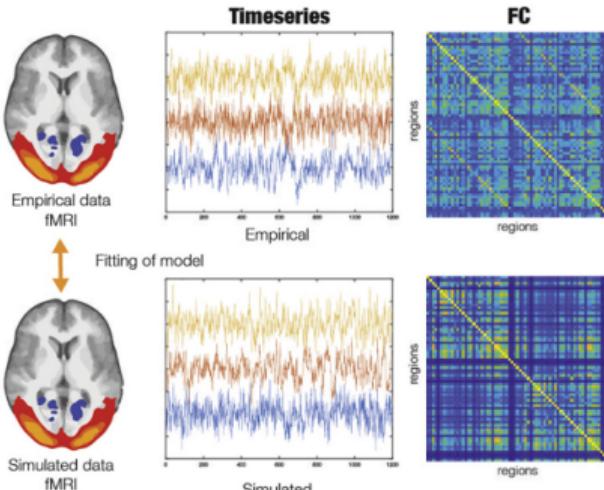
Synergy changes at TUS-IFC



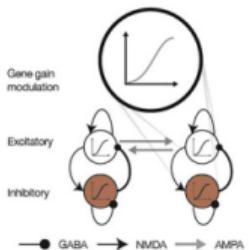
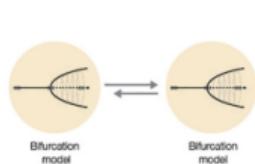
Redundancy changes at TUS-Thal



Synergy changes at TUS-Thal

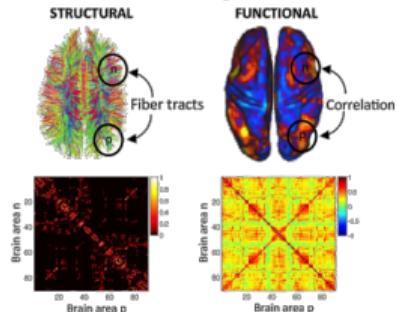
A**Whole-brain ingredients****B****Whole-brain model fitting**

Kringelbach and Deco, Cell Reports, 2020

Dynamic mean field model**Hopf model**

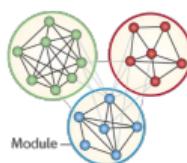
Towards an integrated framework

Pairwise analysis

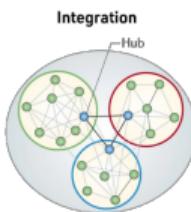


Cabral, et al, 2017, NeuroImage
Deco, et al, 2015, Nature Reviews Neuroscience
Rubinov, Sporns, 2010, NeuroImage

Segregation

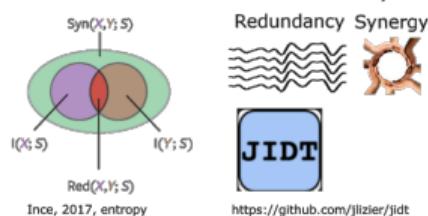


Integration



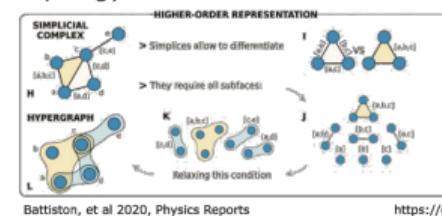
Brain Connectivity Toolbox
brain-connectivity-toolbox.net

Multivariate Information theory

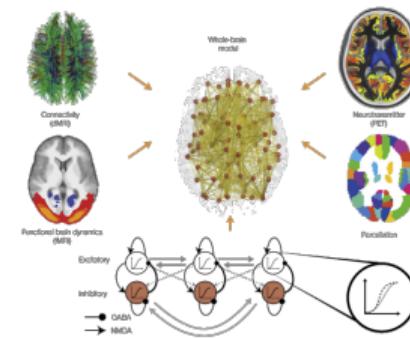


High-order analysis

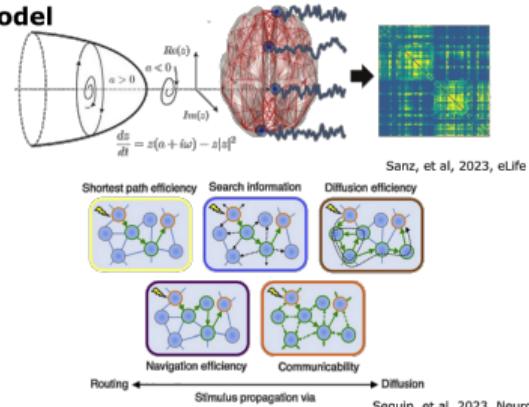
Topology



Whole-Brain Model



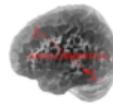
Deco, et al, 2018, Current Biology



Submissions open!

CNS*2025 Workshop on Methods of Information Theory in Computational Neuroscience

July 5-9, 2025
Florence, Italy
CNS*2025



Speakers

- Giovanni Petri, Northeastern University London, UK
- Marilyn Gatica, Northeastern University London, UK
- Luca Faes, University of Palermo, Italy
- Maria Pope, Indiana University, USA
- Xenia Kobeleva, Ruhr University, Germany
- Daniele Marinazzo, Ghent University, Belgium
- Marius Pille, Charité – Berlin University of Medicine, Germany

Organising committee

- Marilyn Gatica
- Joseph T. Lizier
- Abdullah Makkeh,
- Pedro Mediano,



Keynote Speakers

CoBrain 2025
Complexity in the Brain
Satellite @ CCS 2025
September 3rd 2025 • Siena, Italy



Petra Vertes
University of Cambridge, UK
Talk Title



Michele Nardin
HIMI Janelia Research Campus, USA



Giulio Pergola
University of Bari Aldo Moro, Italy



Jaroslav Hlinka
Czech Academy of Sciences, Czech Republic



Organizing Committee



Marilyn Gatica
Northeastern University London



Nicola Pedreschi
University of Bari



Samy Castro
UKE



Jesseba Fernando
Northeastern University Boston



HOI-BrainMod

Workshop on Brain Modeling and High-Order Interactions

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