



Network Science Institute
at Northeastern University

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Nottingham
UK | CHINA | MALAYSIA

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

Marilyn Gatica

Postdoctoral Research Assistant in the 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

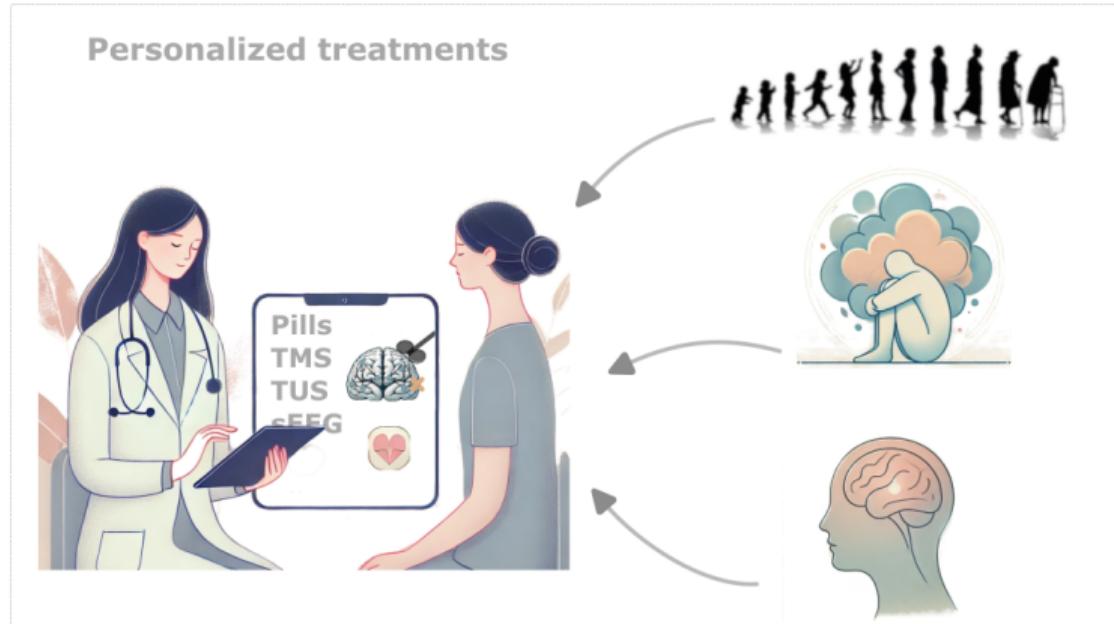
Matteo Neri



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

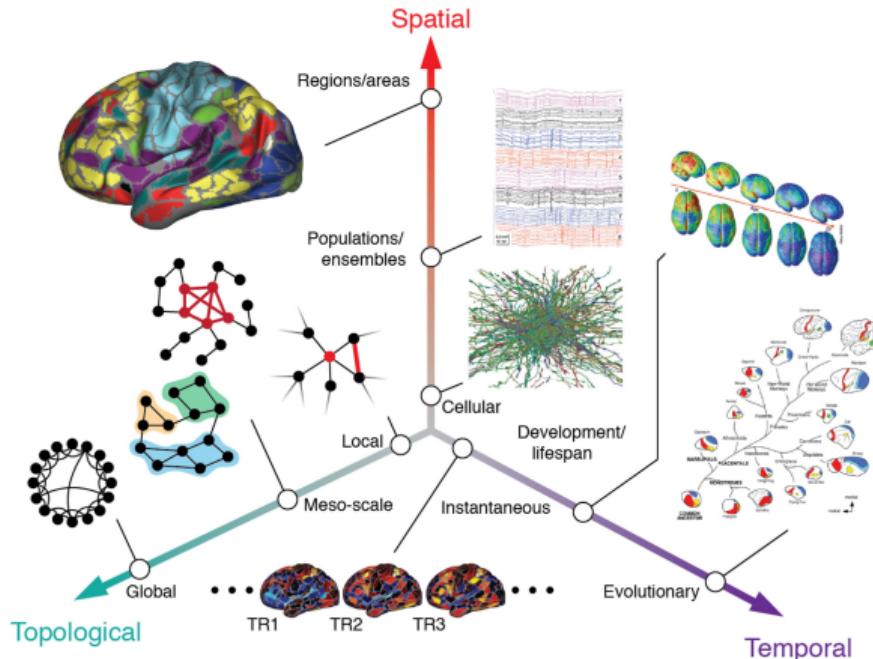
Programme

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)



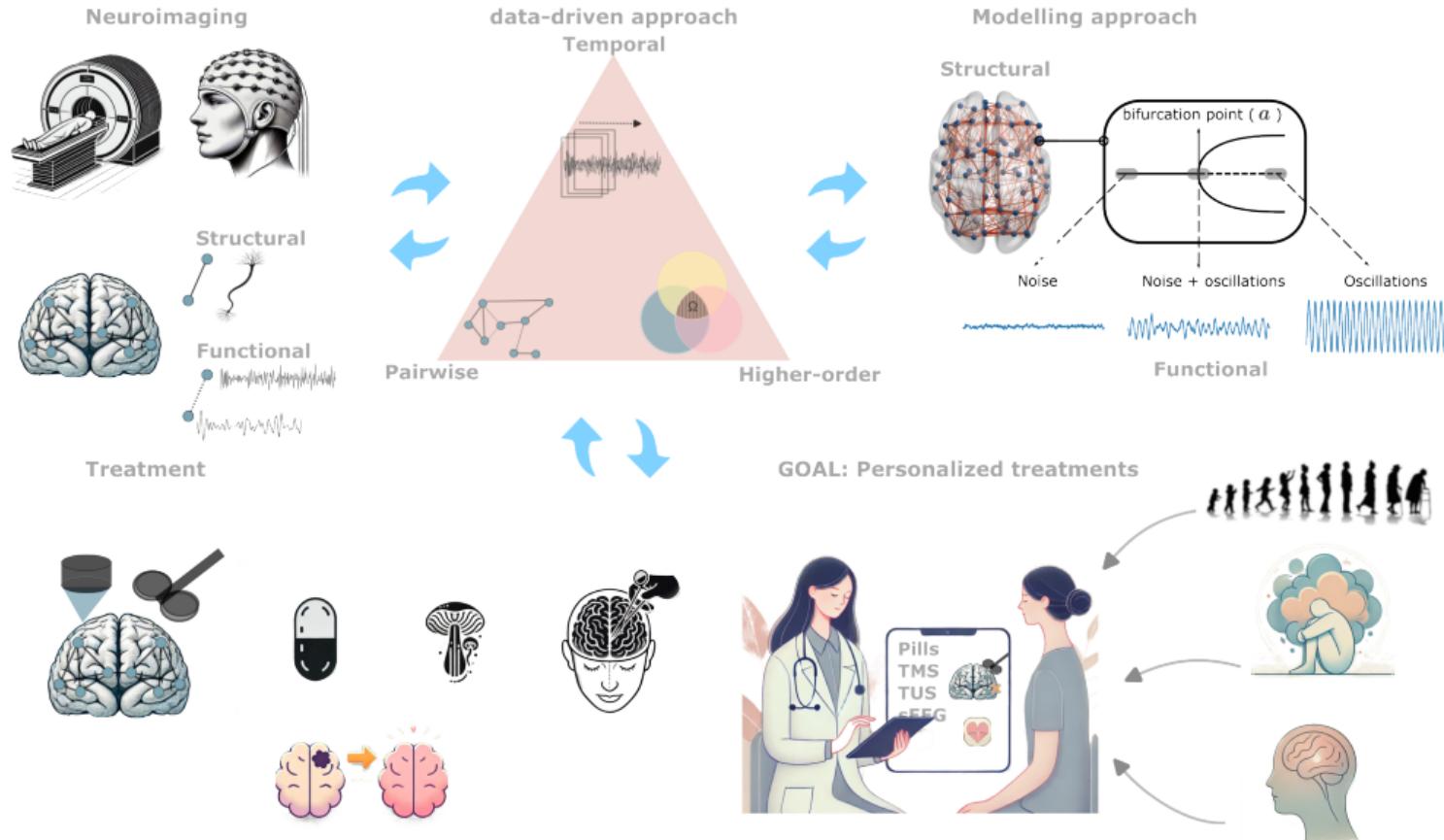
Challenges

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

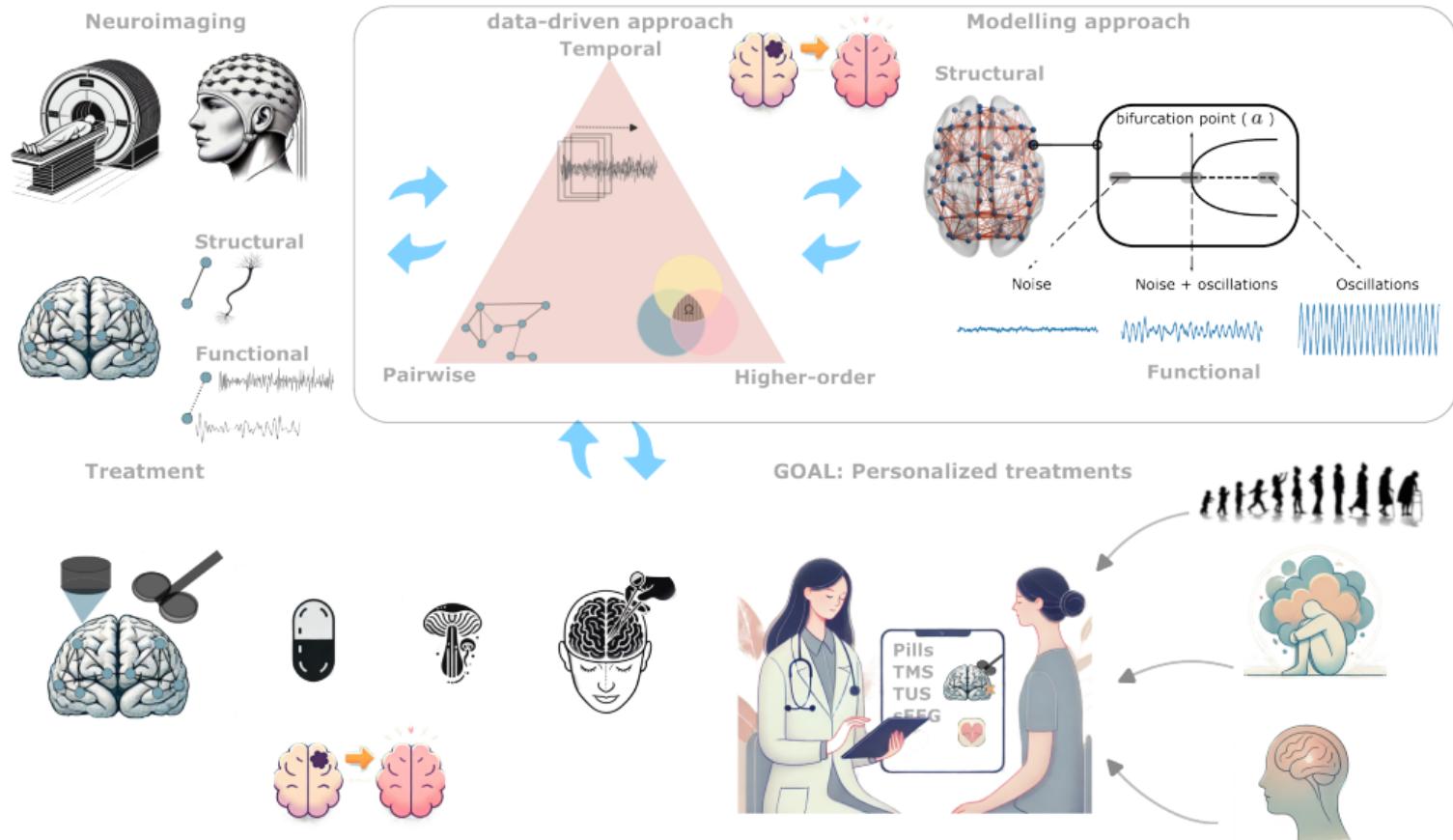


Betzel and Bassett, 2017, Neuroimage

Motivation



Motivation

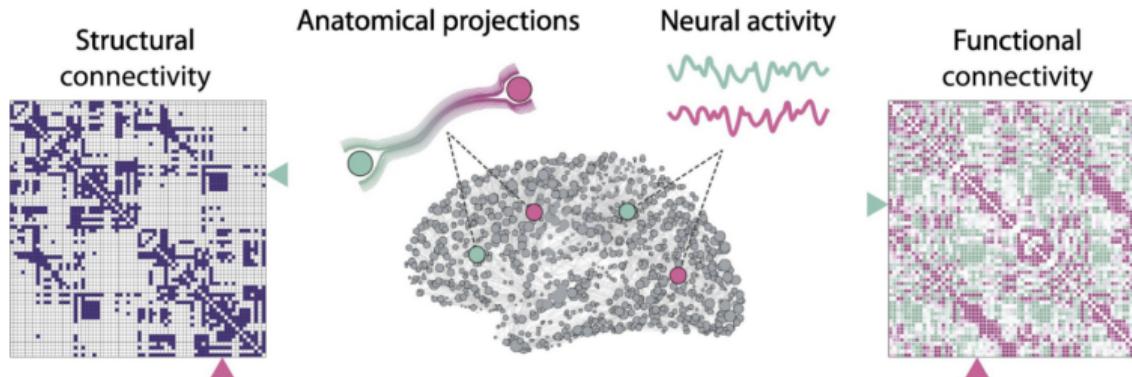


HOI-BrainMod

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



...

High-order fundaments: Information theory

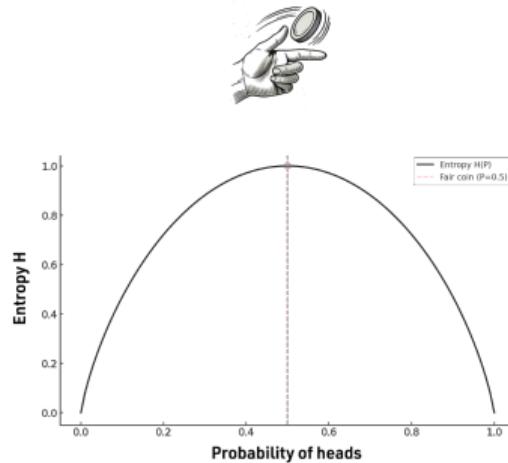


Redundancy



Synergy

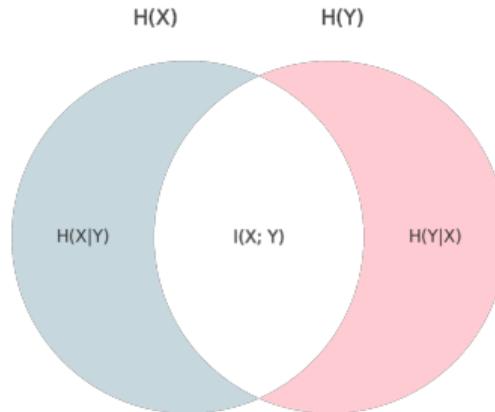
Entropy ($n = 1$)



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

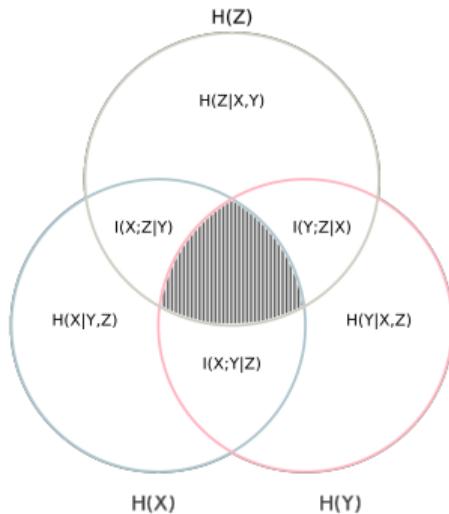
$$h(X) = - \int_X f(x) \log_2 f(x) dx$$

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



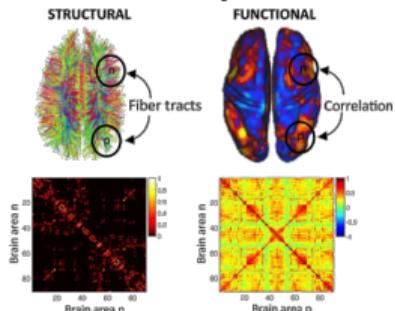


Redundancy

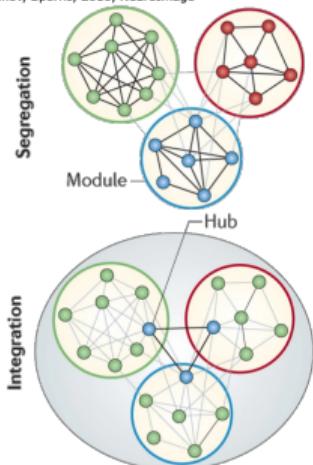


Synergy

Pairwise analysis



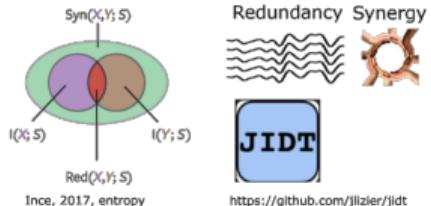
Cabral, et al, 2017, NeuroImage
 Deco, et al, 2015, Nature Reviews Neuroscience
 Rubinov, Sporns, 2010, NeuroImage



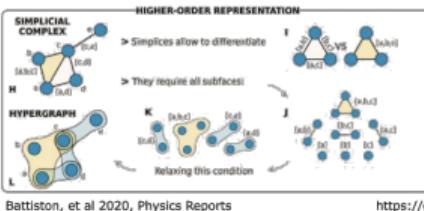
Brain Connectivity Toolbox
brain-connectivity-toolbox.net

High-order analysis

Multivariate Information theory



Topology

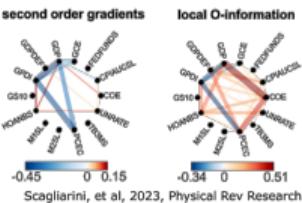


XGI

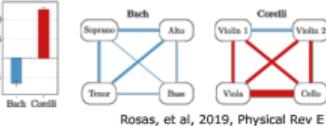
<https://github.com/xgi-org/xgi>

High-order applications

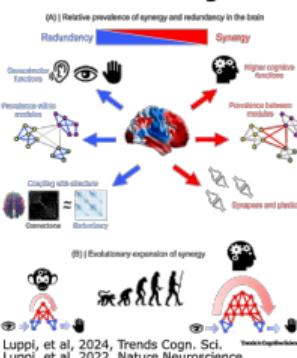
Macroeconomic data



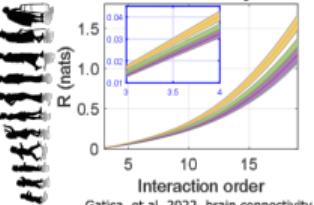
Music



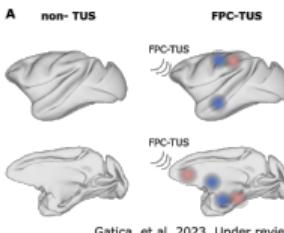
Evolution and cognition



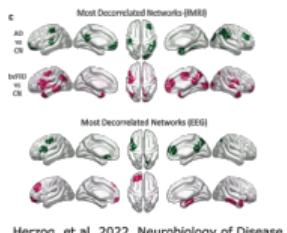
Healthy aging



Transcranial ultrasound Stimulation



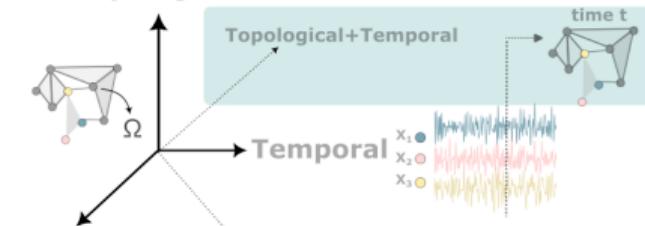
Neurodegeneration



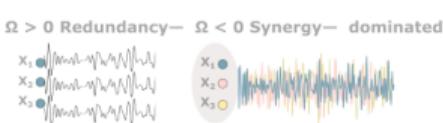
A. Higher-order interdependencies



Topological



Information Theory



B. Higher-order in the human brain



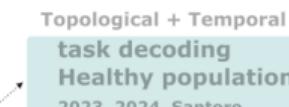
Psychodelics 2013, Petri
Traumatic brain injury 2015, Nielson
Schizophrenia 2020, Stoltz

Topological



Info. Theory + Topological
Healthy population
2023, N Santos

Information Theory



Information Theory + Temporal
Cognition 2022, Luppi
Consciousness 2024, Luppi
Healthy population
2023, Varley, 2025, Pope
Neuromodulation
2024, 2025, Gatica

Healthy aging 2018, Pontes, 2020, 2021, Gatica

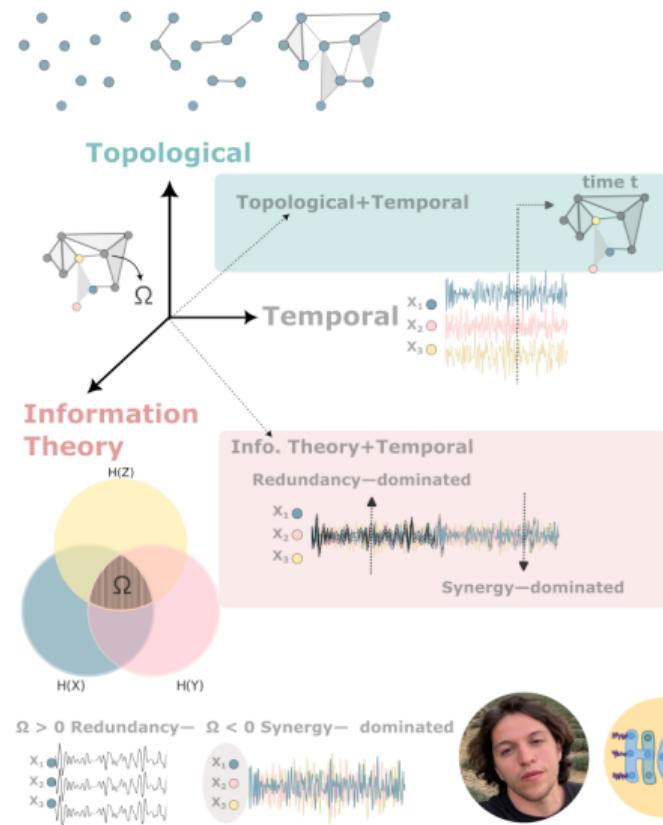
Alzheimer and Frontotemporal Dementia 2023, Herzog

Consciousness (ketamine 2022, Herzog, meditation 2024, Kumar)

Schizophrenia 2023, Li

Infants 2024, Varley

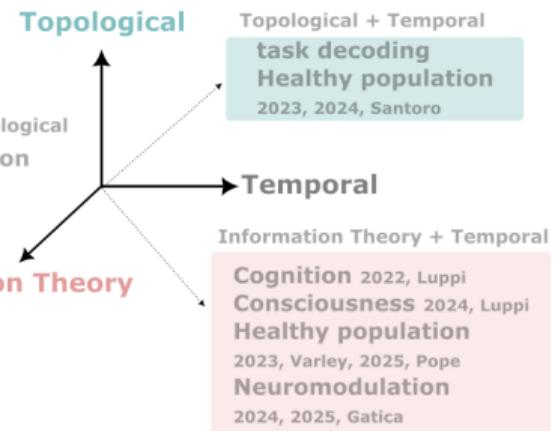
A. Higher-order interdependencies



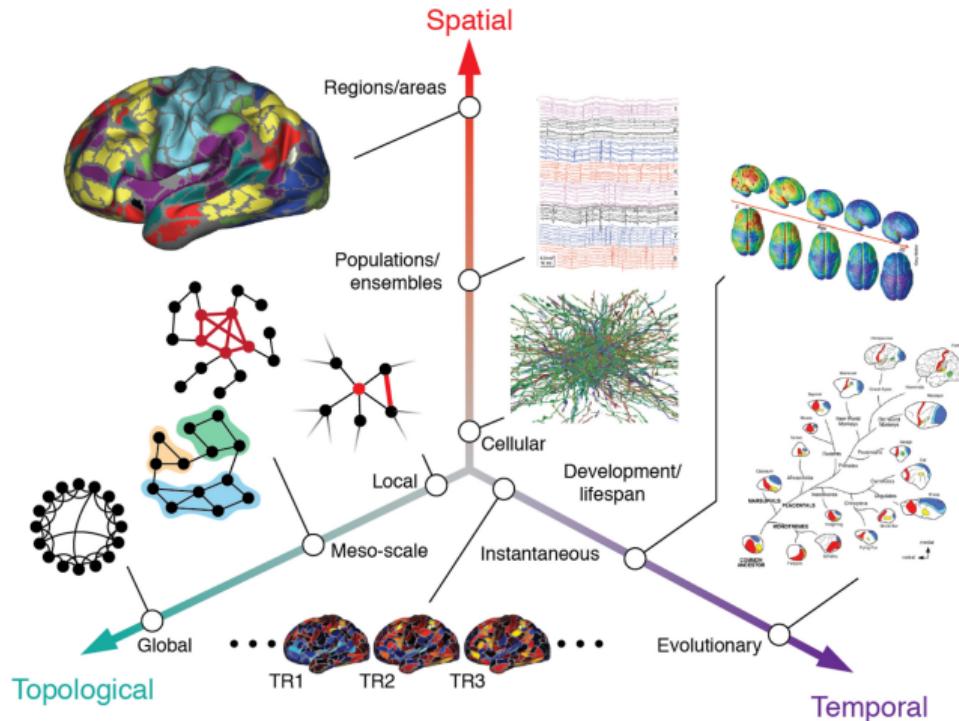
B. Higher-order in the human brain



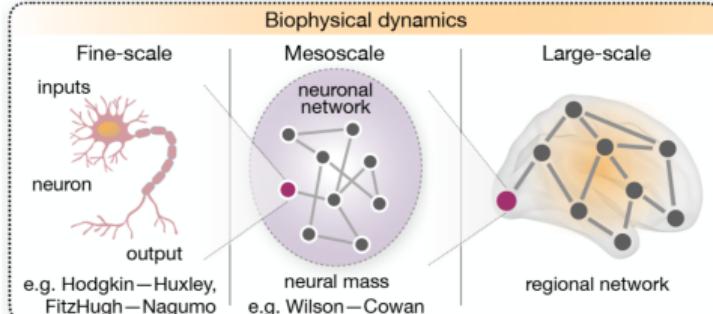
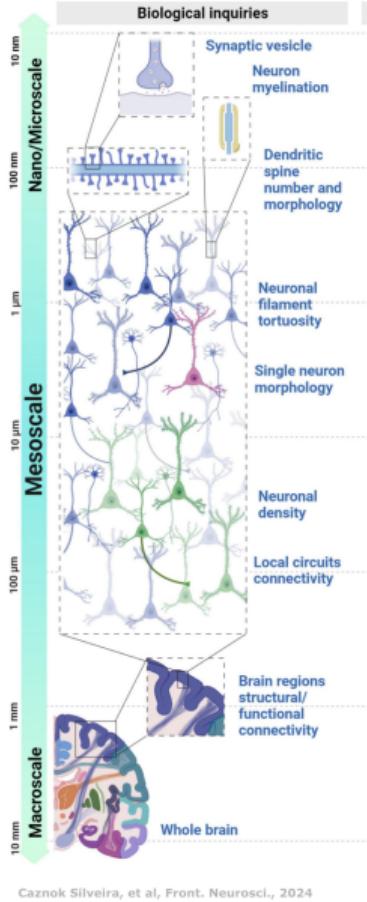
Psychodelics 2013, Petri
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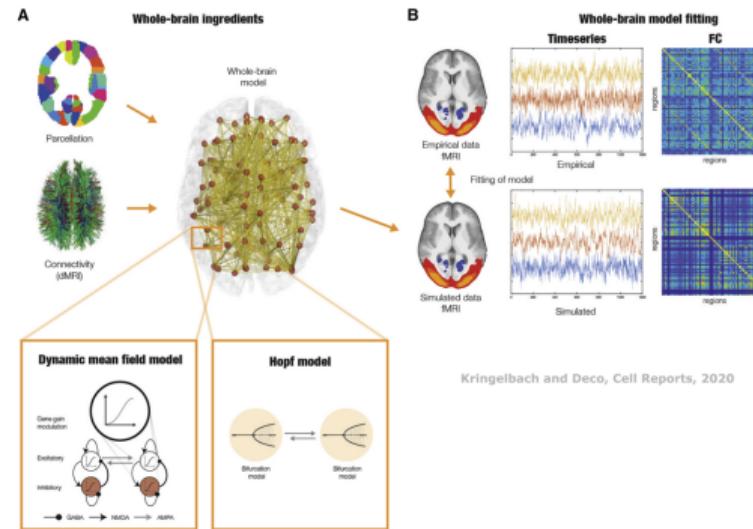
Back to the challenges



Betzel and Bassett, 2017, Neuroimage



Lynn and Bassett, *Nature Reviews Physics*, 2019





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,⁵ 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. Kringlebach^{5,6,7,14,15,*}

Metastable oscillatory modes emerge from synchronization in the brain spacetime connectome

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

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



RESEARCH ARTICLE

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

Carlos Coronel-Olivero ,^{1,2} Rodrigo Cofré ,³ 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 Dornide³, Jochen Mersmann⁴, Anthony R. McIntosh⁵, Viktor Jirsa^{1*}



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

Yonatan Sanz Perl , Carla Pallavicini , Ignacio Pérez Ipíña, Athena Demertzis, Vincent Bonhomme, Charlotte Martial, Rajanikant Panda, Jitka Annen, Agustín Ibáñez, Morten Kringlebach, Gustavo Deco, Helmut Laufs, Jacobo Sitt, Steven Laureys , Enzo Tagliazucchi

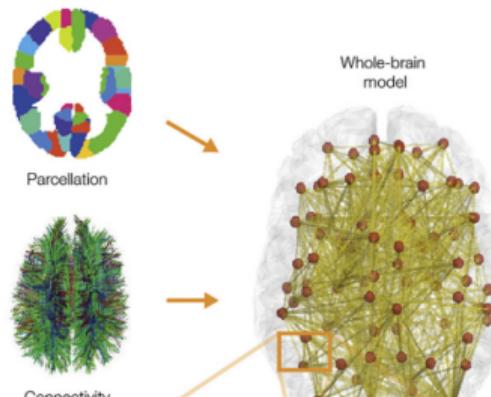
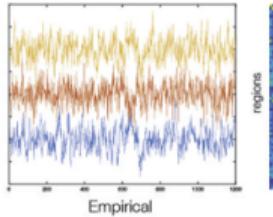
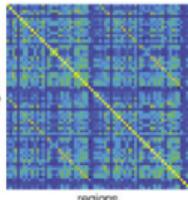
Published: July 27, 2021 • <https://doi.org/10.1371/journal.pcbi.1009139>

➤ *Netw Neurosci.* 2024 Dec 10(8)(4):1590-1612. doi: 10.1162/netn_a_00410. eCollection 2024.

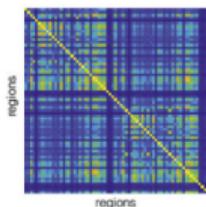
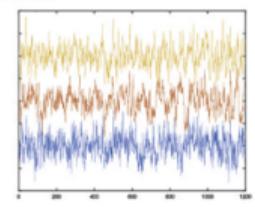
Neural mass modeling for the masses: Democratizing access to whole-brain biophysical modeling with FastDMF

Rubén Herzog ¹, 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 ^{13,15}, Morten L. Kringlebach ^{7,16,17}, Rodrigo Cofré ¹⁸, Gustavo Deco ^{14,19}

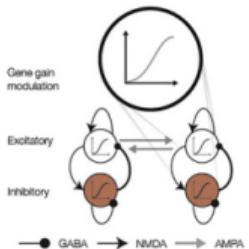
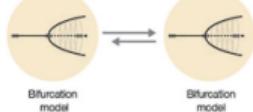


A**Whole-brain ingredients****B****Whole-brain model fitting****Timeseries****FC**

Fitting of model

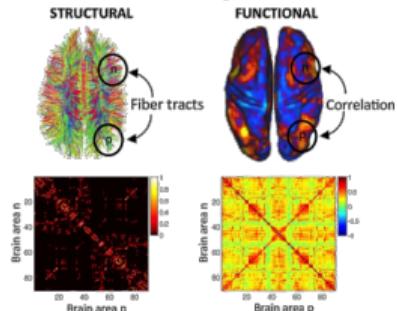


Kringelbach and Deco, Cell Reports, 2020

Dynamic mean field model**Hopf model**

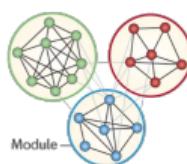
Towards an integrated framework

Pairwise analysis

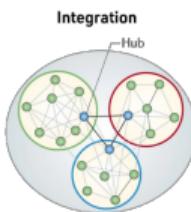


Cabral, et al, 2017, NeuroImage
Deco, et al, 2015, Nature Reviews Neuroscience
Rubinov, Sporns, 2010, NeuroImage

Segregation

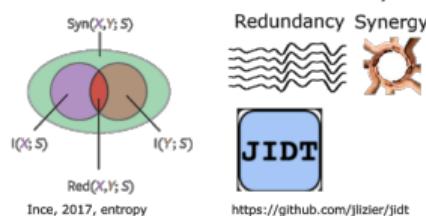


Integration



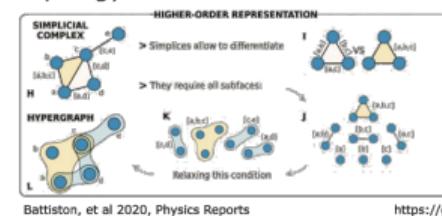
Brain Connectivity Toolbox
brain-connectivity-toolbox.net

Multivariate Information theory

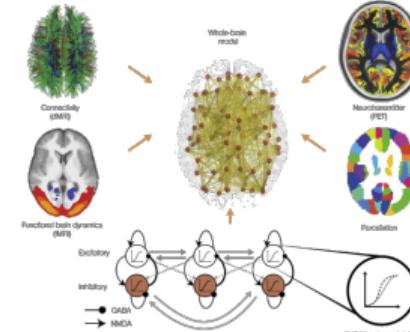


High-order analysis

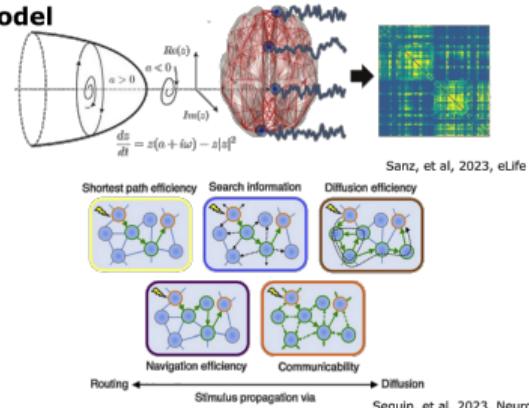
Topology



Whole-Brain Model



Deco, et al, 2018, Current Biology



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