NPL RESEARCH

Network Science Institute
at Northeastern University

Northeastern University
London

IAS

University of
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)

HOUSE RULES

← Toilets: ground floor (end of corridor, left hand) and first floor (upstairs and right hand)

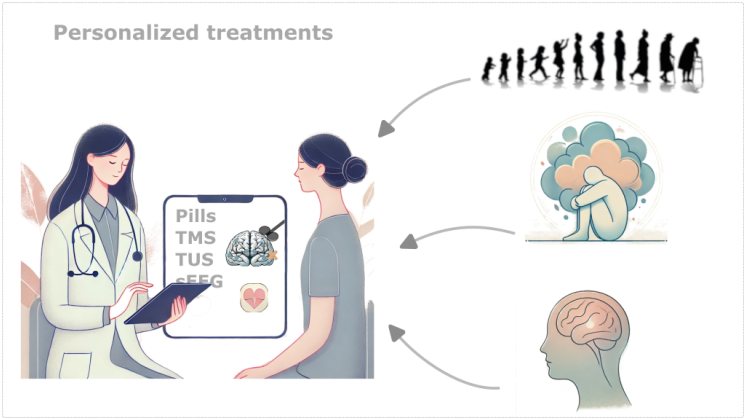
Coffee break and lunch kindly provided by IAS

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

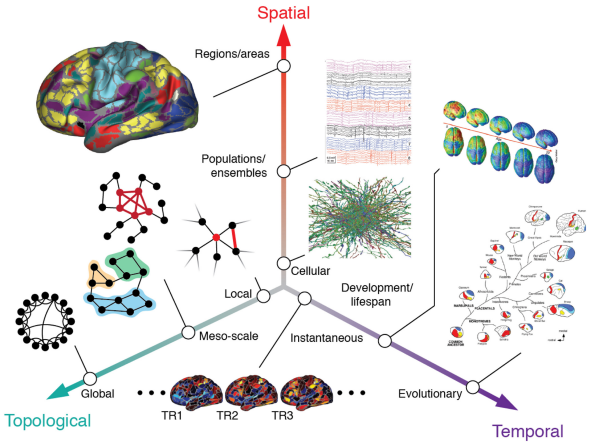
Have fun!

Goal



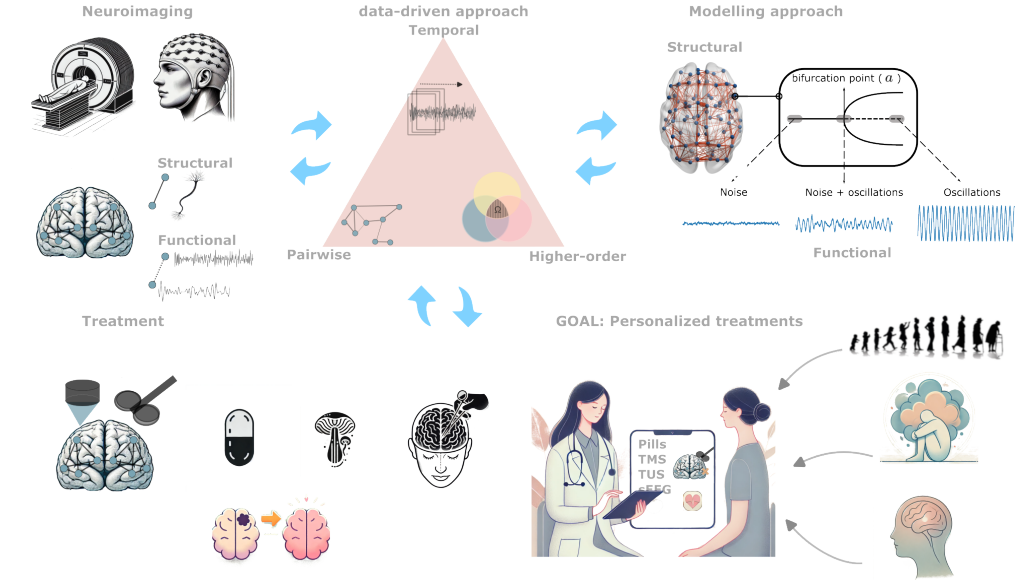
Challenges

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

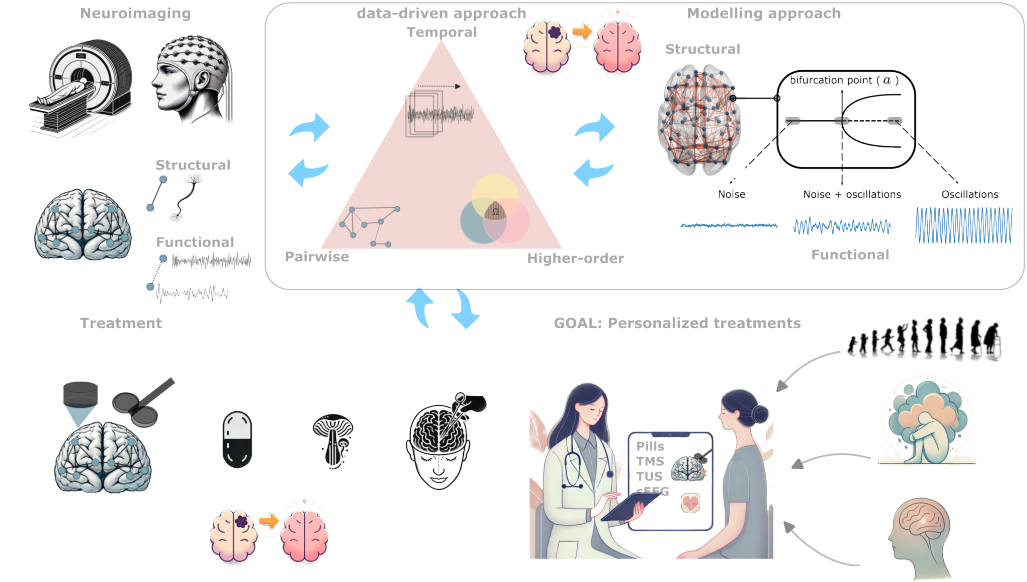


Betzel and Bassett, 2017, Neuroimage

Motivation


Neuroimaging
Structural
Functional
data-driven approach
Temporal
Pairwise
Higher-order
Modelling approach
Structural
bifurcation point (a)
Noise
Noise + oscillations
Oscillations
Functional
Treatment
GOAL: Personalized treatments
Pills
TMS
TUS

Motivation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GOAL: Personalized treatments
Pills
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TUS

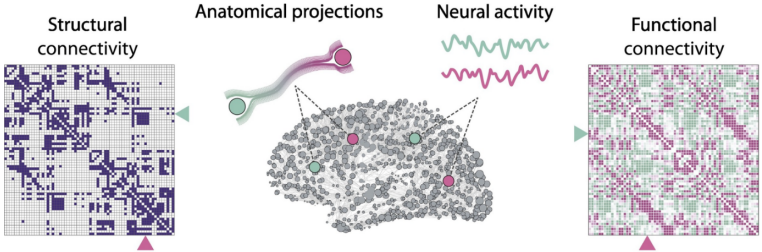
University of Amsterdam | DIEP | Institute for Advanced Study (IAS)

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).

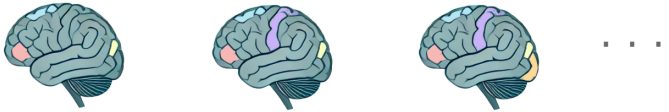
Functional and structural connectivity



Suarez, et al 2020, Trends in Cognitive sciences

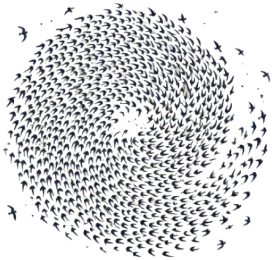
Higher-order interactions

order 3 order 4 order 5



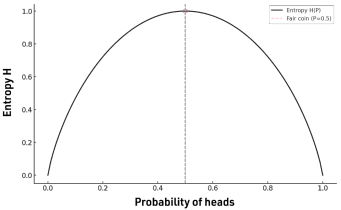
High-order fundaments: Information theory

Redundancy



Synergy

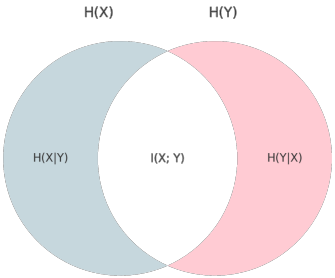
Entropy (n = 1)



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

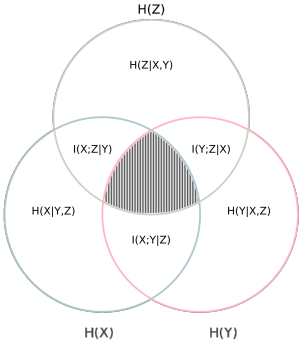
$$h(X) = -\int_{\mathcal{X}} f(x) \log_2 f(x)\, dx$$

Mutual Information (n = 2)



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

Interaction Information (n=3)



$$I(X;Y;Z) = I(X;Y) - I(X;Y \mid Z)$$

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

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

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

order 3 order 4 order 5



. . .

O-Information (n>=3)

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

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

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

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

Note:

Higher-order interactions (HOI) could also be computed between pairs of regions...

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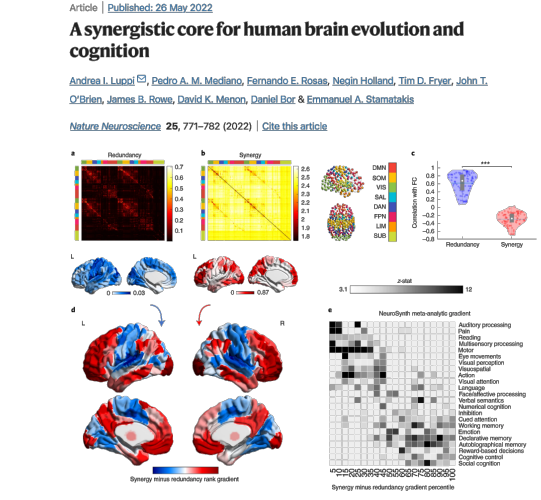
Higher-order interactions (HOI) could also be computed between pairs of regions...



Article | Published: 26 May 2022

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

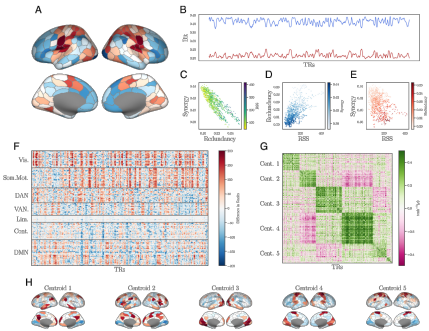
Nature Neuroscience **25**, 771–782 (2022) | Cite this article

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

Thomas F. Varley, Maria Pope, Maria Grazia Puxeddu, +1, 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

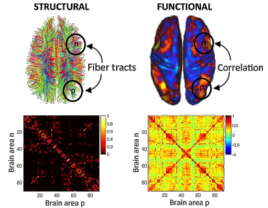
July 19, 2023 | 120 (30) e2300888120 | https://doi.org/10.1073/pnas.2300888120



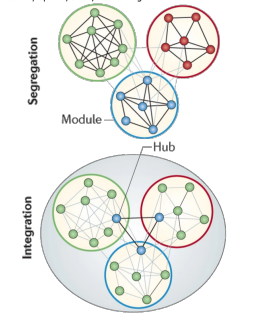
Redundancy

Synergy

Pairwise analysis



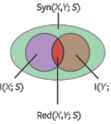
Cabral, et al, 2017, NeuroImage
Deco, et al, 2015, Nature Reviews Neuroscience
Rubinov, Sporns, 2010, NeuroImage



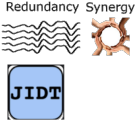
Brain Connectivity Toolbox
brain-connectivity-toolbox.net

High-order analysis

Multivariate Information theory

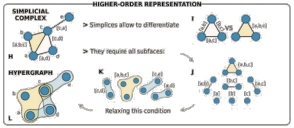


Ince, 2017, entropy



https://github.com/jlizier/jidt

Topology

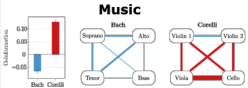


Battiston, et al 2020, Physics Reports

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

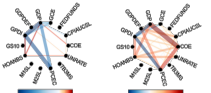
High-order applications

Music



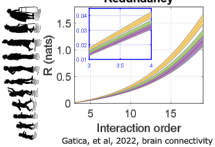
Rosas, et al, 2019, Physical Rev E

Macroeconomic data



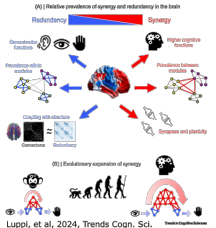
Scagliarini, et al, 2023, Physical Rev Research

Healthy aging



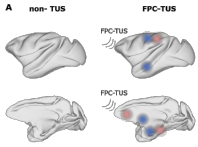
Gatica, et al, 2022, brain connectivity

Evolution and cognition



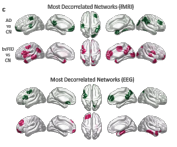
Luppi, et al, 2024, Trends Cogn. Sci.
Luppi, et al, 2022, Nature Neuroscience

Transcranial ultrasound Stimulation



Gatica, et al, 2023, Under review

Neurodegeneration



Herzog, et al, 2022, Neurobiology of Disease

A. Higher-order interdependencies

Topological

Topological+Temporal

time t

Ω

Temporal

X_1 X_2 X_3

Information Theory

Info. Theory+Temporal

Redundancy—dominated

X_1 X_2 X_3

Synergy—dominated

H(Z)

Ω

H(X) H(Y)

Ω > 0 Redundancy— Ω < 0 Synergy— dominated

X_1 X_2 X_3

X_1 X_2 X_3

B. Higher-order in the human brain

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

Topological

Topological + Temporal

task decoding
Healthy population
2023, 2024, Santoro

Info. Theory + Topological
Healthy population
2023, N Santos

Temporal

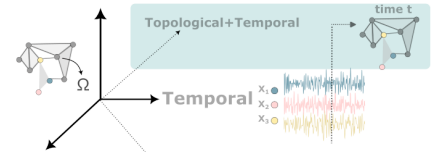
Information Theory + Temporal

Information Theory

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 (ketamina 2022, Herzog, meditation 2024, Kumar)
Schizophrenia 2023, Li
Infants 2024, Varley

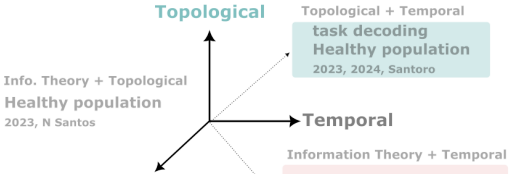
A. Higher-order interdependencies



B. Higher-order in the human brain

fMRI
EEG

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



Healthy aging 2018, Pontes, 2020, 2021, Gatica
Alzheimer and Frontotemporal Dementia 2023, Herzog
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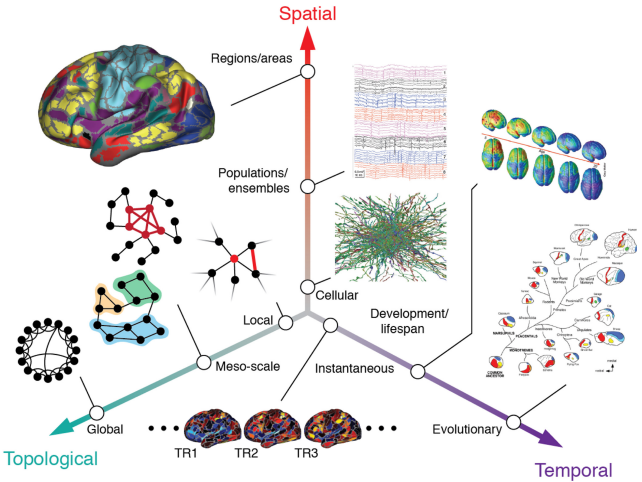
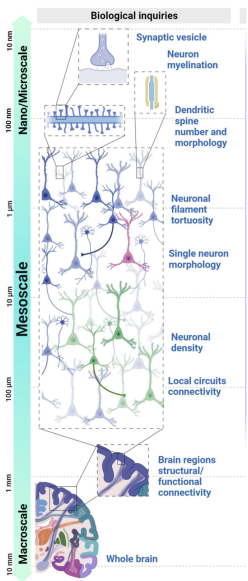
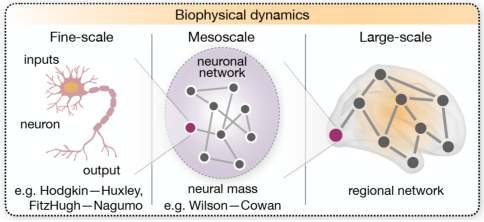
Back to the challenges



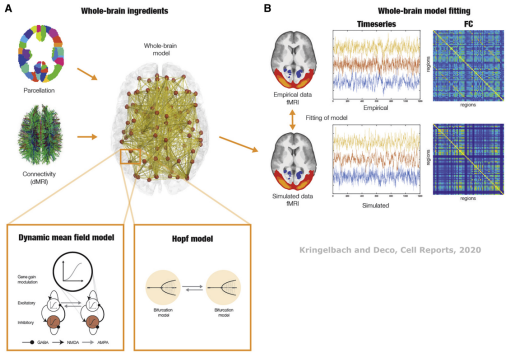
Betzel and Bassett, 2017, Neuroimage



Caznok Silveira, et al, Front. Neurosci., 2024



Lynn and Bassett, Nature Reviews Physics, 2019



Kringelbach and Deco, Cell Reports, 2020

Current Biology

Article

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 Gónzalez Gómez [1 5], Kamalini Ranasinghe [6], Agustín Sainz-Ballesteros [1], Agustina Legaz [7], Sol Fittipaldi [1 2 3 7], Josephine Cruzat [1], Rubén Herzog [1], Gorsev Yener [8 9], Mario Parra [10], David Aguillon [11], Francisco Lopera [11], Hernando Santamaria-Garcia [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 Cofré[3], Patricio Orio[1,4]*

The Virtual Brain: a simulator of primate brain network dynamics

THEVIRTUALBRAIN.

Paula Sanz Leon[1]* Stuart A. Knock[2] M. Marmaduke Woodman[1] Lia Domide[3]
Jochen Mersmann[4] Anthony R. McIntosh[5] Viktor Jirsa[1]*

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. 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, Carla Pallavicini, Ignacio Pérez Ipiña, Athena Demertzi, Vincent Bonhomme, Charlotte Martial, Rajanikant Panda, Jitka Annen, Agustin Ibañez, Morten Kringelbach, 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

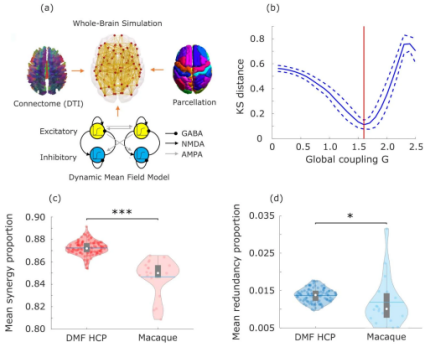
Rubén Herzog [1], Pedro A M Mediano [2 3], Fernando E Rosas [4 5 6 7], Andrea I Luppi [7 8 9 10], Yonatan Sanz-Perl [11 12 13 14], Enzo Tagliazucchi [11 15], Morten L Kringelbach [7 16 17], Rodrigo Cofré [18], Gustavo Deco [14 19]

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

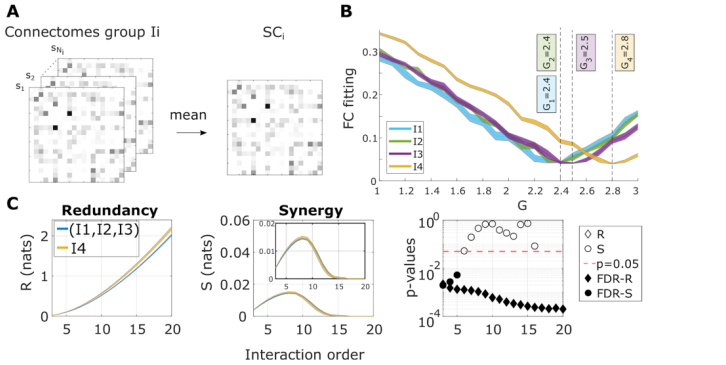
Nature Neuroscience **25**, 771–782 (2022) | Cite this article



PLOS COMPUTATIONAL BIOLOGY

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

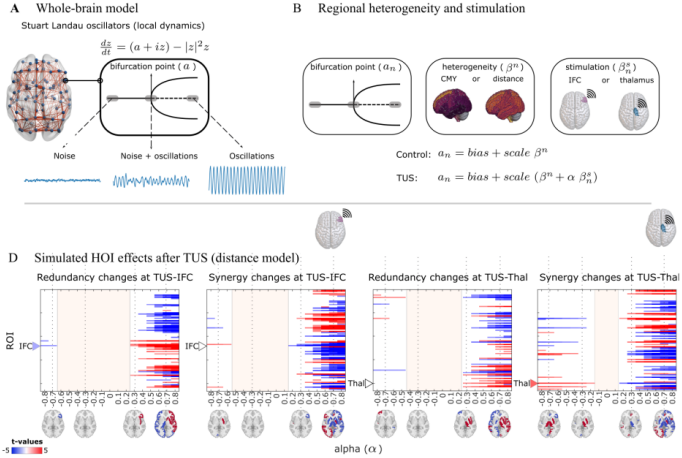
Marilyn Gatica, Fernando E. Rosas, Pedro A. M. Mediano, Ibai Diez, Stephan P. Swinnen, Patricio Orio, Rodrigo Cofré, Jesus M. Cortes

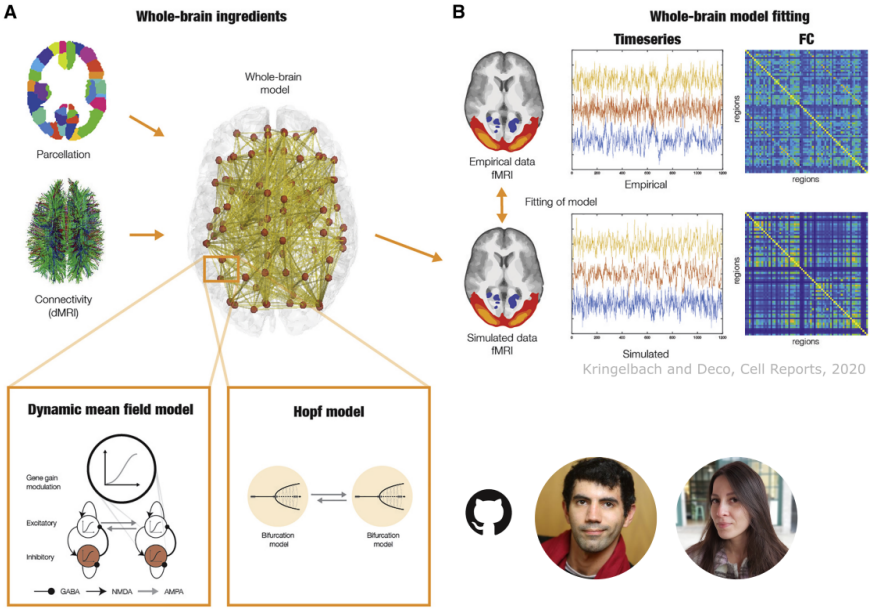


Understanding the high-order network plasticity mechanisms of ultrasound neuromodulation

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

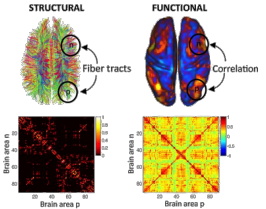




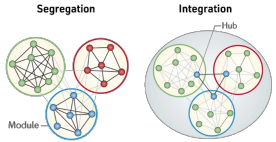
Kringelbach and Deco, Cell Reports, 2020

Towards an integrated framework

Pairwise analysis



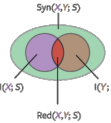
Cabral, et al, 2017, NeuroImage
Deco, et al, 2015, Nature Reviews Neuroscience
Rubinov, Sporns, 2010, NeuroImage



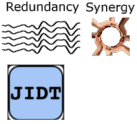
Brain Connectivity Toolbox
brain-connectivity-toolbox.net

High-order analysis

Multivariate Information theory

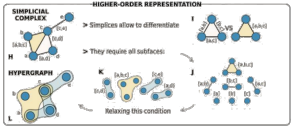


Ince, 2017, entropy



https://github.com/jlizier/jidt

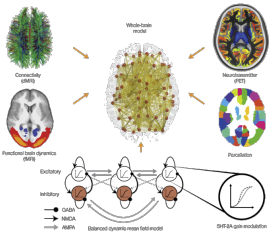
Topology



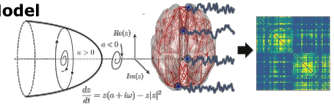
Battiston, et al 2020, Physics Reports

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

Whole-Brain Model



Deco, et al, 2018, Current Biology



Sanz, et al, 2023, eLife

Seguin, et al, 2023, Neuron

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,

CoBrain 2025

Complexity in the Brain

Satellite @ CCS 2025

September 3rd 2025 • Siena, Italy

Keynote Speakers

Petra Vertes
University of Cambridge, UK
Talk Title

Michele Nardin
HHMI Janelia Research Campus, USA

Giulio Pergola
University of Bari Aldo Moro, Italy

Jaroslav Hlinka
Czech Academy of Sciences, Czech Republic

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Northeastern University Boston

University of Amsterdam | DIEP | Institute for Advanced Study (IAS)

HOI-BrainMod

Workshop on Brain Modeling and High-Order Interactions

	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)