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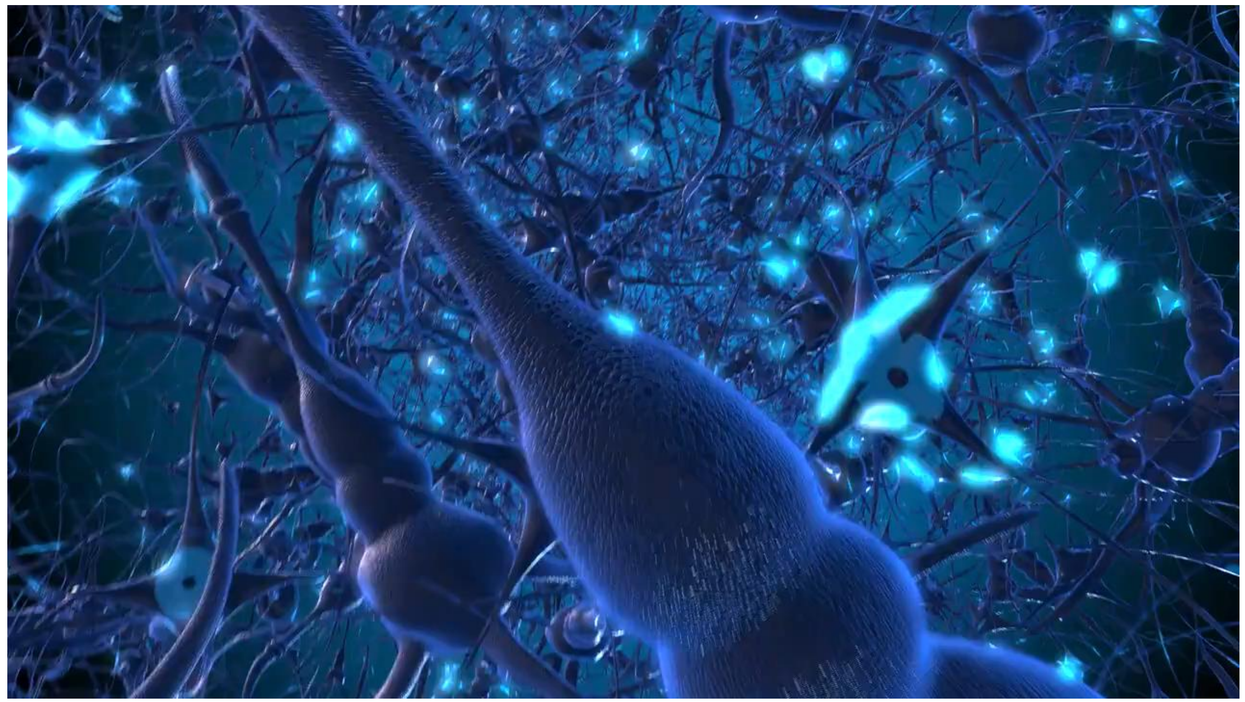
Probing consciousness in the electrical brain

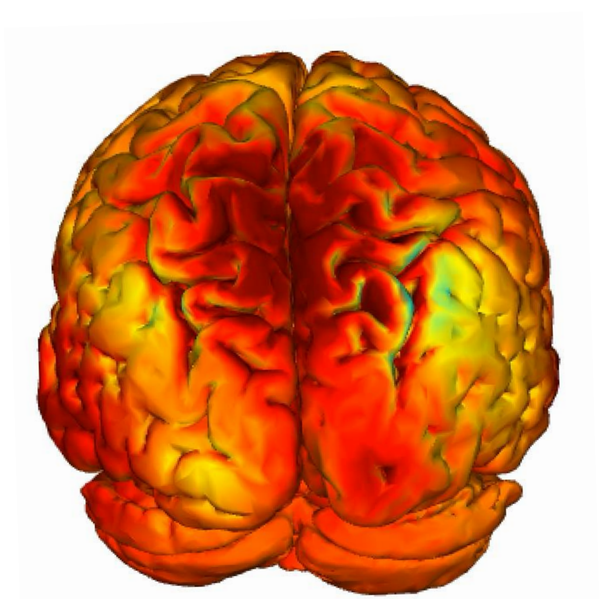
Dr. Giulio Ruffini

Co-founder & CTO **Starlab/Neuroelectrics**

The Science of Consciousness, Barcelona, July 6, 2025

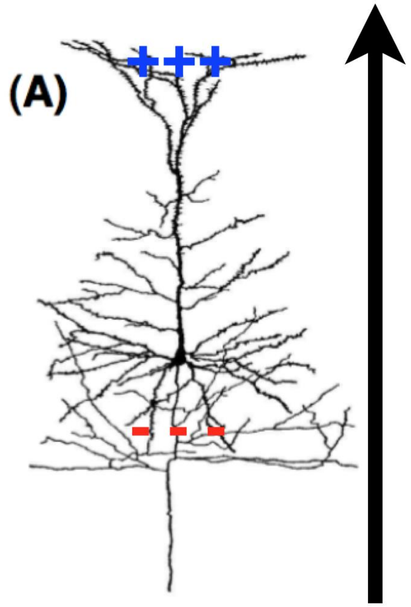
The Electric Brain

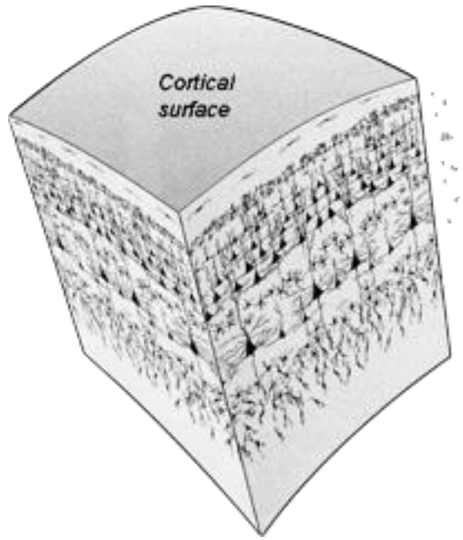


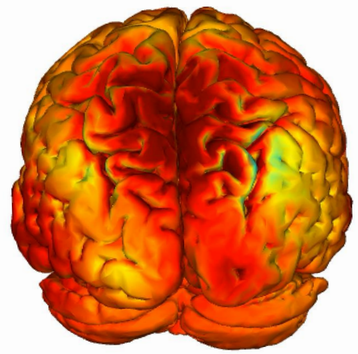


The brain appears to **compute electrically**. What do electric field **patterns** have to do with **mind**?
Can we harness them for **communication** or **therapy**?

M/EEG and tES (electrical stimulation)

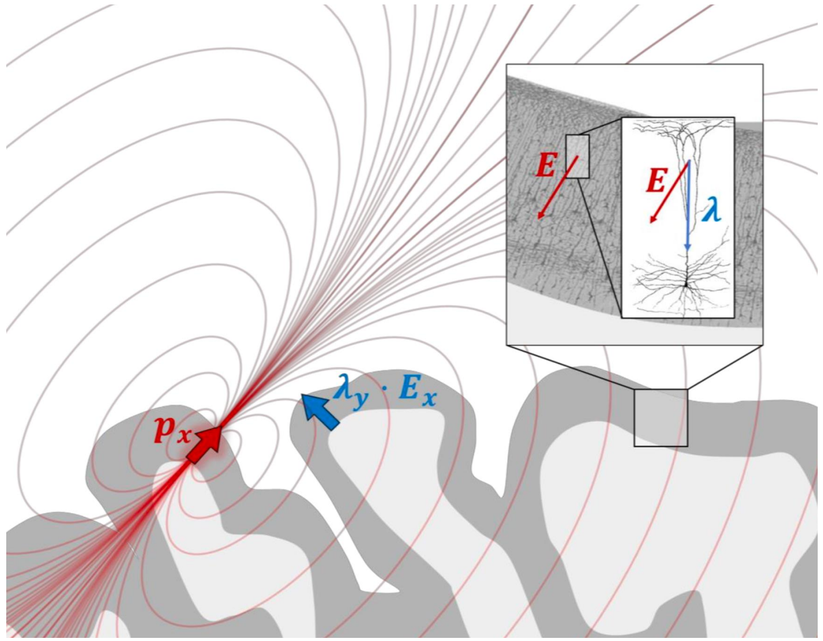




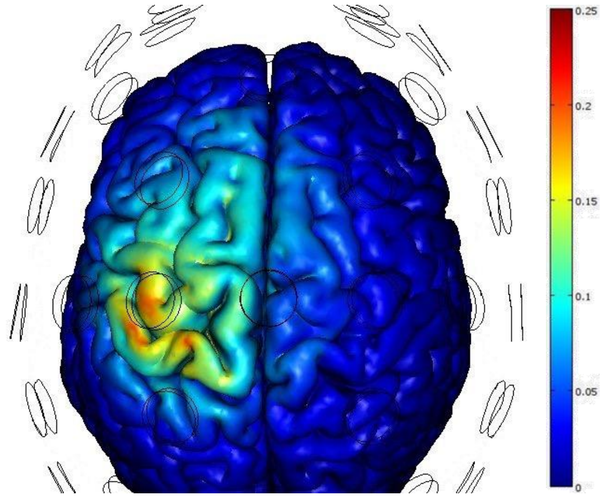


Realistic modeling of mesoscopic ephaptic coupling in the human brain

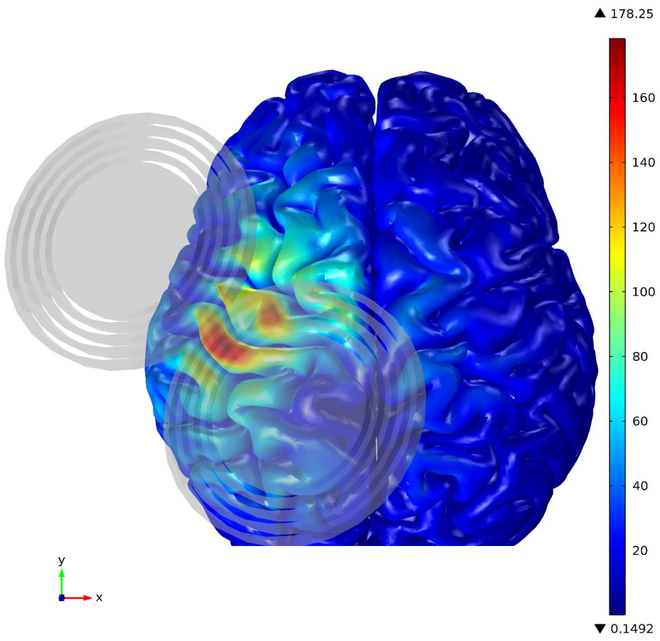
Giulio Ruffini, Ricardo Salvador, Ehsan Tadayon, Roser Sanchez-Todo, Alvaro Pascual-Leone, Emiliano Santarnecchi



tES and TMS (both electrical)



0.25 V/M



180 V/M

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BCI/CBI Applications

Brain to Brain Communication

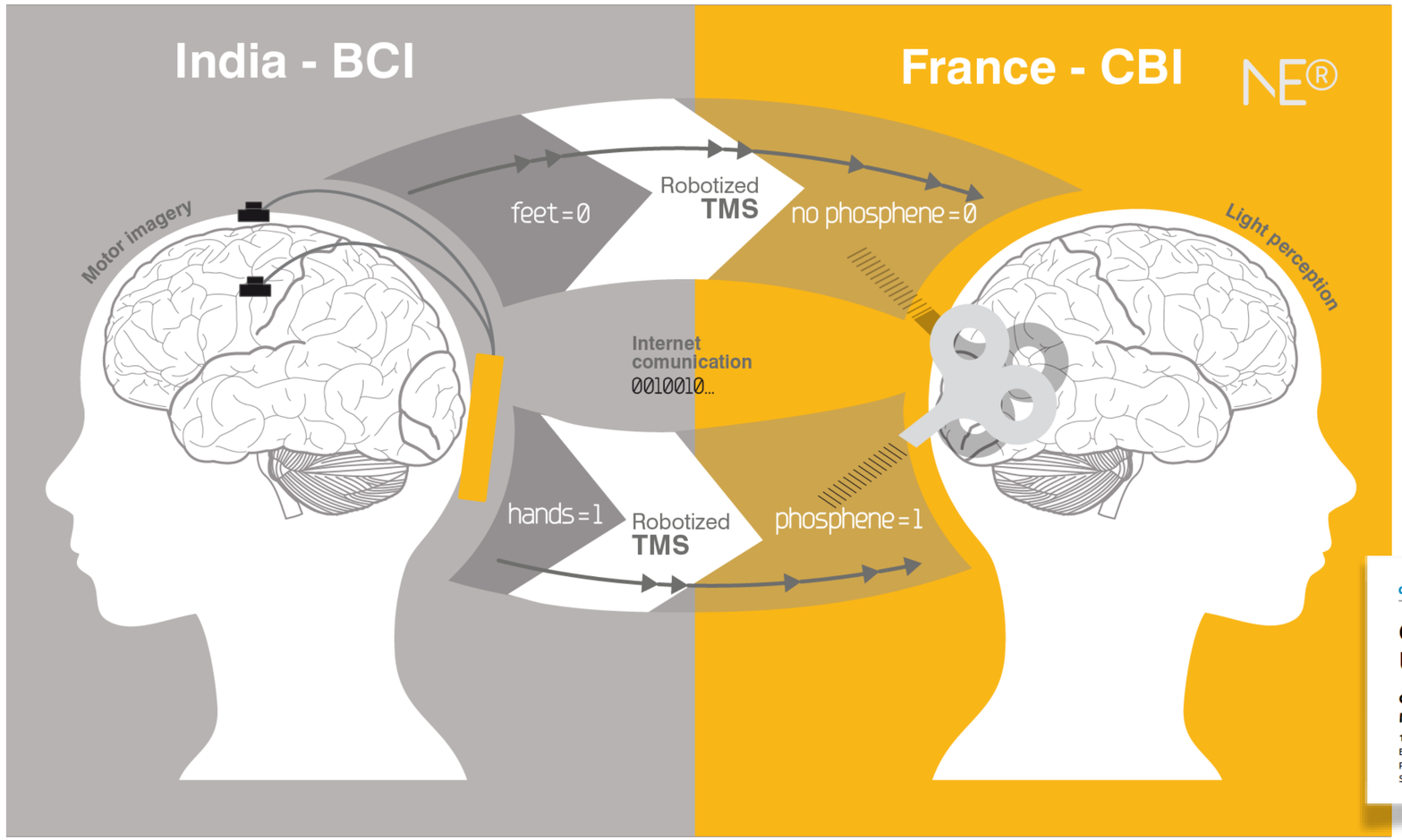
NE neuroelectrics®

Brain–computer interfaces for communication and control

Jonathan R Wolpaw [a b], Niels Birbaumer [c d], Dennis J McFarland [a], Gert Pfurtscheller [e], Theresa M Vaughan [a]

Magnetic Stimulation of Visual Cortex: Factors Influencing the Perception of Phosphenes

Ray, Patty G.; Meador, Kimford J.; Epstein, Charles M.*; Loring, David W.; Day, Larry J.



OPEN ACCESS Freely available online

PLOS ONE

Conscious Brain-to-Brain Communication in Humans Using Non-Invasive Technologies

Carles Grau[1,2], Romuald Ginhoux[3], Alejandro Riera[1,4], Thanh Lam Nguyen[3], Hubert Chauvat[3], Michel Berg[3], Julià L. Amengual[5], Alvaro Pascual-Leone[6], Giulio Ruffini[1,4]*

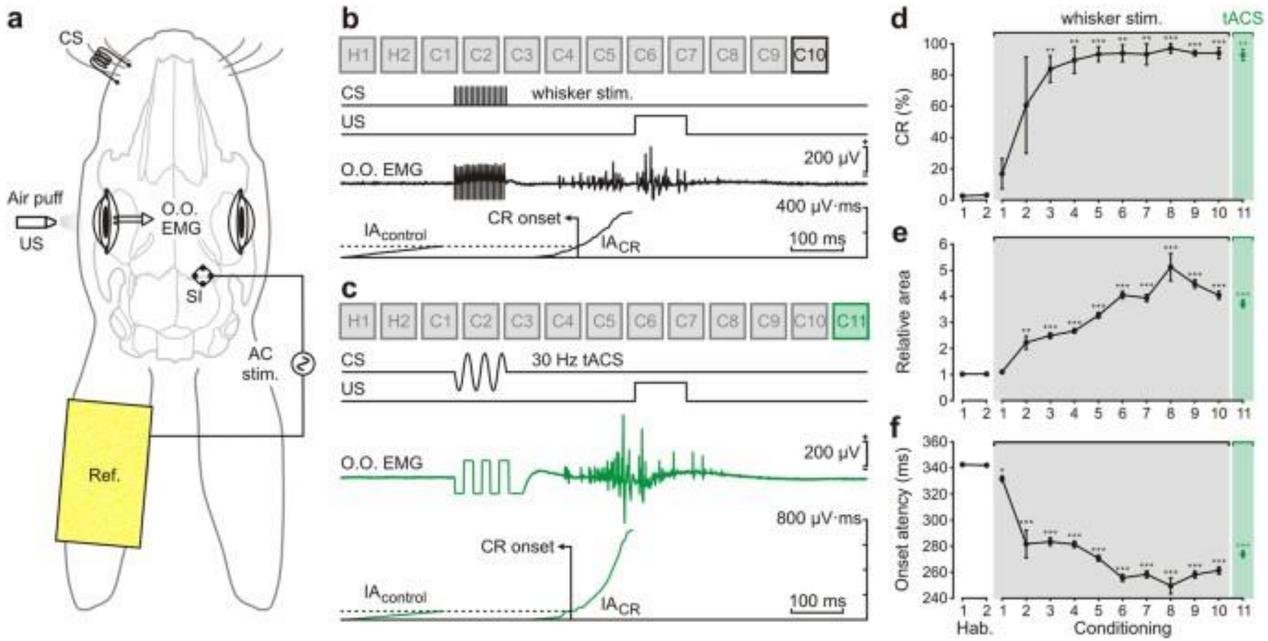
1 Starlab Barcelona, Barcelona, Spain, 2 Neurodynamics Laboratory, Department of Psychiatry and Clinical Psychobiology, Psychology and Medicine Faculties, University of Barcelona, Barcelona, Spain, 3 Axilum Robotics, Strasbourg, France, 4 Neuroelectrics Barcelona, Barcelona, Spain, 5 Cognition and Brain Plasticity Unit, Department of Basic Psychology, University of Barcelona, Barcelona, Spain, 6 Berenson Allen Center for Noninvasive Brain Stimulation, Beth Israel Deaconess Medical Center, Harvard Medical School, Boston, Massachusetts, United States of America

Matrix

Article | Open access | Published: 21 January 2016

Synthetic tactile perception induced by transcranial alternating-current stimulation can substitute for natural sensory stimulus in behaving rabbits

Javier Márquez-Ruiz, Claudia Ammann, Rocío Leal-Campanario, Giulio Ruffini, Agnès Gruart & José M. Delgado-García



Animals can be entirely conditioned by using tACS stimuli.

Once trained, they **respond in a conditioned manner** when peripheral sensory stimulus is presented for the first time.

Lucid Dreams

Induction of self awareness in dreams through frontal low current stimulation of gamma activity

Nature Neuroscience, May 2014

Ursula Voss, Romain Holzmann, Allan Hobson,
Walter Paulus, Judith Koppehele-Gossel, Ansgar Klimke &
Michael A Nitsche

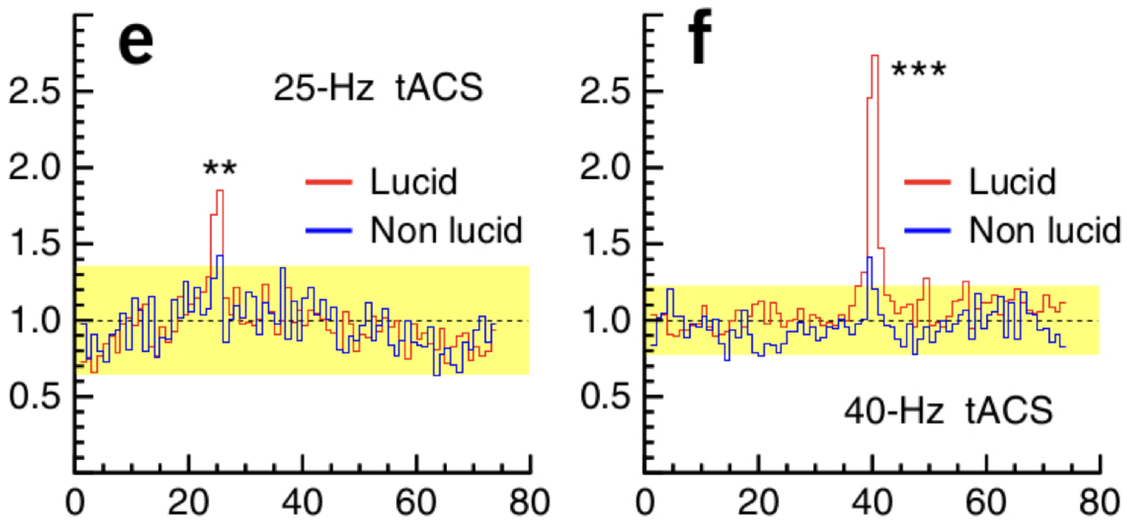


Figure 1 Brain stimulation in the gamma frequency range during REM sleep enhances lucid dreaming. Voss *et al.*[3] report that gamma stimulation during REM sleep enhances the ability to gain conscious awareness in dreams. Through achieving such lucidity, the sleeper in this image gains control over her dream and is able to fly.

Thought to Speech

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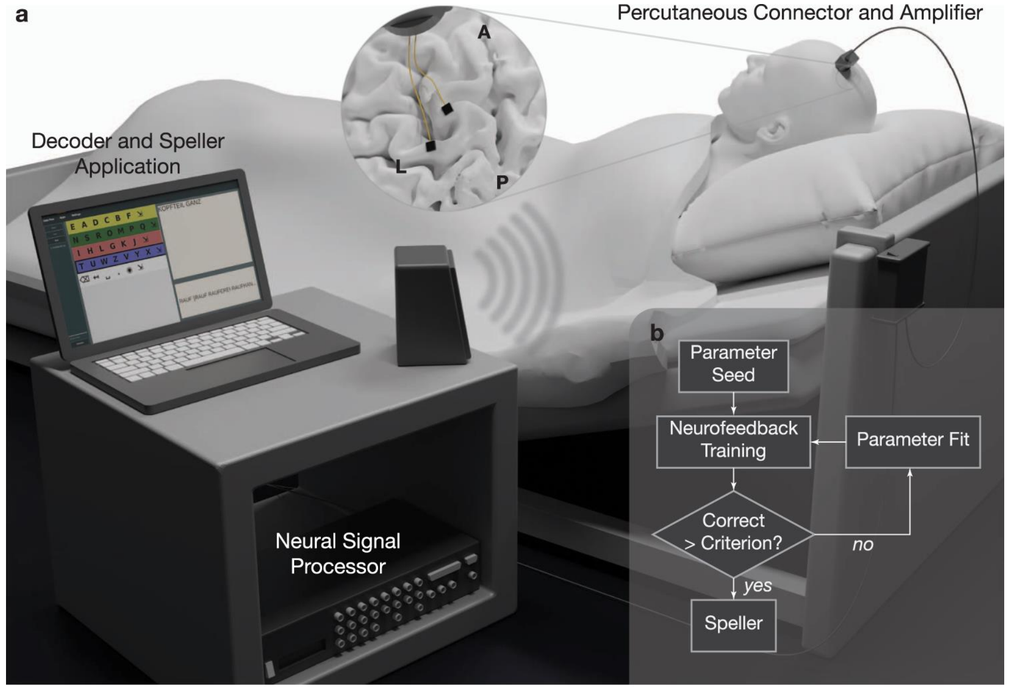
Article | Open access | Published: 22 March 2022

Spelling interface using intracortical signals in a completely locked-in patient enabled via auditory neurofeedback training

Ujwal Chaudhary, Ioannis Vlachos, Jonas B. Zimmermann, Arnau Espinosa, Alessandro Tonin, Andres Jaramillo-Gonzalez, Majid Khalili-Ardali, Helge Topka, Jens Lehmberg, Gerhard M. Friehs, Alain Woodtli, John P. Donoghue & Niels Birbaumer

Nature Communications **13**, Article number: 1236 (2022) | Cite this article



NEWS | 31 March 2025

Brain implant translates thoughts to speech in an instant

Improvements to brain–computer interfaces are bringing the technology closer to natural conversational speed.

EEGNet: A Compact Convolutional Neural Network for EEG-based Brain-Computer Interfaces

Vernon J. Lawhern[1,*], Amelia J. Solon[1,2], Nicholas R. Waytowich[1,3], Stephen M. Gordon[1,2], Chou P. Hung[1,4], and Brent J. Lance[1]

Thought2Text: Text Generation from EEG Signal using Large Language Models (LLMs)

Abhijit Mishra*, Shreya Shukla*, Jose Torres, Jacek Gwizdka, Shounak Roychowdhury
School of Information, University of Texas at Austin
{abhijitmishra, shreya.shukla, jtorres1221, jacekg, shounak.roychowdhury}@utexas.edu

Integrating Biological and Machine Intelligence: Attention Mechanisms in Brain-Computer Interfaces

Jiyuan Wang[a,b,1], Weishan Ye[a,b,1], Jialin He[a,b], Li Zhang[a,b], Gan Huang[a,b], Zhuliang Yu[c,d], and Zhen Liang[a,b,*]

EEG/tES as an affective interface

Multichannel tDCS with advanced targeting for major depressive disorder: a tele-supervised at-home pilot study

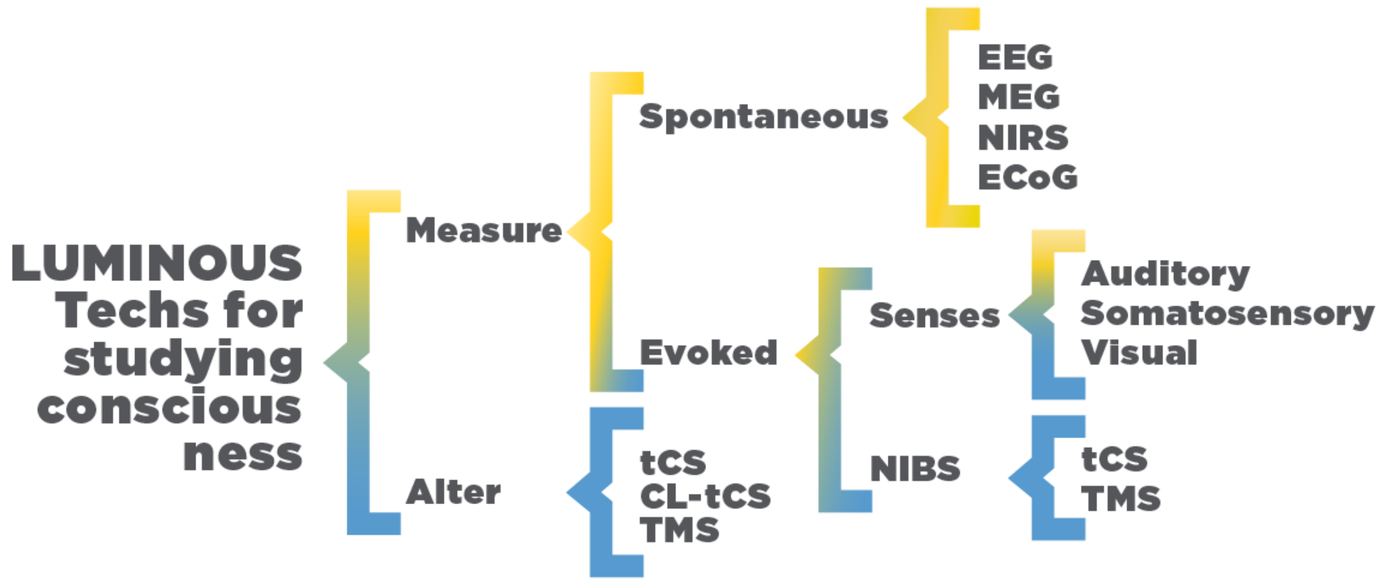
Giulio Ruffini[1*] Ricardo Salvador[1] Francesca Castaldo[1]
Thais Baleeiro[1] Joan A. Camprodon[2] Mohit Chopra[3]
Davide Cappon[3,4,5] Alvaro Pascual-Leone[3,4,5]

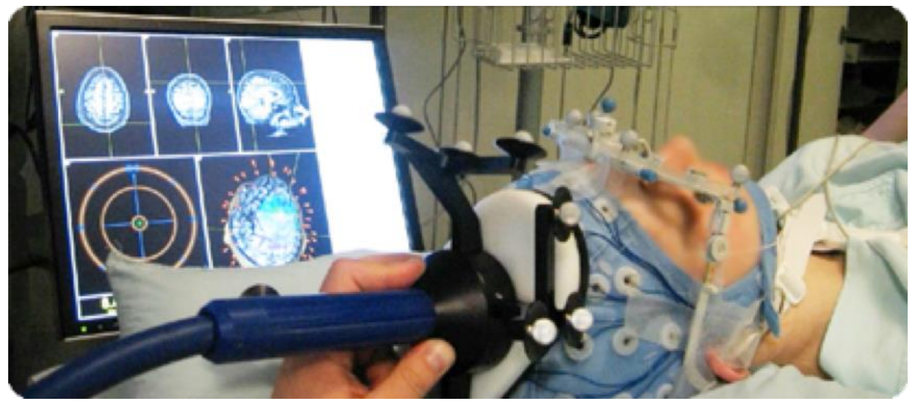
ENAKD – Enobio-powered Affective Interface

The Luminous Project

2016-2020

Consciousness will someday be electromagnetically **measured and altered**, and that the associated needed insights will prove crucial to the development cognitive sciences.





Perturbational Complexity Index (TMS-EEG)

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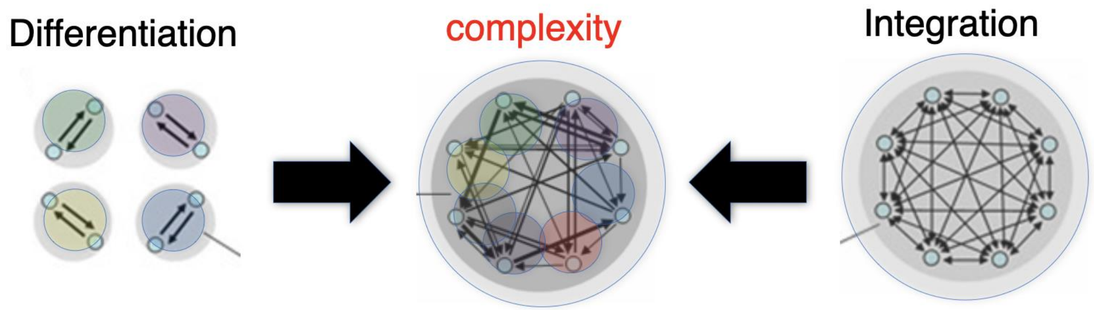
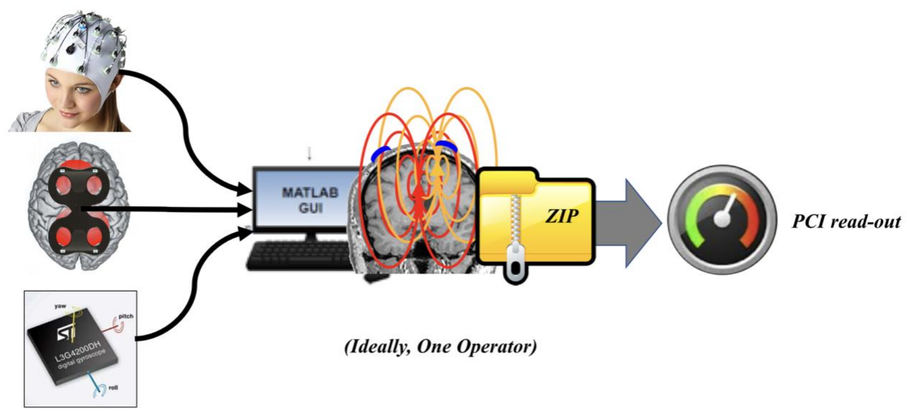
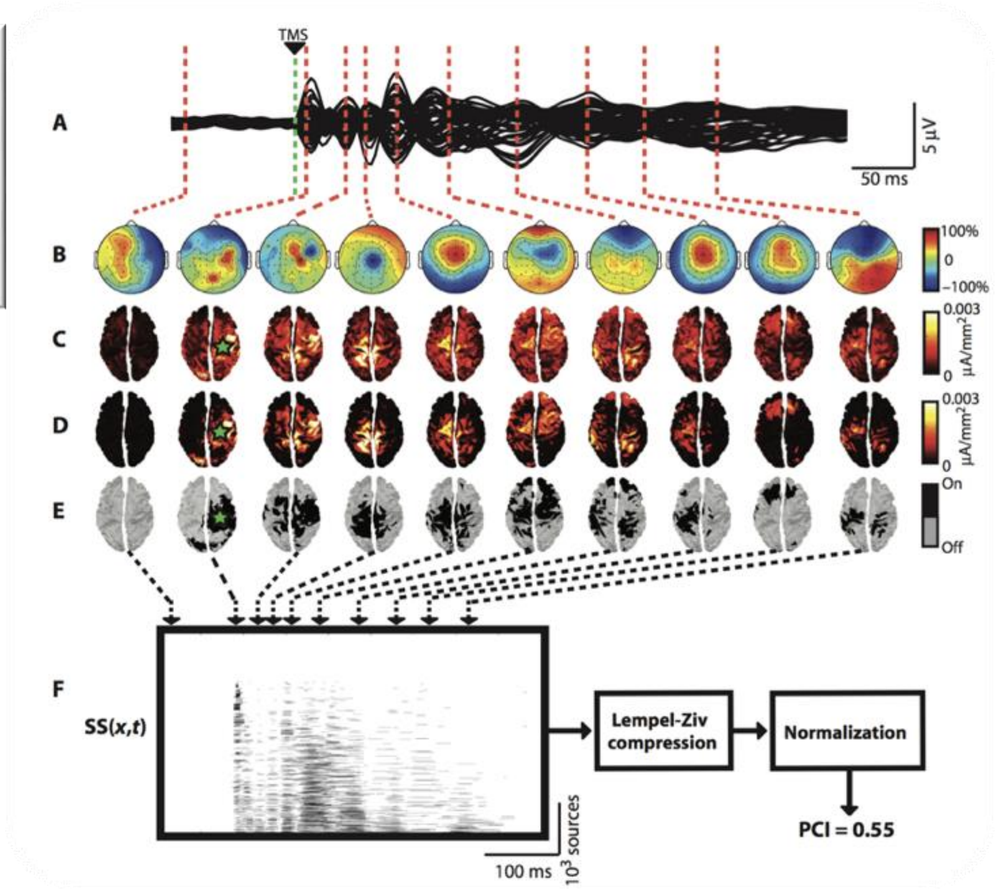
A Theoretically Based Index of Consciousness Independent of Sensory Processing and Behavior

Adenauer G. Casali,[1*†] Olivia Gosseries,[2*] Mario Rosanova,[1] Mélanie Boly,[2‡] Simone Sarasso,[1] Karina R. Casali,[1,3] Silvia Casarotto,[1] Marie-Aurélie Bruno,[2] Steven Laureys,[2] Giulio Tononi,[4] Marcello Massimini[1,5§]



Perturbational Complexity (simple)





2014

The perturbational complexity index detects capacity for consciousness earlier than the recovery of behavioral responsiveness in subacute brain-injured patients

Mario Rosanova [1] · Silvia Casarotto [2,3] · Camilla Derchi [3] · Gabriel Hassan [1] · Simone Russo [1] · Simone Sarasso [1] · Alessandro Viganò [3] · Marcello Massimini [1,3] · Angela Comanducci [3] Show less

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Complexity of M/EEG Signals

Evaluating Complexity of Fetal MEG Signals: A Comparison of Different Metrics and Their Applicability

Julia Moser[1*] Siouar Bensaid[2] Eleni Kroupi[3]
Franziska Schleger[1] Fabrice Wendling[2] Giulio Ruffini[3]
Hubert Preißl[1]

Complexity of Multi-Dimensional Spontaneous EEG Decreases during Propofol Induced General Anaesthesia

Michael Schartner, Anil Seth, Quentin Noirhomme, Melanie Boly, Marie-Aurelie Bruno, Steven Laureys, Adam Barrett

Magnetoencephalographic signatures of conscious processing before birth

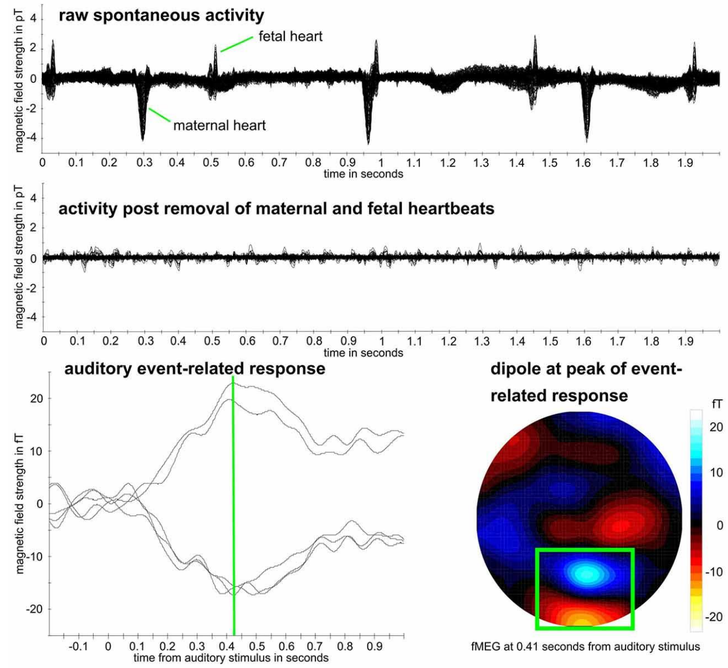
Julia Moser [a b], Franziska Schleger [a], Magdalene Weiss [a c], Katrin Sippel [a d], Lorenzo Semeia [a b], Hubert Preissl [a d e]

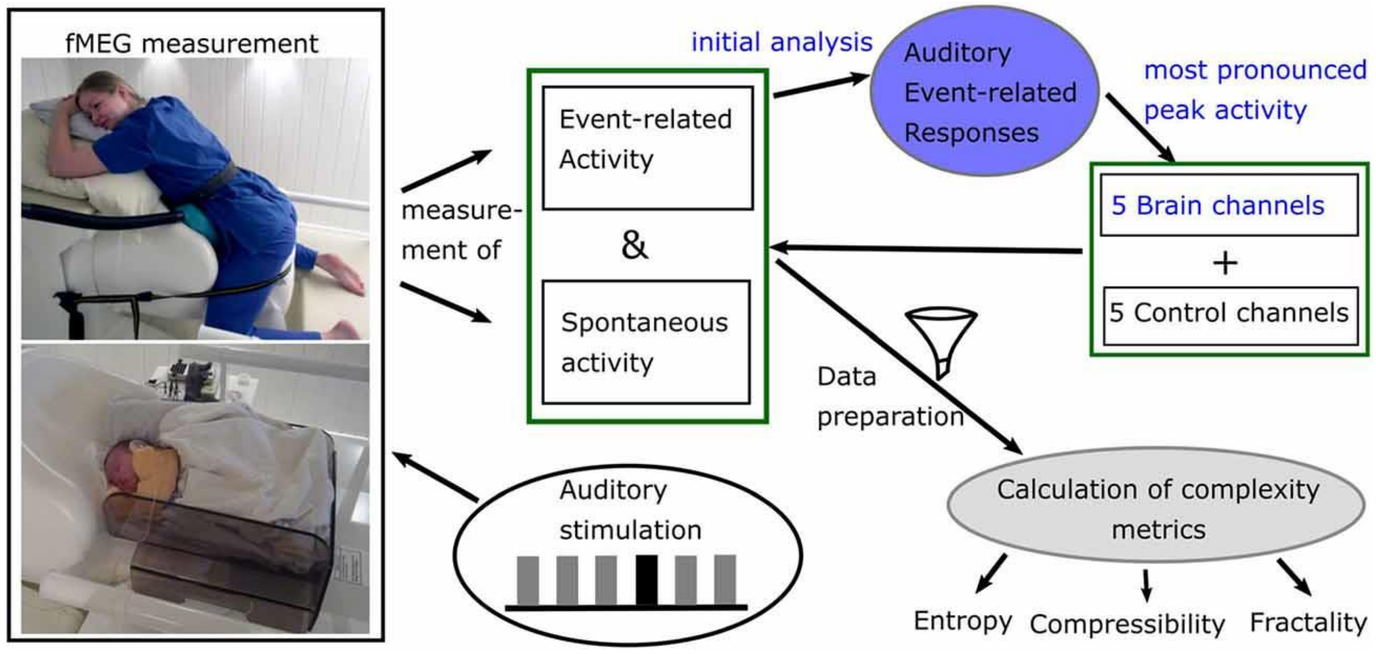
Article | Published: 23 February 2024

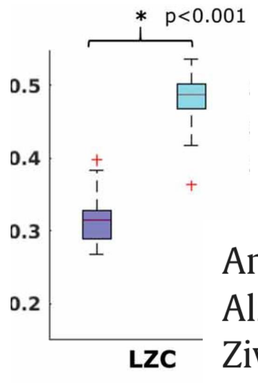
Sex differences in prenatal development of neural complexity in the human brain

Joel Frohlich, Julia Moser, Katrin Sippel, Pedro A. M. Mediano, Hubert Preissl & Alireza Gharabaghi

Nature Mental Health **2**, 401–416 (2024) | Cite this article







Algorithmic Complexity of EEG for Prognosis of Neurodegeneration in Idiopathic Rapid Eye Movement Behavior Disorder (RBD)

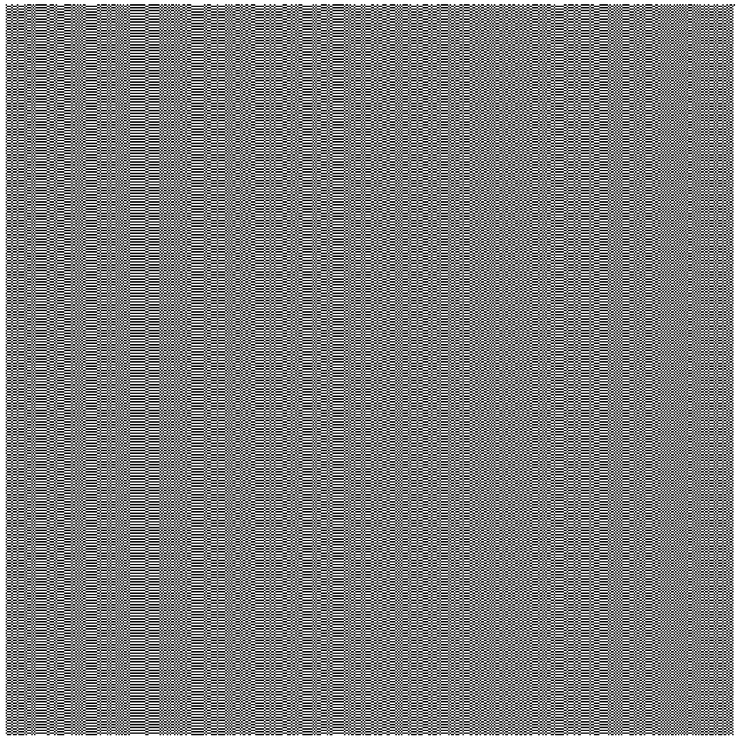
Published: 30 August 2018
Volume 47, pages 282–296, (2019) Cite this article

Analysis of EEG background activity in Alzheimer's disease patients with Lempel–Ziv complexity and central tendency measure

Daniel Abásolo, Roberto Hornero, Carlos Gómez, María García, Miguel López

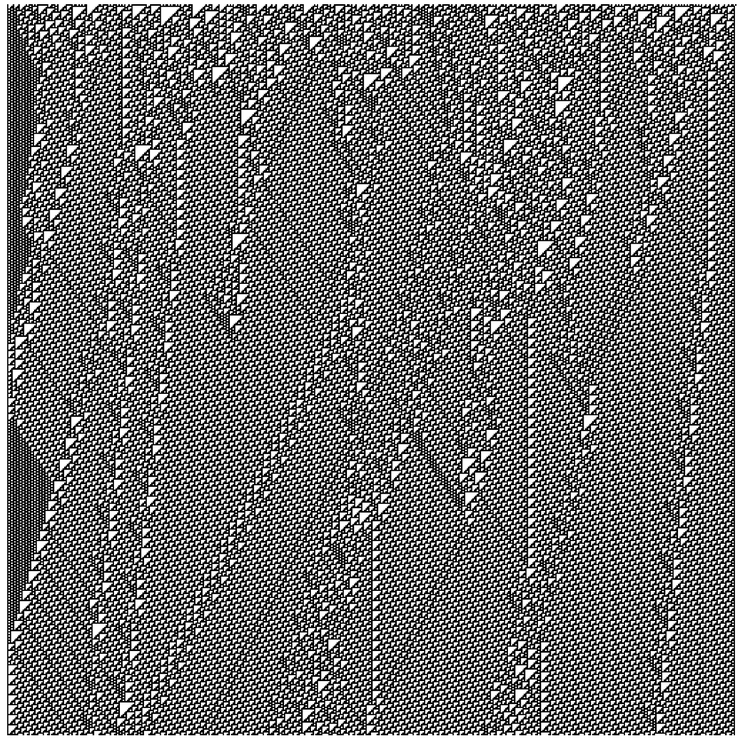
Apparent complexity perspective

ECA Rule 51



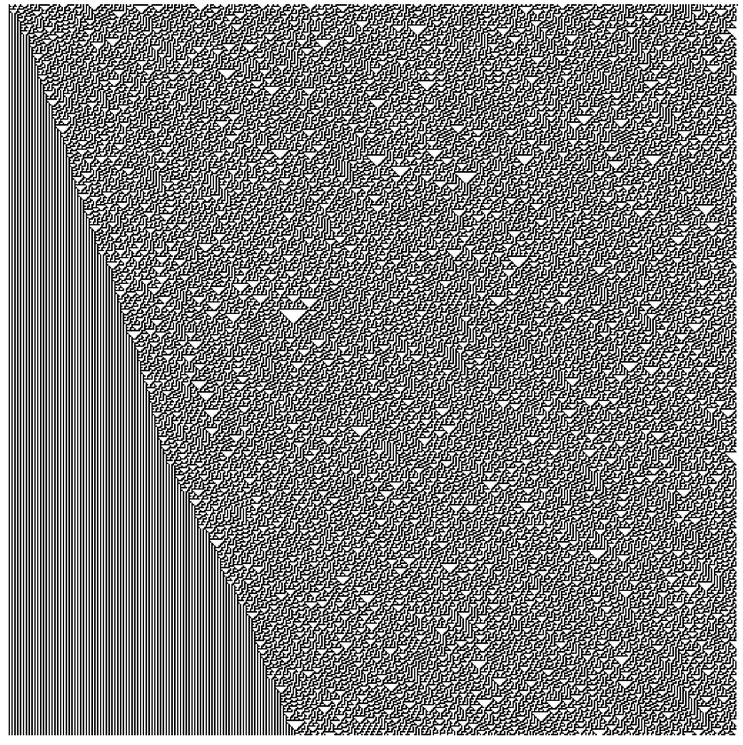
Epilepsy, deep sleep, DOC

ECA Rule 110 (TC)



Healthy wakefulness

ECA Rule 30 (chaotic)



Psychedelics

Complexity, Network Integration, Segregation

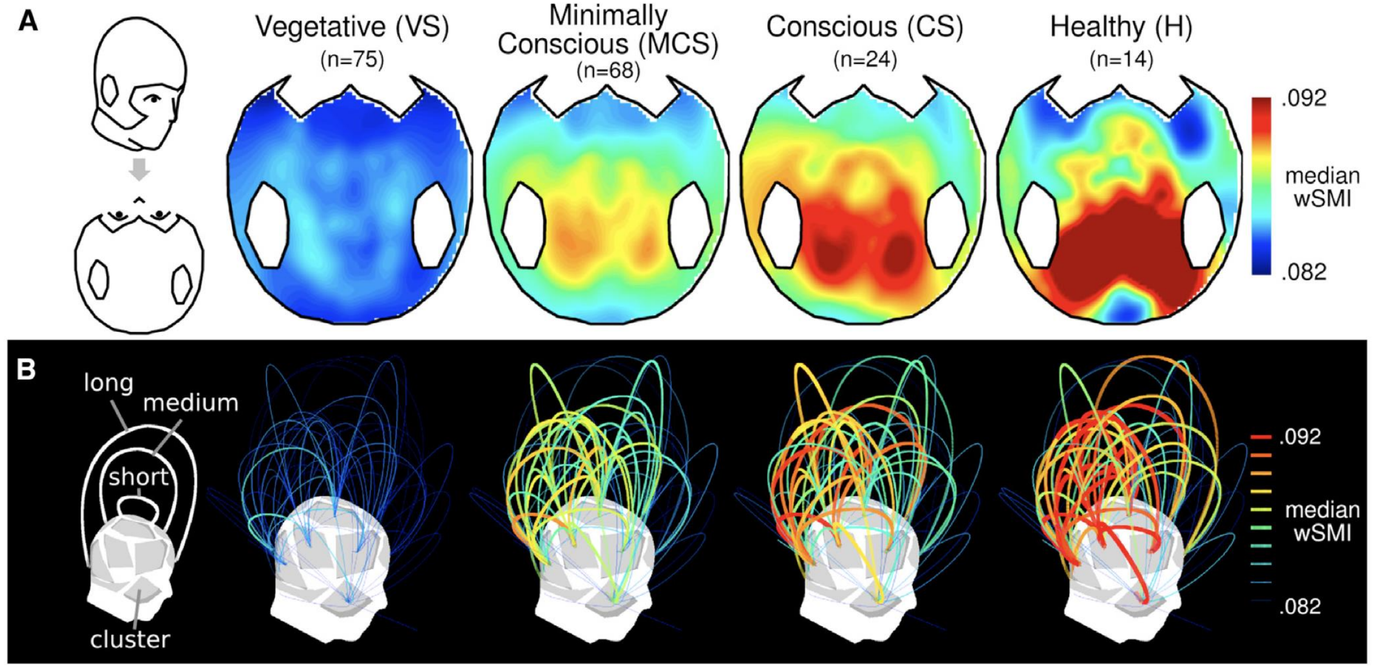
Information Sharing in the Brain Indexes Consciousness in Noncommunicative Patients

Jean-Rémi King,[1,2,3,9,*] Jacobo D. Sitt,[1,2,3,9,*]
Frédéric Faugeras,[3,4] Benjamin Rohaut,[3,8] Imen El Karoui,[3]
Laurent Cohen,[3,4,5] Lionel Naccache,[3,4,5]
and Stanislas Dehaene[1,2,6,7]

patients
those w
studies
stimuli,

Robust EEG-based cross-site and cross-protocol classification of states of consciousness

Denis A. Engemann,[1,2,3,*] Federico Raimondo,[3,4,5,6,*] Jean-Rémi King,[2,7,8]
Benjamin Rohaut,[3,9] Gilles Louppe,[7] Frédéric Faugeras,[3] Jitka Annen,[10] Helena Cassol,[10]
Olivia Gosseries,[10] Diego Fernandez-Slezak,[4,5] Steven Laureys,[10] Lionel Naccache,[3,6]
Stanislas Dehaene[2,11] and Jacobo D. Sitt[3,6]



Quarterly Medical Review - Disorders of consciousness

The current and future contribution of neuroimaging to the understanding of disorders of consciousness

Naji Alnagger [a b], Paolo Cardone [a b], Charlotte Martial [a b], Steven Laureys [a b c],
Jitka Annen [a b 1], Olivia Gosseries [a b 1]

Article | Open access | Published: 24 October 2024

Measuring the dynamic balance of integration and segregation underlying consciousness, anesthesia, and sleep in humans

Hyunwoo Jang, George A. Mashour, Anthony G. Hudetz & Zirui Huang

Computational Circuitry

Propofol Mediated Unconsciousness Disrupts Progression of Sensory Signals through the Cortical Hierarchy

John M Tauber [1,2,3], Scott L Brincat [1,2], Emily P Stephen [4], Jacob A Donaghue [1,2,5], Leo Kozachkov [2], Emery N Brown [1,2,3,5,6,7,#], Earl K Miller [1,2,#,*]

Neural effects of propofol-induced unconsciousness and its reversal using thalamic stimulation

André M Bastos, Jacob A Donoghue, Scott L Brincat, Meredith Mahnke, Jorge Yanar, Josefina Correa, Ayan S Waite, Mikael Lundqvist, Jefferson Roy ... Earl K Miller see all »

Cell

Volume 180, Issue 4, 20 February 2020, Pages 666-676.e13

CellPress

Article

General Anesthesia Decouples Cortical Pyramidal Neurons

Mototaka Suzuki [1, 2], Matthew E. Larkum [1]

REBUS and the Anarchic Brain: Toward a Unified Model of the Brain Action of Psychedelics

R L Carhart-Harris [1,✉], K J Friston [1]

RESEARCH ARTICLE | NEUROSCIENCE

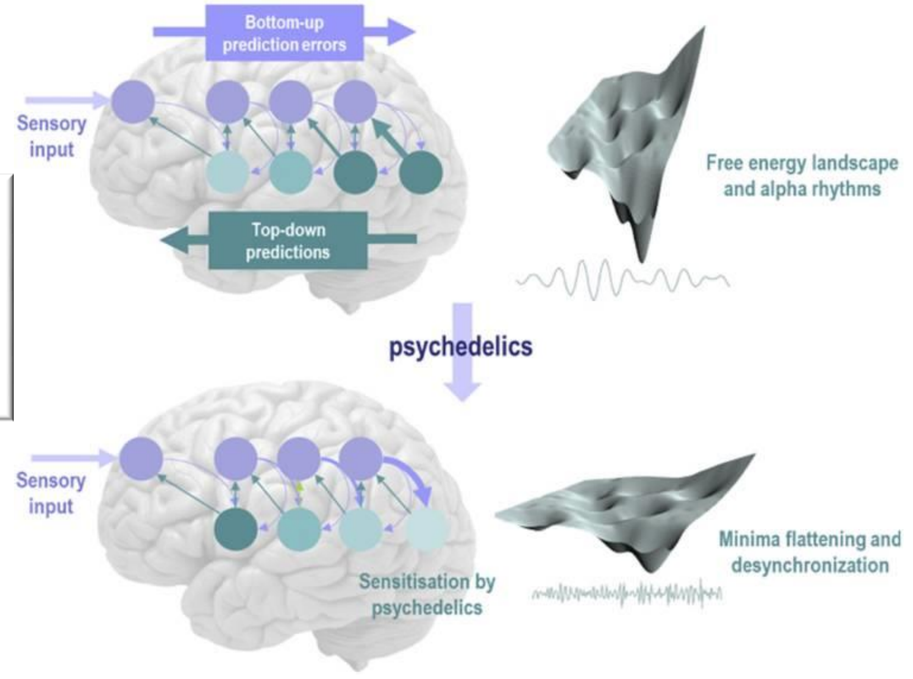
Human brain effects of DMT assessed via EEG-fMRI

Christopher Timmermann, Leor Roseman, Sharad Haridas, +11, and Robin L. Carhart-Harris Authors Info & Affiliations

LSD-induced increase of Ising temperature and algorithmic complexity of brain dynamics

Giulio Ruffini, Giada Damiani, Diego Lozano-Soldevilla, Nikolas Deco, Fernando E. Rosas, Narsis A. Kiani, Adrián Ponce-Alvarez, Morten L. Kringelbach, Robin Carhart-Harris, Gustavo Deco

Hierarchical predictive coding

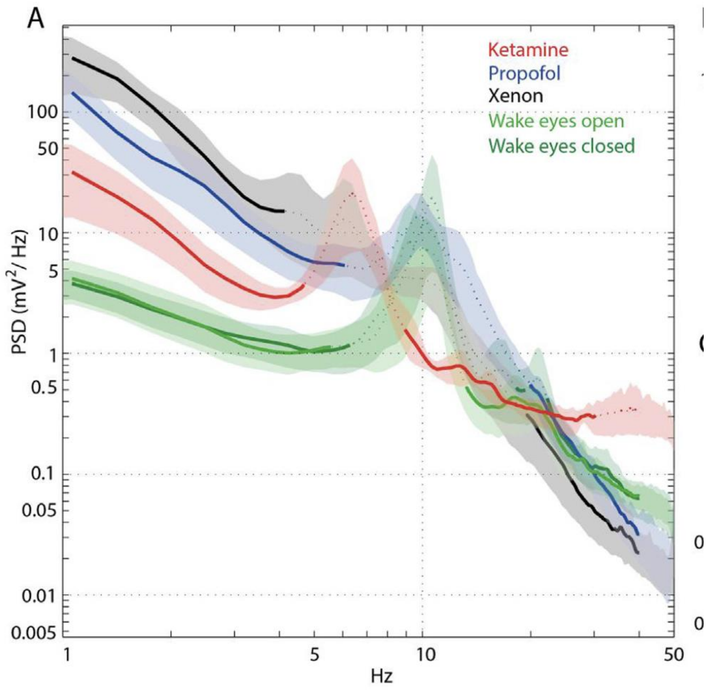


Criticality: prerequisite for healthy computation?

The spectral exponent of the resting EEG indexes the presence of consciousness during unresponsiveness induced by propofol, xenon, and ketamine

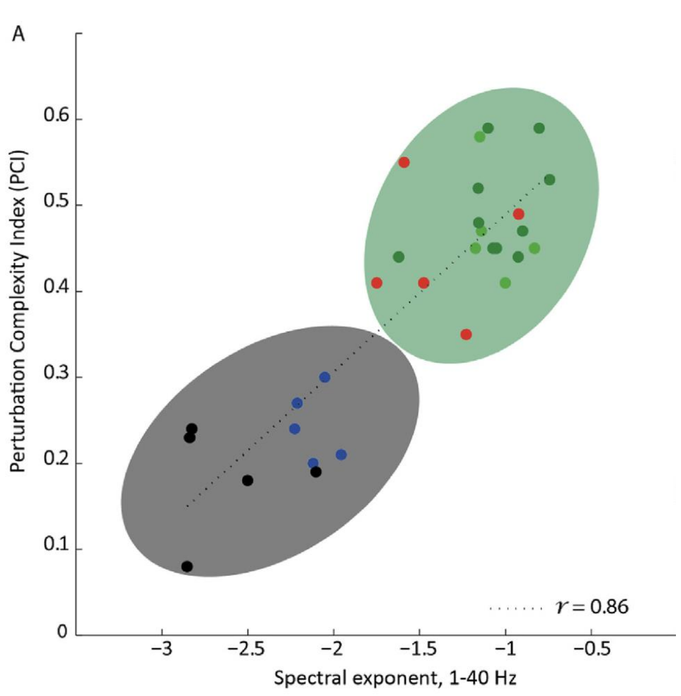
Michele Angelo Colombo [a,*], Martino Napolitani [b,c], Melanie Boly [d], Olivia Gosseries [e], Silvia Casarotto [b], Mario Rosanova [b,f], Jean-Francois Brichant [g], Pierre Boveroux [g], Steffen Rex [h], Steven Laureys [e], Marcello Massimini [b,i], Arturo Chieregato [a], Simone Sarasso [b,**]

[a] Neurosurgical Intensive Care, ASST Grande Ospedale Metropolitano Niguarda, Milan, 20162, Italy
[b] Dipartimento di Scienze Biomediche e Cliniche "L. Sacco", Università Degli Studi di Milano, 20157 Milan, Italy



LSD-induced increase of Ising temperature and algorithmic complexity of brain dynamics

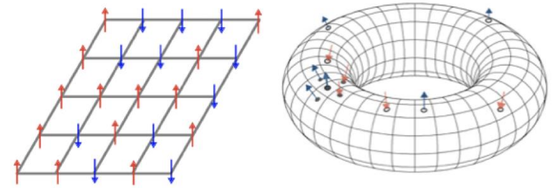
Giulio Ruffini, Giada Damiani, Diego Lozano-Soldevilla, Nikolas Deco, Fernando E. Rosas, Narsis A. Kiani, Adrián Ponce-Alvarez, Morten L. Kringelbach, Robin Carhart-Harris, Gustavo Deco



The 2D Ising model, criticality and AIT

G. Ruffini[a,b,*], G. Deco[c]

2D Ising model

Nodes	spins σ_i
Links	neighbor coupling
System	
Temperature	T

The Challenge

We are missing a principled, unifying framework to define and operationalize **what** we want to measure and understand what its physiological signatures are – **how** to measure it.

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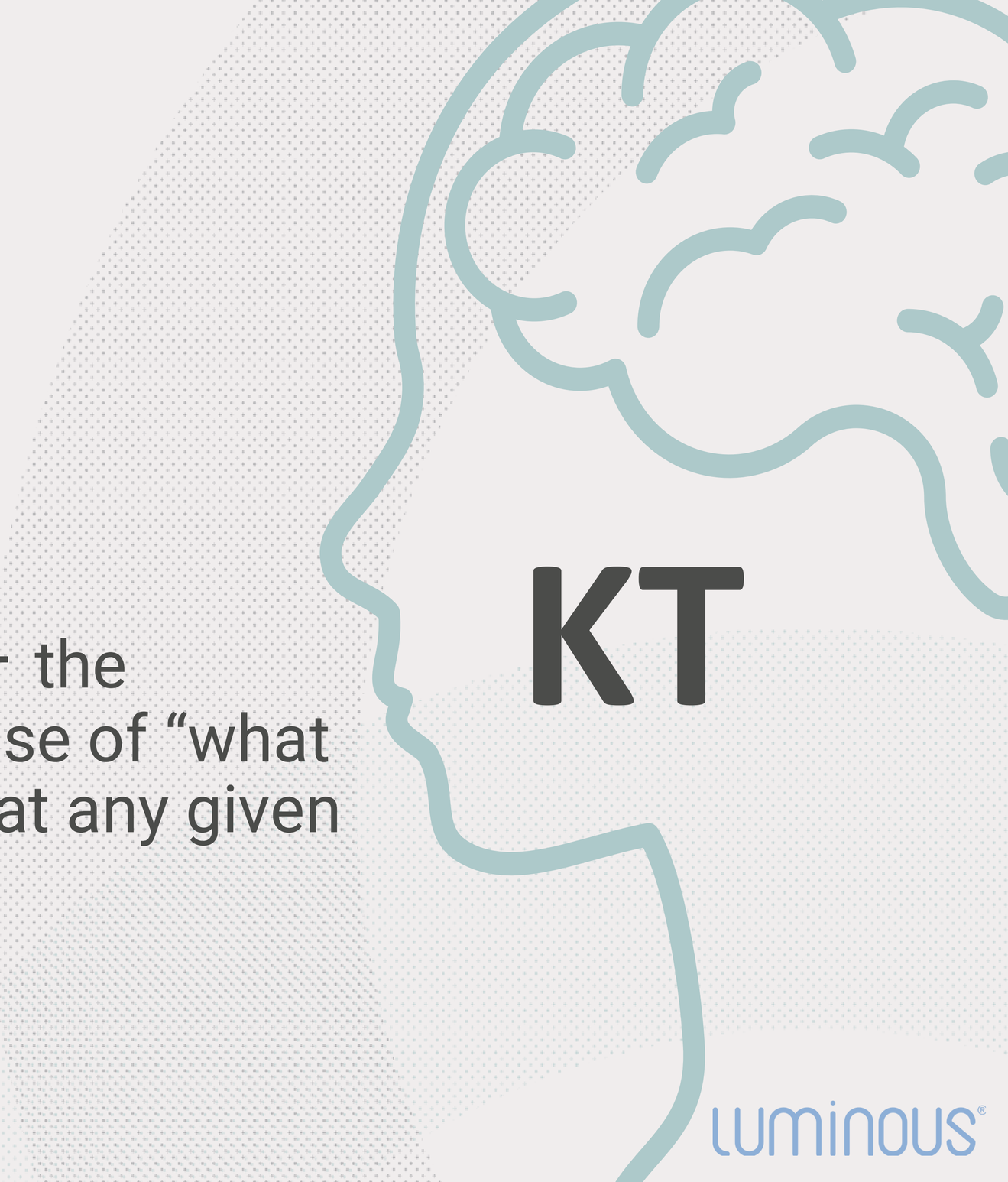
Kolmogorov Theory of Consciousness



1. **There is Experience** – the immediate, subjective sense of “what it feels like” to be oneself at any given moment.

2. Focus on **Structured Experience**

What is *structured experience*?

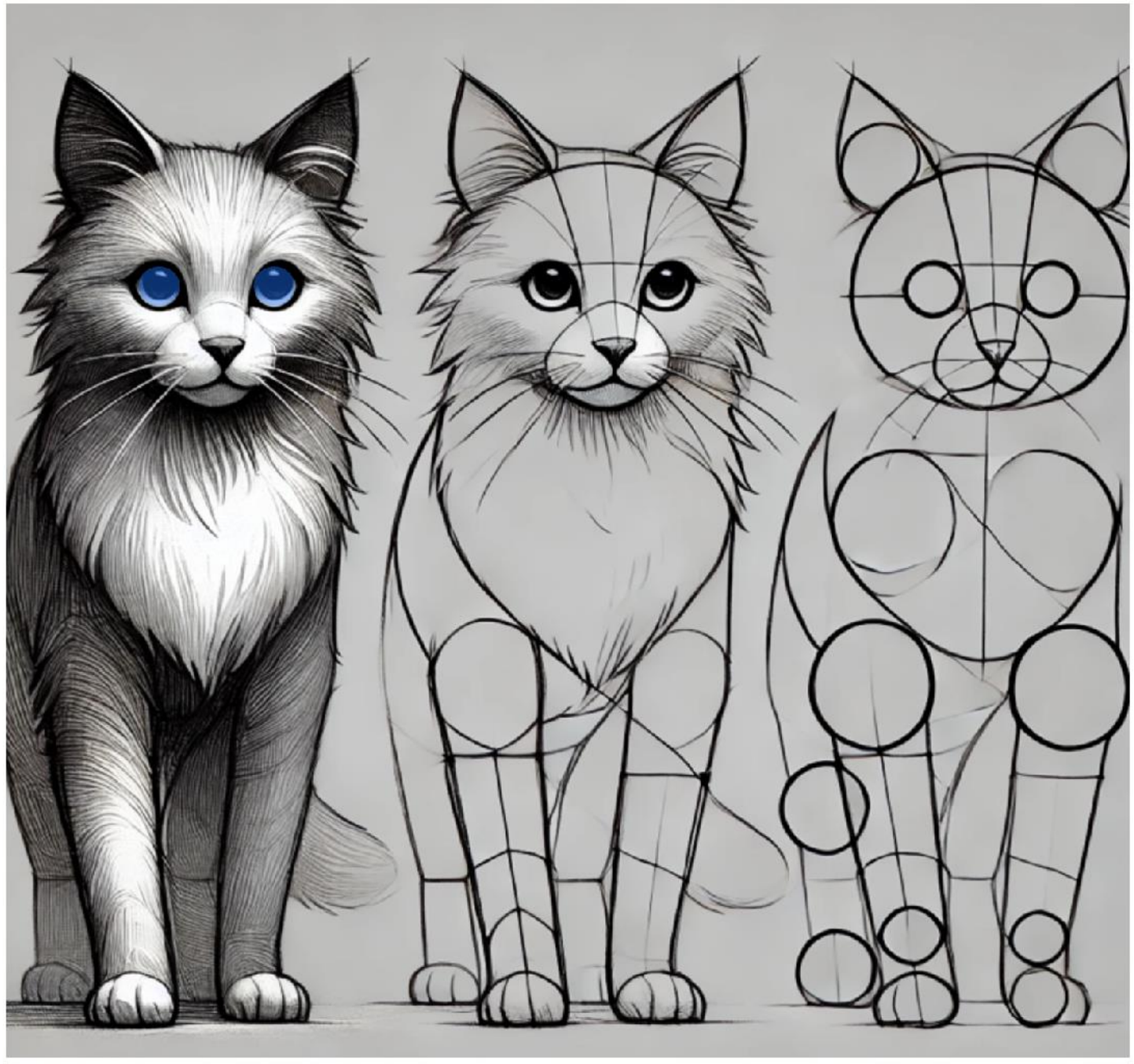
The spatial, temporal, and conceptual organization of our first-person experience of the world and of ourselves as agents in it.

An algorithmic information theory of consciousness

Giulio Ruffini

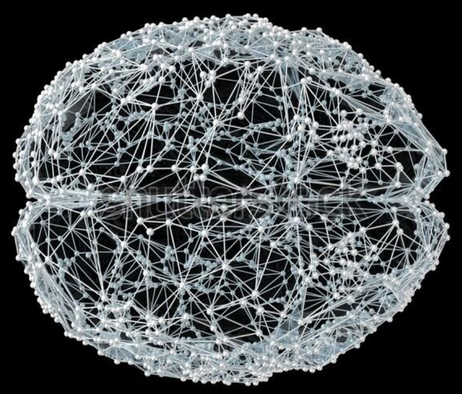
Neuroscience of Consciousness, Volume 2017, Issue 1, 2017, nix019,
https://doi.org/10.1093/nc/nix019

Coarse-graining, compressing to extract useful structure

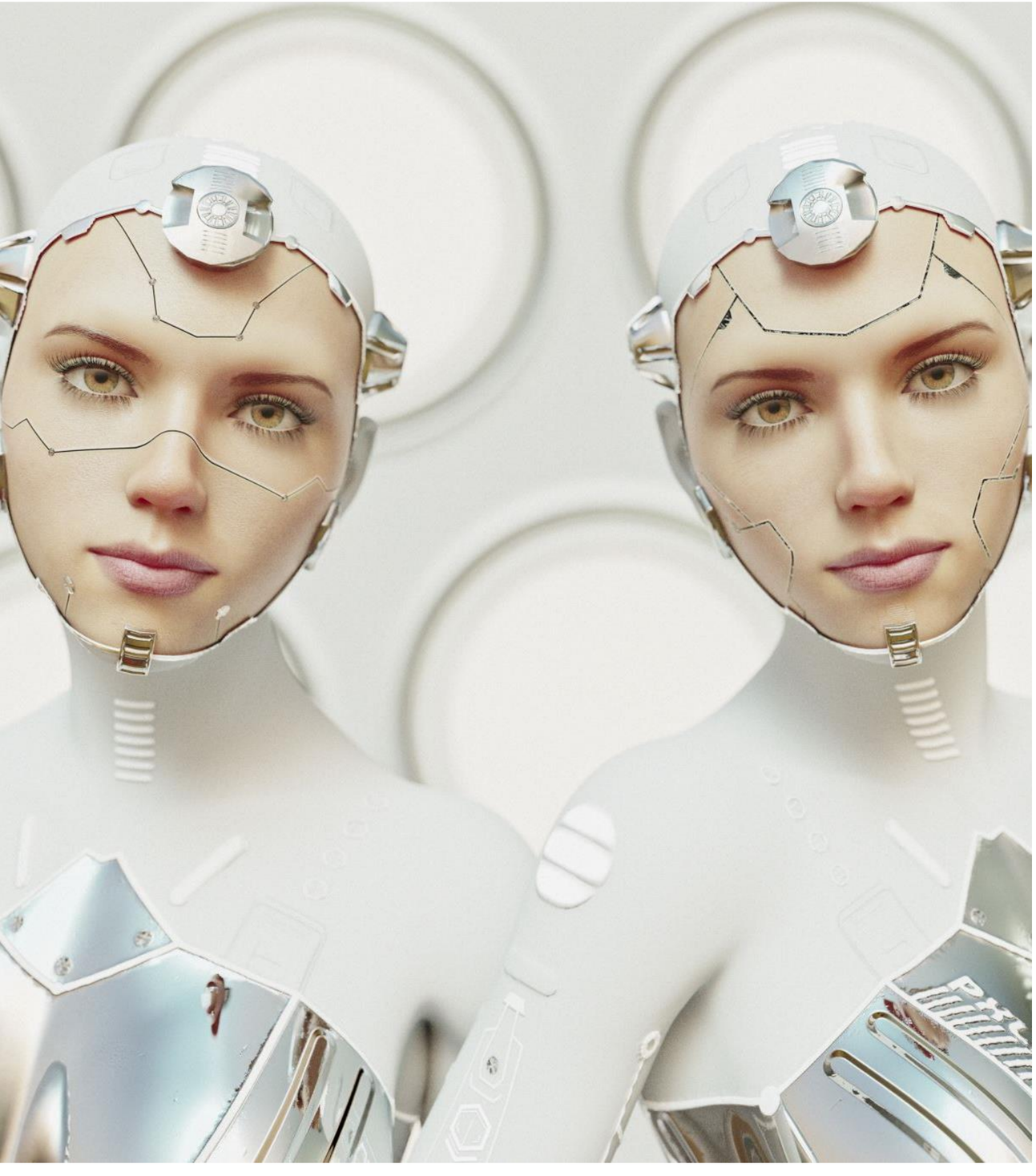


What is special about brains?

#1 High Mutual Algorithmic Information with the world



#2 They compute: modeling and decision making



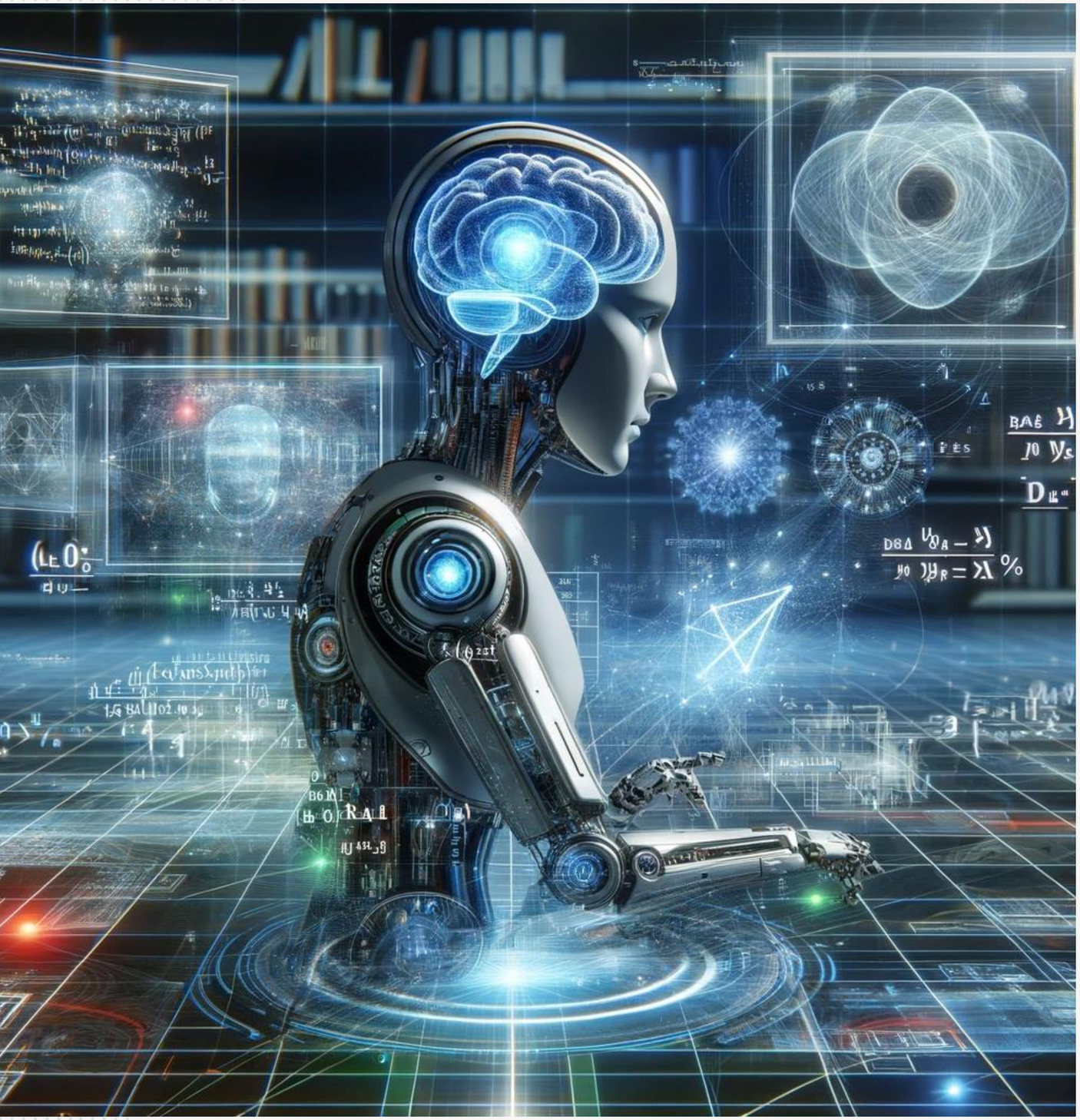
KT in a Nutshell

Ask what creates *structured experience* in an *algorithmic* context

A. Evolution gives rise to *agents* (and we are agents)

B. Agents run *models of the world* and enjoy structured experience!

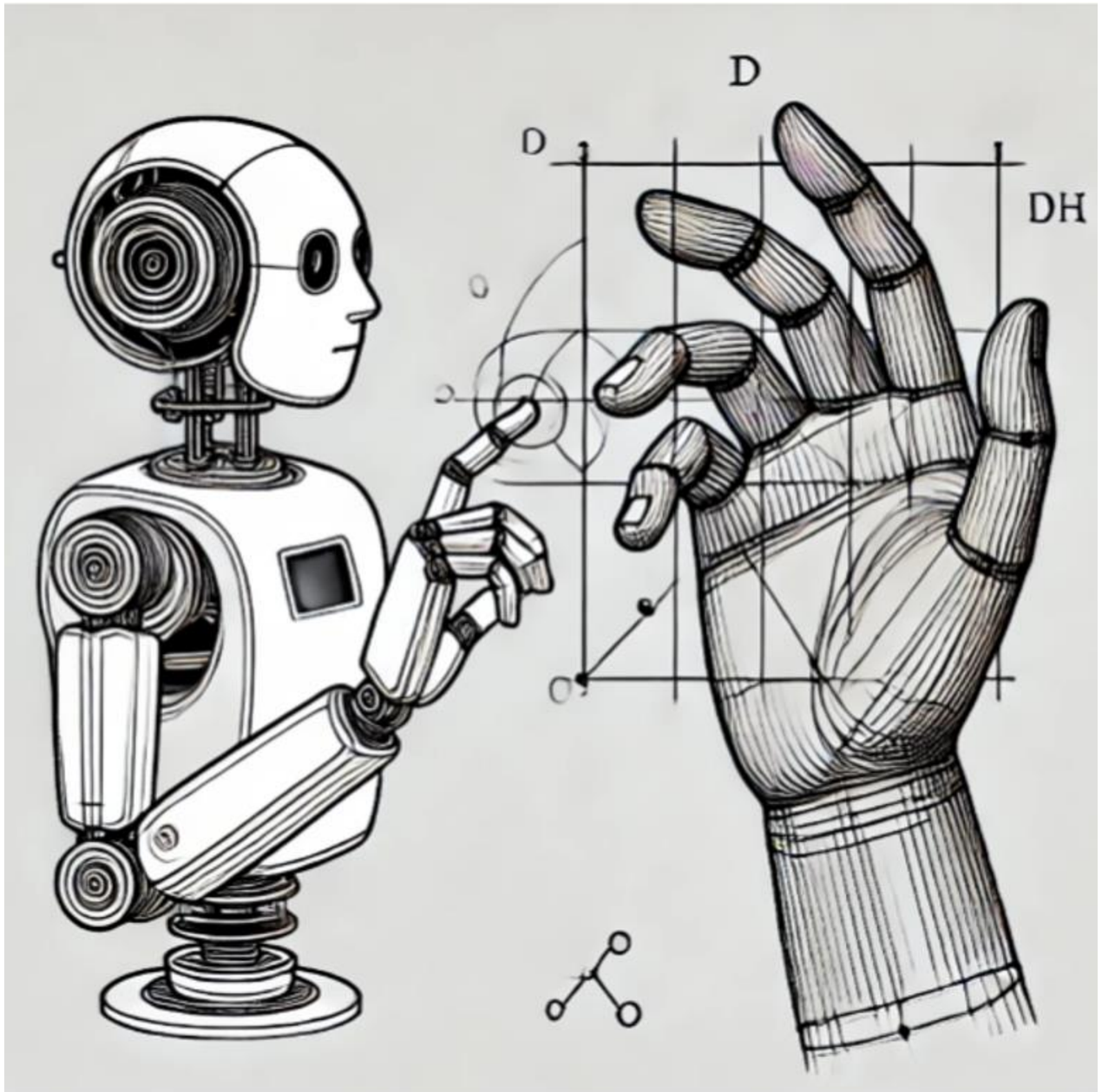
C. Agents have *goals*. This gives origin to *valence* & *emotions*

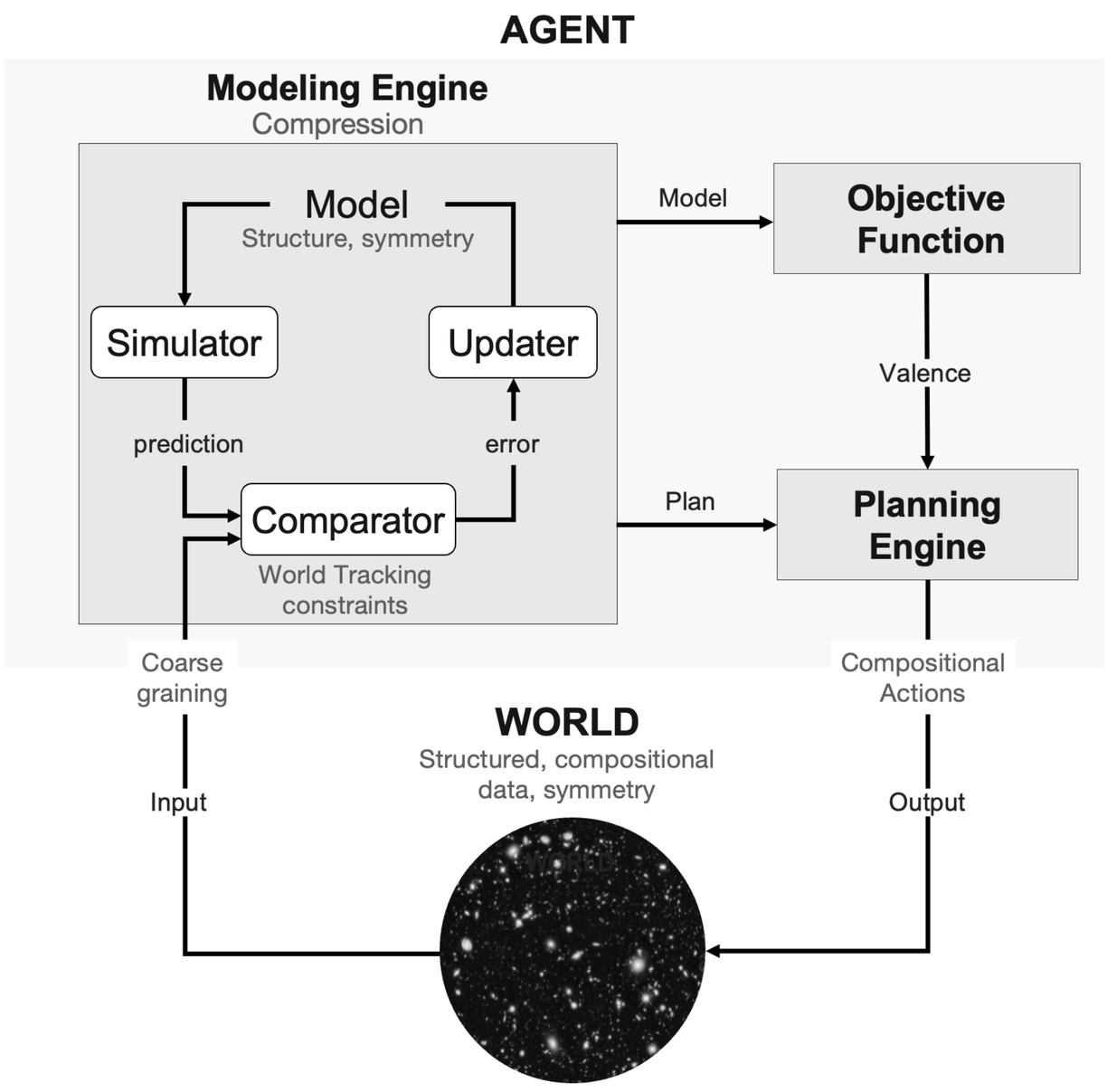


What is an algorithmic *agent*?

A computational system that interacts effectively with its environment by **planning** actions using **compressive predictive models** to maximize an **objective function**.

Using a model entails ***computation*** and ***dynamics***.





Open Access Perspective

The Algorithmic Agent Perspective and Computational Neuropsychiatry: From Etiology to Advanced Therapy in Major Depressive Disorder

by Giulio Ruffini [1,*], Francesca Castaldo [1,*], Edmundo Lopez-Sola [1,2], Roser Sanchez-Todo [1,2] and Jakub Vohryzek [2,3]

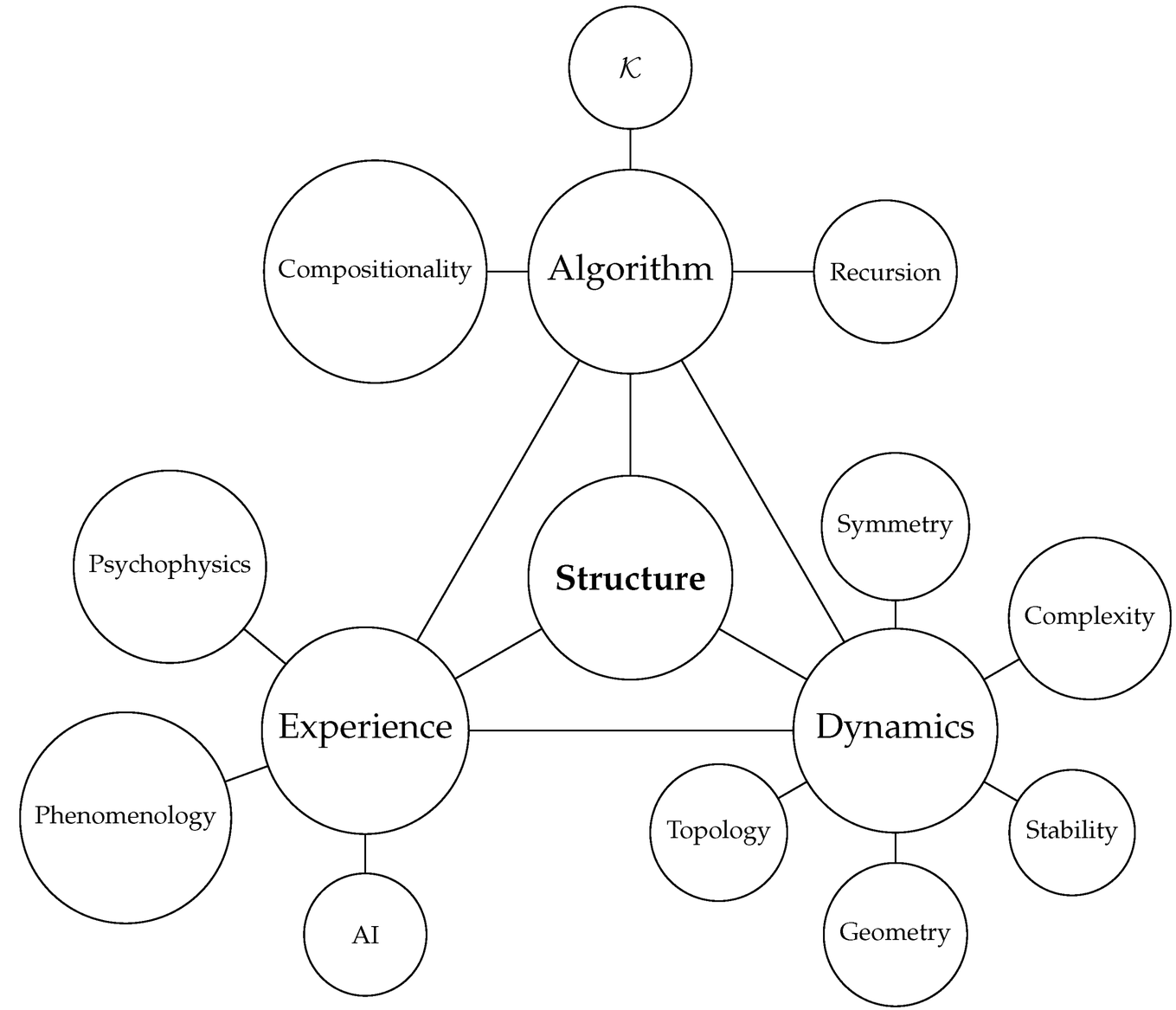
The central hypothesis in KT

An agent has **structured experience** ($\mathcal{S}$) to the extent it has access to encompassing and **compressive models** to interact with the world.

More specifically, **the event of structured experience arises in the act of running models**.

Model structure determines **the structure of experience**.

Successful comparison with data leads to **wakeful presence**.



How do we define **model structure**?

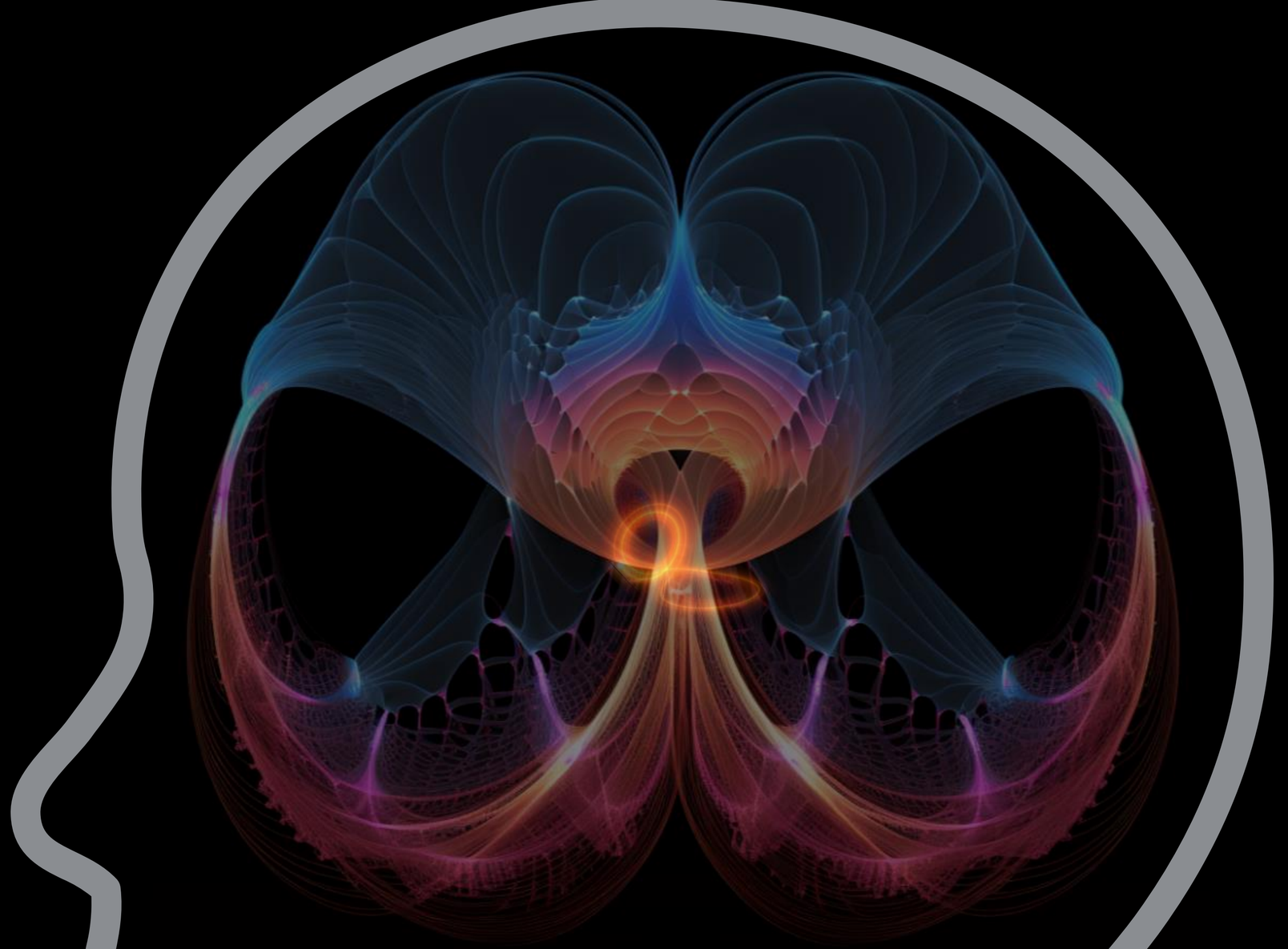
Formalize *model* using **group theory,** capturing the idea of **simplicity** as **symmetry**. Then, we can show that

1) Tracking the world forces the agent as a dynamical system to mirror the symmetry in the data. Dynamics collapses to **reduced manifolds**.
2) The hierarchical nature of world data leads to **coarse-graining** and the notion of hierarchical constraints and manifolds

Open Access Article

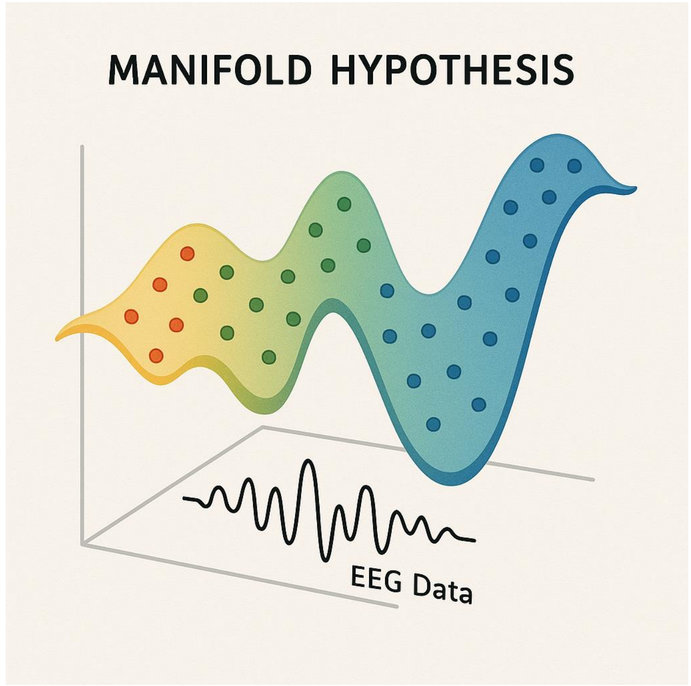
Structured Dynamics in the Algorithmic Agent

by Giulio Ruffini [1,*], Francesca Castaldo [1] and Jakub Vohryzek [2,3]



Structured Experience

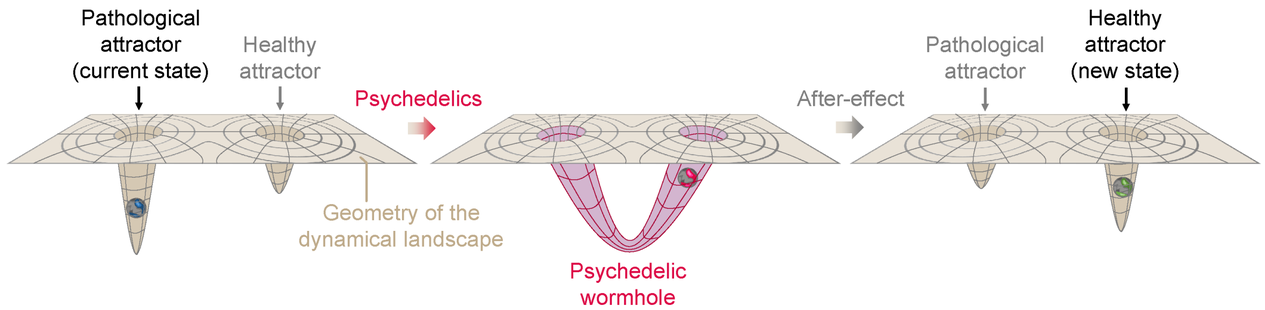
Tool 1: Topology, Group Theory



Open Access Perspective

Neural Geometrodynamics, Complexity, and Plasticity: A Psychedelics Perspective

by Giulio Ruffini [1,*], Edmundo Lopez-Sola [1,2], Jakub Vohryzek [2,3] and Roser Sanchez-Todo [1,2]



Netw Neurosci. 2019 Jul 1;3(3):725–743. doi: 10.1162/netn_a_00080

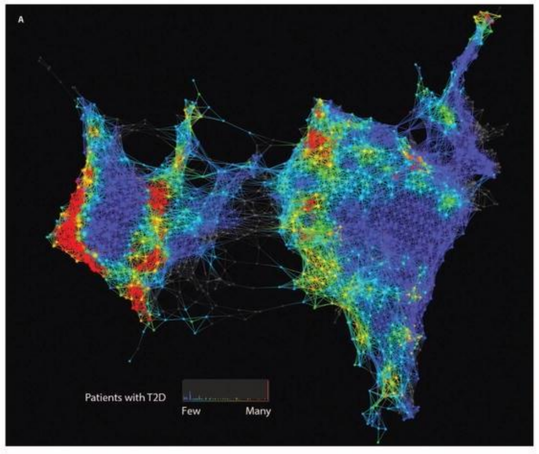
Topological exploration of artificial neuronal network dynamics

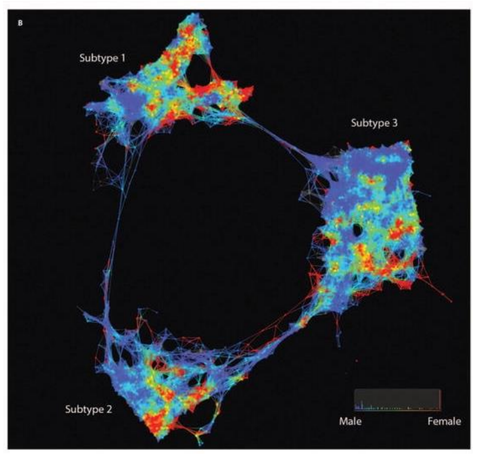
Jean-Baptiste Bardin [1], Gard Spreemann [2], Kathryn Hess [3,*]

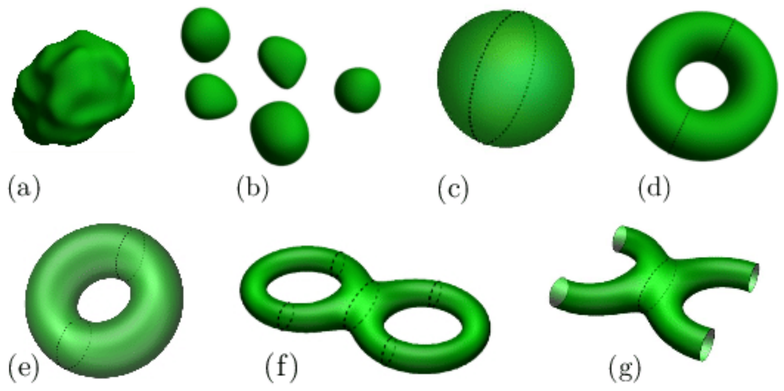
Open Access Article

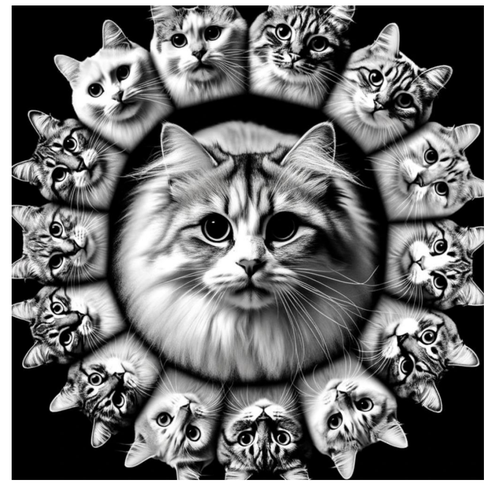
Structured Dynamics in the Algorithmic Agent

by Giulio Ruffini [1,*], Francesca Castaldo [1] and Jakub Vohryzek [2,3]

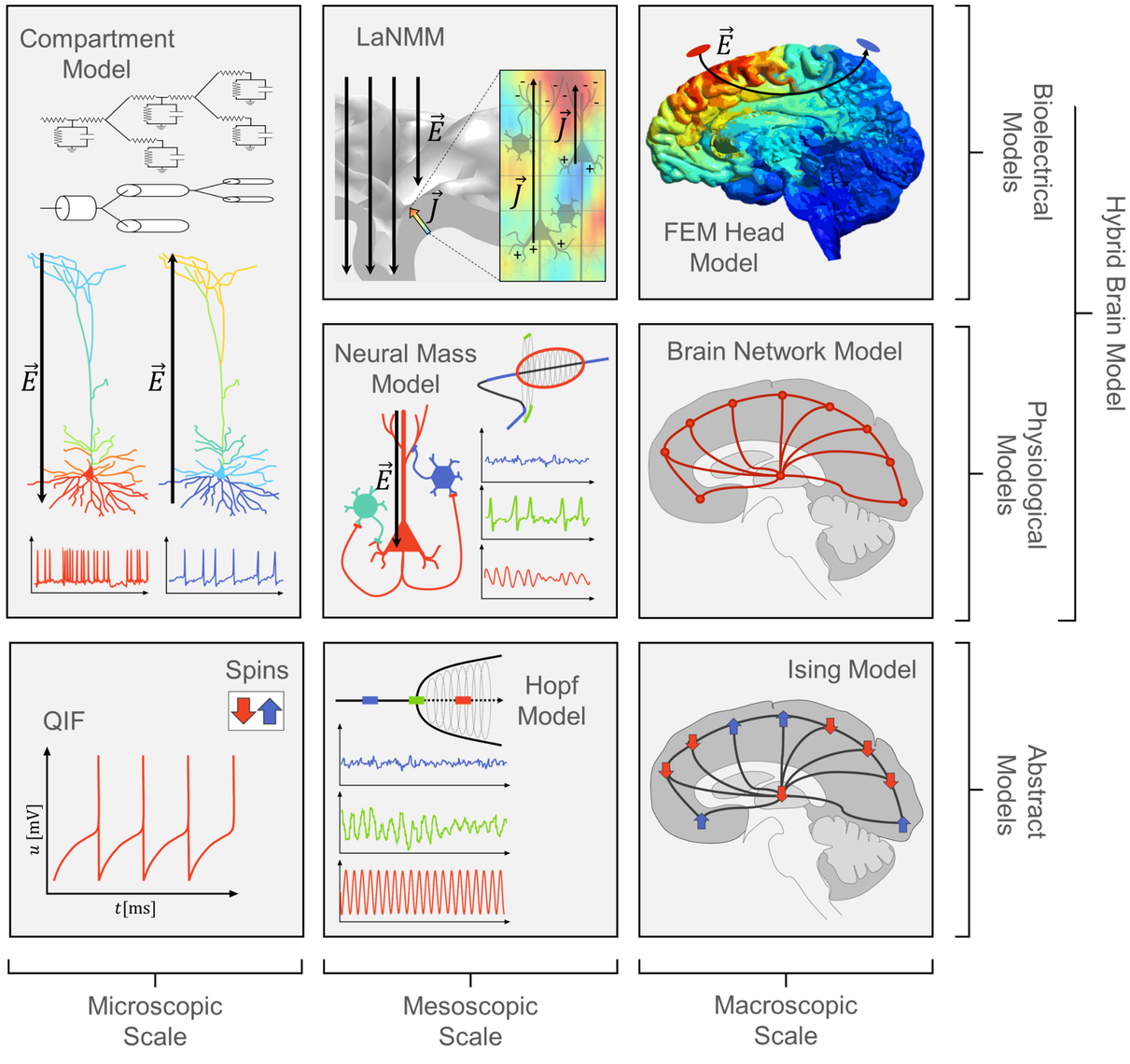




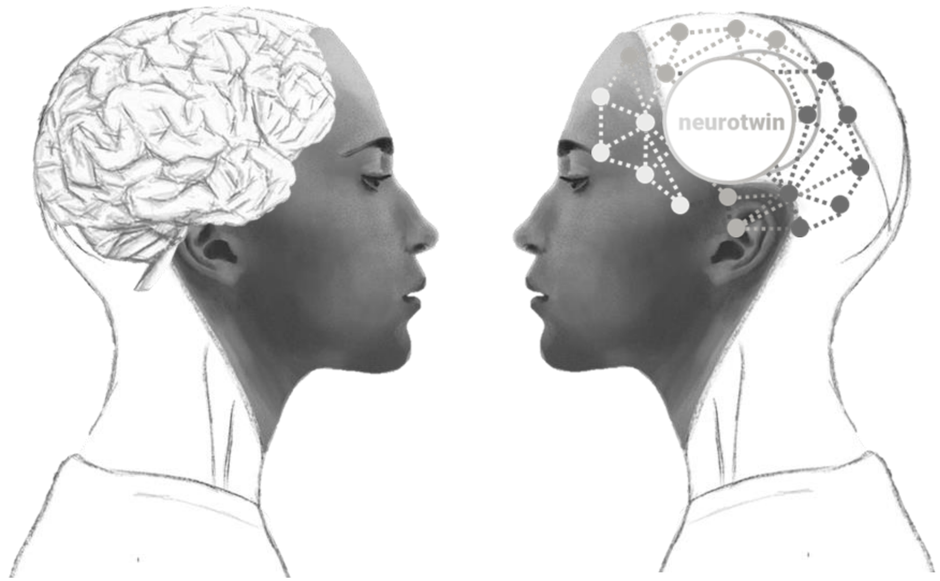




Tool 2: Computational Modeling, Criticality



Aim: Mechanistic interpretation of brain data using whole-brain computational models. The brain as computer – requirements.



Summary

1) We focused on the requirements for *structured experience*
2) EEG/MEG/tES/TMS can all be used, in principle, to measure and alter structured experience in the electrical brain.
3) Tracking the world requires computation to run models
4) This constrains brain structure and also collapses dynamics to reduced manifolds, the characteristics of which are good candidates for “neural correlates of structured experience (NCSE)”

Special Issue

The Mathematics of Structured Experience: Exploring Dynamics, Topology, and Complexity in the Brain

Guest Editors

Dr. Giulio Ruffini
Dr. Johannes Kleiner
Dr. Ryota Kanai

Deadline

20 March 2026

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Thank You

Scan me!

Dr. Giulio Ruffini
Co-founder & CTO
Starlab/Neuroelectrics
giulio.ruffini@neuroelectrics.com

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The Science of Consciousness, Barcelona, July 6, 2025