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PIANO NAZIONALE DI RIPRESA E RESILIENZA
INFN

Simulations of learning, consciousness, dreaming and deep sleep

Pier Stanislao Paolucci,

APE Lab, INFN Roma

…on behalf of many authors,

see **last** slide

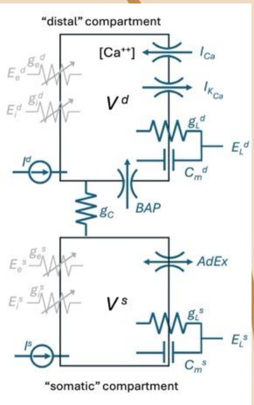
Bari – Computing@CNS5

Oct 10th, 2024

Contributing to CNS5 BRAINSTAIN project

Novel two-compartment spiking neuron supporting brain-state specific apical mechanisms, …

$$
\begin{cases}
\begin{cases}
C_m^s \frac{dV^s}{dt} &= -g_L^s(V^s - E_L^s) + g_L^s \Delta_T \exp\left(\frac{V^s - V_{th}^s}{\Delta_T}\right) + \\
& -g_e^s(t)(V^s - E_e^s) - g_i^s(t)(V^s - E_i^s) + \\
& -w + I_e^s - g_C(V^s - V^d) \\
\tau_w \frac{dw}{dt} &= a(V^s - E_L^s) + b\sum_k \delta(t - t_k) - w
\end{cases} \\
\begin{cases}
C_m^d \frac{dV^d}{dt} &= -g_L^d(V^d - E_L^d) - g_e^d(t)(V^d - E_e^d) - g_i^d(t)(V^d - E_i^d) + \\
& +I_{Ca} + I_{K_{Ca}} + w_{BAP}\sum_k \delta(t - (t_k + d_{BAP})) + \\
& +I_e^d + g_C(V^d - V^s) \\
\frac{d[Ca]}{dt} &= \phi_{Ca} I_{Ca} + \frac{[Ca] - [Ca]_0}{\tau_{Ca}}
\end{cases}
\end{cases}
$$



… for real-time incremental learning through Spike Timing Dependent Plasticity (in spiking networks)

… and ThetaPlanes: piecewise transfer function for bio-inspired artificial intelligence

$$\nu_F(I_s, I_d; \nu) = \Theta_\rho(1 - \Theta_H) \cdot \nu_- + \Theta_H \cdot \nu_+$$

INFN and Computing @CNS5: a leading role in European foundational and applied research on brain cognition, next gen bio-AI, related HPC systems and tools

Computational neuroscience (and its application to AI) is the realm of physicists, and specialists in parallel, distributed, and cloud computing. INFN Roma and INFN Cagliari played a leadership role in the **Human Brain Project** and now continue their work in the **EBRAINS** infrastructure, the **FAIR** (Future AI Research) partnership and the **CNS5 Brainstain** projects. See also **RED-SEA, TEXTAROSSA**, **DARE** (openHW/SW RISC-V based), **NET4EXA** (interconnect for EXASCALE).

During this workshop:

Mechanisms underlying **Brain Cognition and Consciousness** with a focus on those enabling **incremental learning and sleep** in Thalamo-cortico-hippocampal systems…towards **Bio – inspired next generation explicable Artificial Intelligence** (*this presentation*)

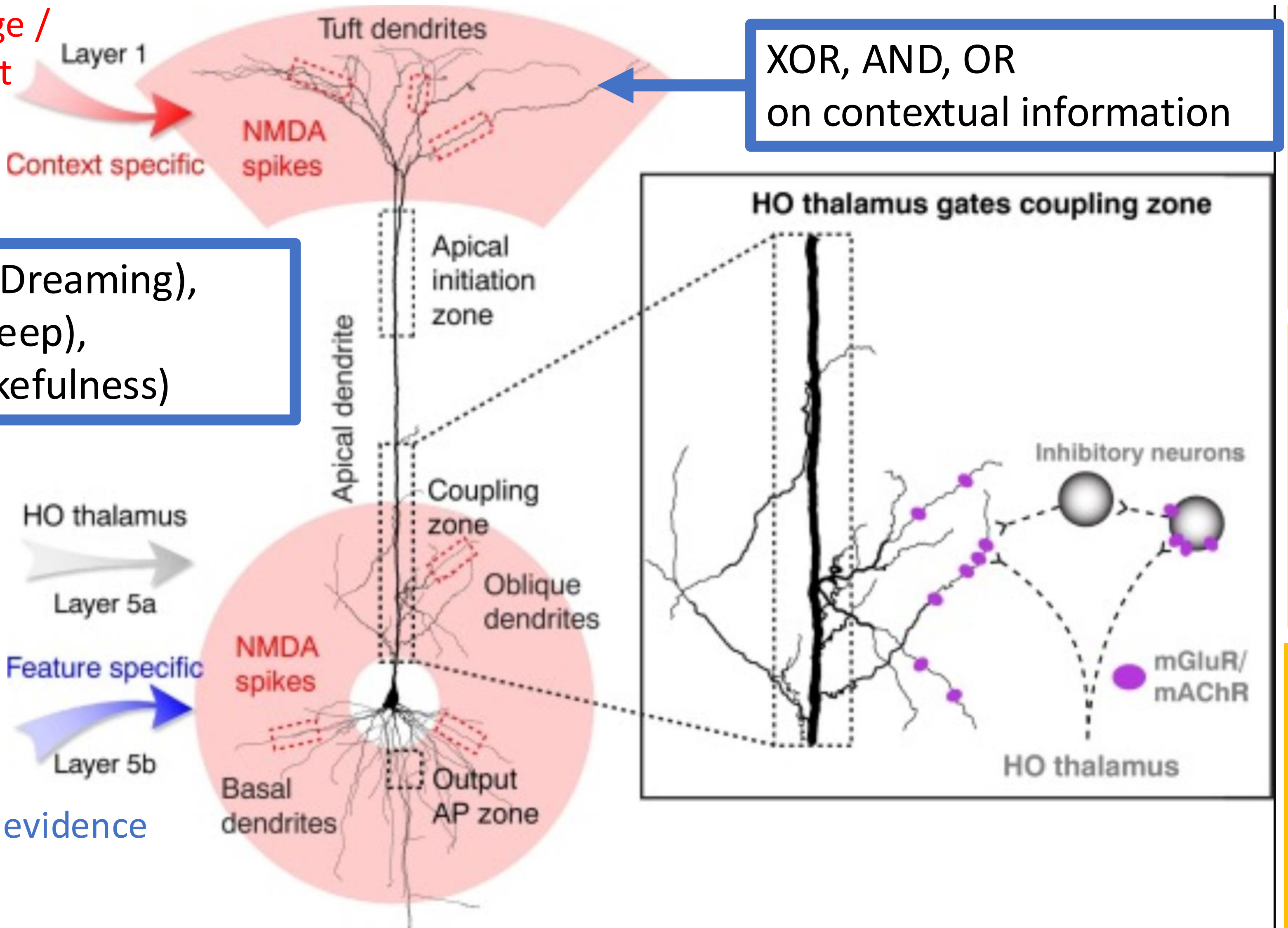
Analysis worflows for brain activity applicable to both experimental data acquired with multiple-methodologies and at multiple spatio-temporal scales and simulation outputs, and for their comparison (*see Cosimo Lupo presentation*)

Models of working memories, multi-area visual systems, and simulations engines for largest multi-area networks on thousands GPUs systems (NEST-GPU) (*see Gianmarco Tiddia presentation*)

Design of interconnection and acceleration technologies for simulations, analysis and bio-AI (*see Andrea Biagioni presentation)*

Pyramidal neurons are NOT point like entities. Also, they have brain-state dependent neural mechanisms supporting conscious / unconscious processing.

Prior knowledge / specific context



XOR, AND, OR
on contextual information

Apical Drive (REM Dreaming),
Isolation (NREM sleep),
Amplification (Wakefulness)

100 micron

Incoming evidence

Integration of prior knowledge and specific context with novel incoming evidence

Trends in Cognitive Sciences

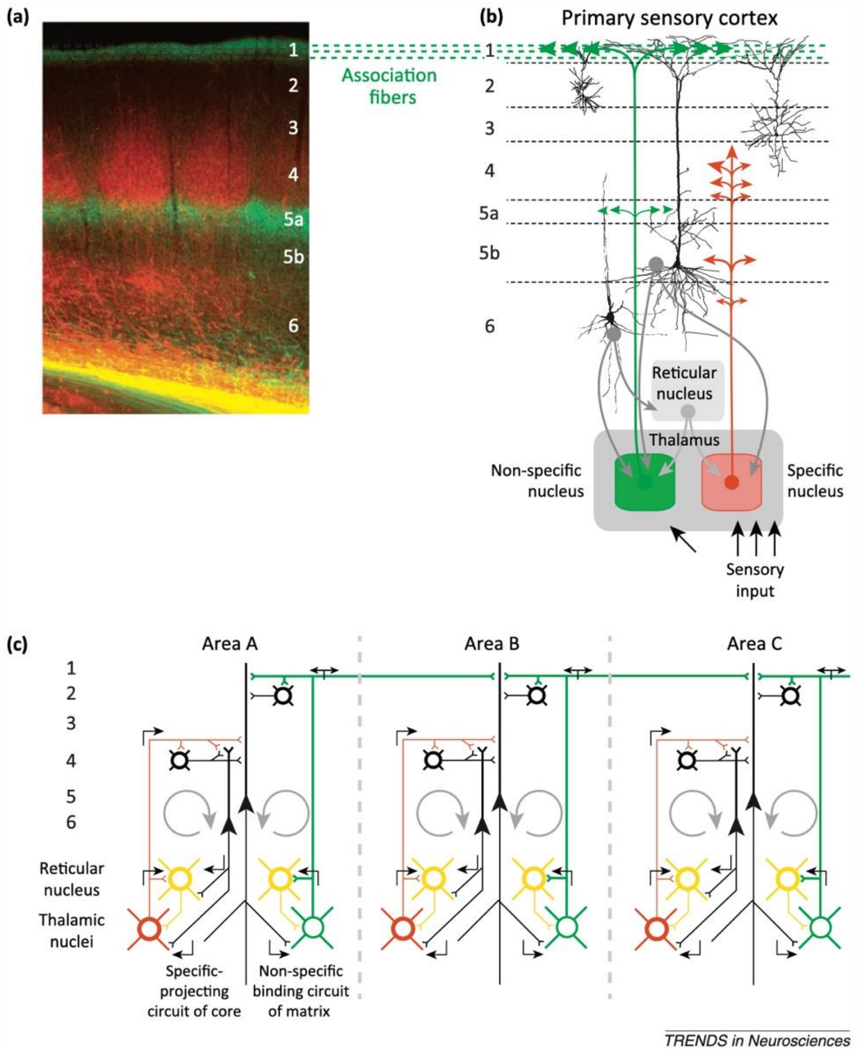
W. A. Phillips (2023)
The Cooperative Neuron. Cellular Foundations of Mental Life.
Oxford University Press

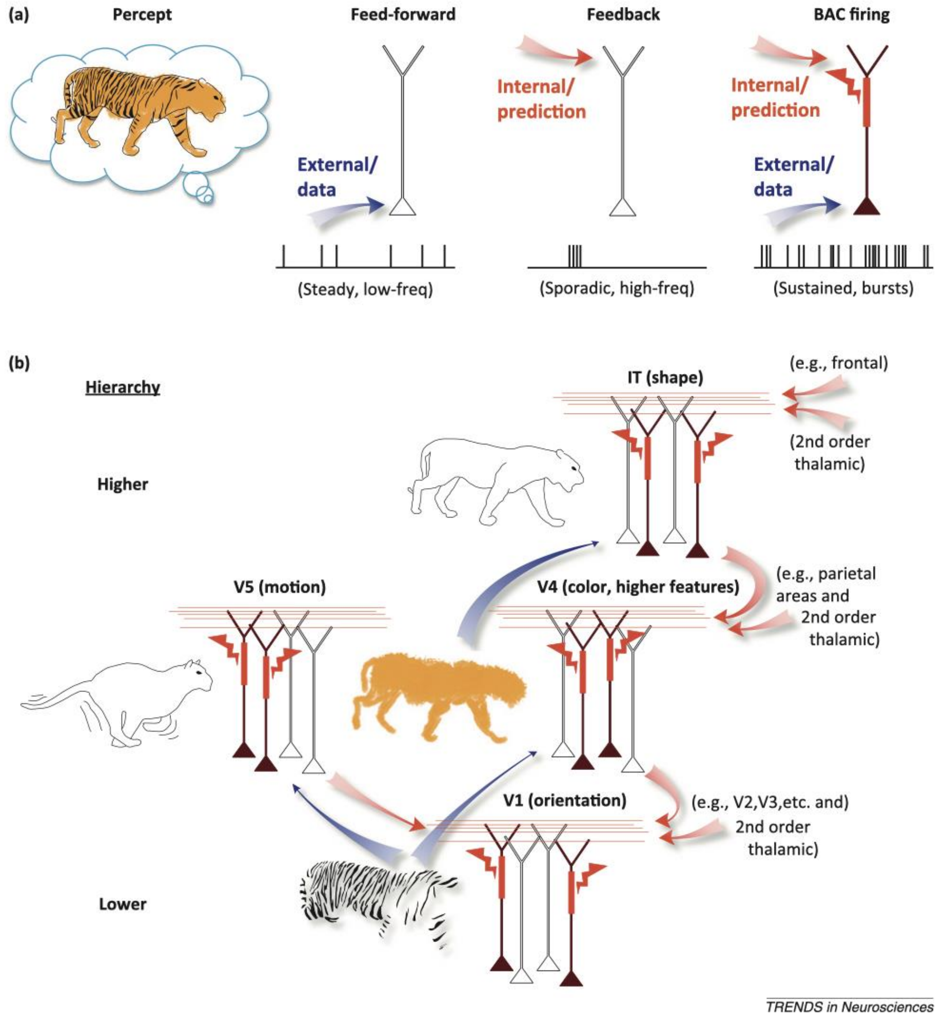
J. Aru, M. Suzuki, M. E. Larkum, (2020)
Cellular Mechanisms of Conscious Processing
Trends in Cognitive Sciences

J. Aru, F. Siclari, W. A. Phillips, J. F. Storm (2020)
Apical drive—A cellular mechanism of dreaming?
Neuroscience & Biobehavioral Reviews

Connectomic supporting integration of priors and evidence

experience by integration of internal and external information in a multi-area system





Larkum, M. A cellular mechanism for cortical associations: an organizing principle for the cerebral cortex. *Trends in Neurosciences*, 36 (2013), 141.

PNAS

(2023)

RESEARCH ARTICLE | NEUROSCIENCE

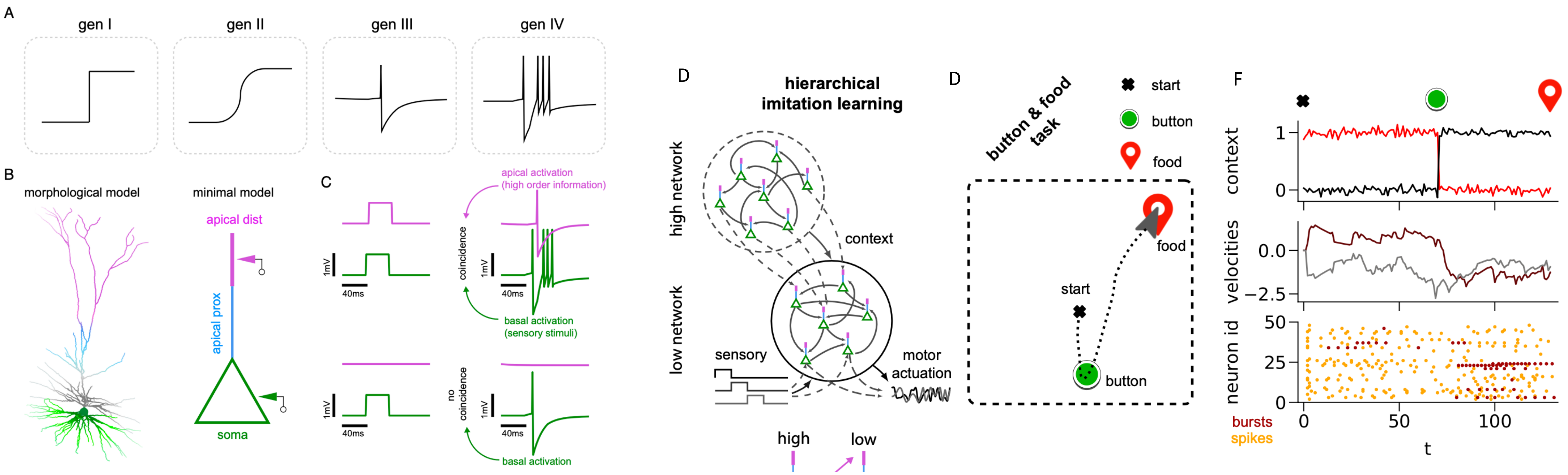
Beyond spiking networks: The computational advantages of dendritic amplification and input segregation

Cristiano Capone, Cosimo Lupo, Paolo Muratore, and Pier Stanislao Paolucci Authors Info & Affiliations

Edited by Terrence Sejnowski, Salk Institute for Biological Studies, San Diego, CA; received December 7, 2022; accepted October 11, 2023

November 29, 2023 | 120 (49) e2220743120 | https://doi.org/10.1073/pnas.2220743120

Three-compartment neuron, contextual signals, bursts enables efficient hierarchical imitation learning of a temporal task



(A) The four generations of neural networks, from "threshold gate" and "activation function" models to spiking neurons and finally to multicompartment neurons producing high-frequency bursts. (B) (Left) Representation of the morphology of a pyramidal neuron, from the Allen Brain Atlas (19) (human brain, middle temporal gyrus) (Right) Our three-compartment simplified model. The soma (green) receives sensory inputs; the apical proximal compartment (blue) receives recurrent connections from neurons in the network; the apical distal compartment (purple) receives teaching/contextual signals. (C) (Top) When a dendritic spike occurs in coincidence with a somatic spike, a high-frequency burst of somatic spikes is generated. (Bottom) When this coincidence does not occur, only isolated spikes can be generated.

Learning using our novel two-compartment neuron in a spontaneously oscillating plastic Winner Takes All network. Contextual apical amplification mechanisms proposed by DIT (Dendritic Integration Theory) in action.

Aspecific signal reaching the soma of all neurons. See blue and green neurons.

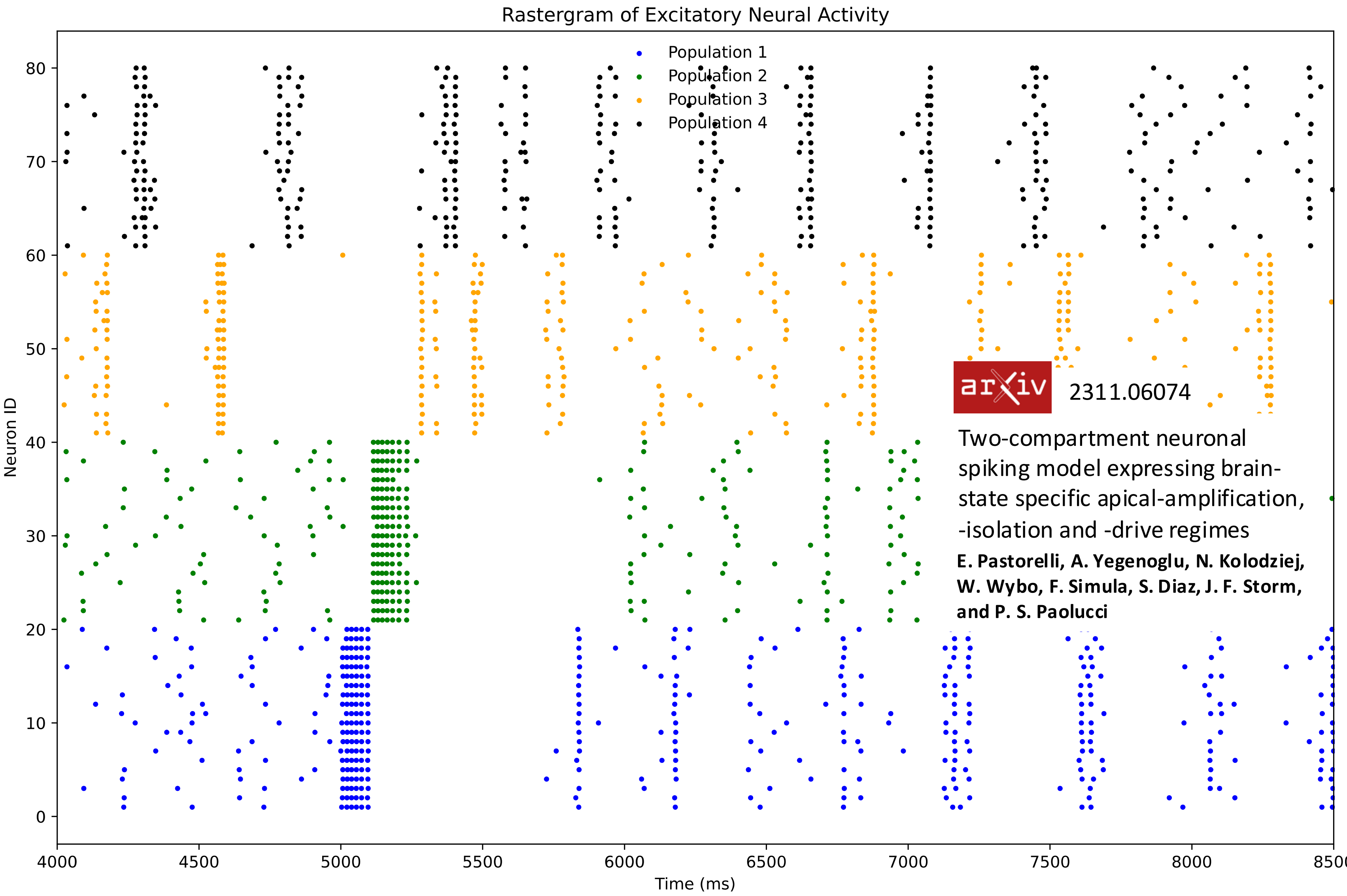
Inhibitory neurons mediating WTA not shown.

Oscillations between two preexisting memories (recurrent connections), see black and orange neural assemblies

Apical (contextual signals) targeting for 25 ms only the blue assembly (starting at 5000ms) and the green assembly (starting at 5100ms)

STDP depending only on spike-timing scultps two novel sets of recurrent connections (blue and green).

After learning, four memories (assemblies) compete in the WTA dynamics induced by aspecific somatic stimulus



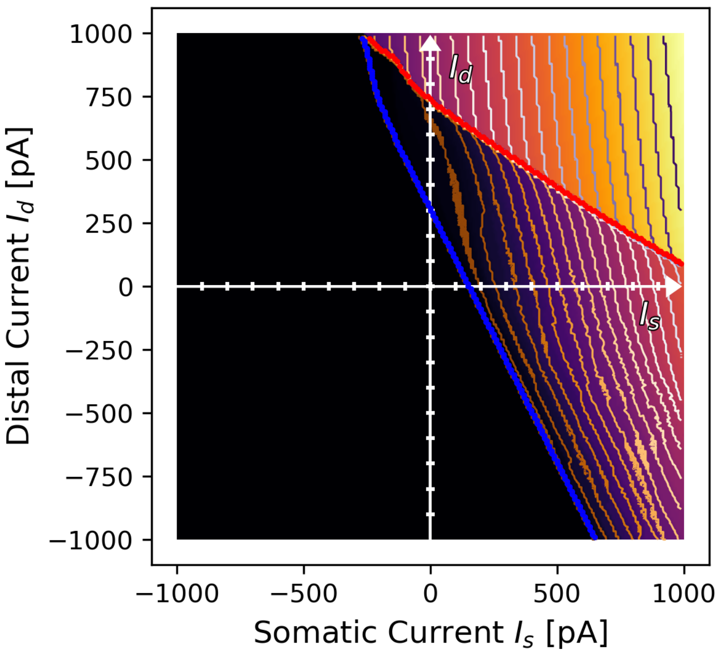
arXiv 2311.06074

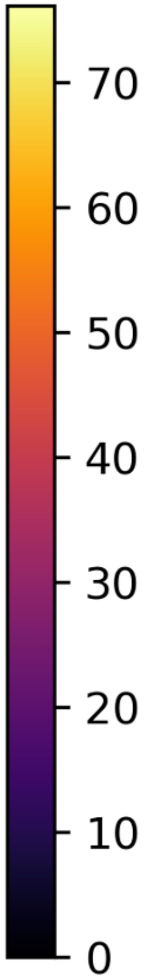
Two-compartment neuronal spiking model expressing brain-state specific apical-amplification, -isolation and -drive regimes

E. Pastorelli, A. Yegenoglu, N. Kolodziej, W. Wybo, F. Simula, S. Diaz, J. F. Storm, and P. S. Paolucci

Our novel two-compartment neuron MC-AdEx spiking model.
Left panel: apical-amplification in awake-like regime for prolonged stimuli

Firing rate (Hz), response to different combinations of currents reaching the somatic and distal compartment.



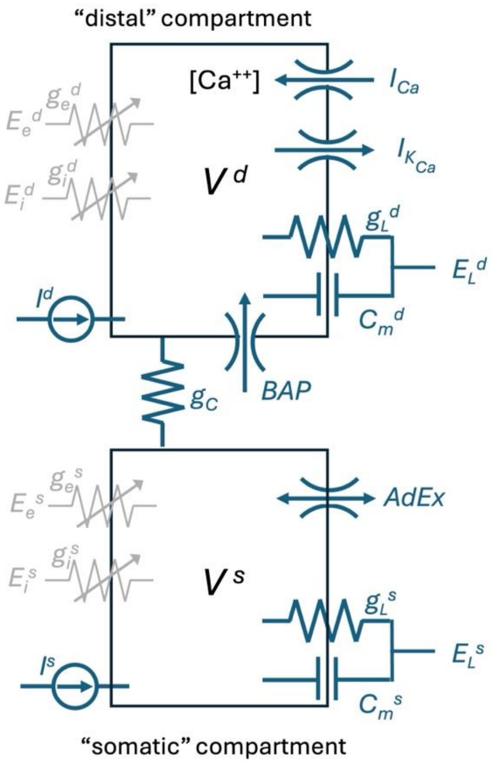


nest::
nest-simulator.org

Somatic AdEx-like compartment

$$
\begin{cases}
C_m^s \frac{dV^s}{dt} = -g_L^s(V^s - E_L^s) + g_L^s \Delta_T \exp\left(\frac{V^s - V_{th}^s}{\Delta_T}\right) + \\
\quad -g_e^s(t)(V^s - E_e^s) - g_i^s(t)(V^s - E_i^s) + \\
\quad -w + I_e^s - g_C(V^s - V^d) \\
\tau_w \frac{dw}{dt} = a(V^s - E_L^s) + b \sum_k \delta(t - t_k) - w \\
C_m^d \frac{dV^d}{dt} = -g_L^d(V^d - E_L^d) - g_e^d(t)(V^d - E_e^d) - g_i^d(t)(V^d - E_i^d) + \\
\quad + I_{Ca} + I_{K_{Ca}} + w_{BAP} \sum_k \delta(t - (t_k + d_{BAP})) + \\
\quad + I_e^d + g_C(V^d - V^s) \\
\frac{d[Ca]}{dt} = \phi_{Ca} I_{Ca} + \frac{[Ca] - [Ca]_0}{\tau_{Ca}}
\end{cases}
$$

Distal compartment supporting apical-mechanisms



arXiv

2023 doi: 10.48550/arXiv.2311.06074

Two-compartment neuronal spiking model expressing brain-state specific apical-amplification, -isolation and -drive regimes

E. Pastorelli, A. Yegenoglu, N. Kolodziej, W. Wybo, F. Simula, S. Diaz, J. F. Storm, and P. S. Paolucci

Two-compartments MC-AdEx neuron.

Detecting coincidence between apical underthreshold short duration signal and a single somatic spike

Response: short-duration high frequency burst

(Panel C) A short underthreshold apical signal (orange) is administered in coincidence with a liminar somatic input. A short duration (60 ms) high-frequency burst is the response.

2023 doi: 10.48550/arXiv.2311.06074
Two-compartment neuronal spiking model expressing brain-state specific apical-amplification, -isolation and -drive regimes

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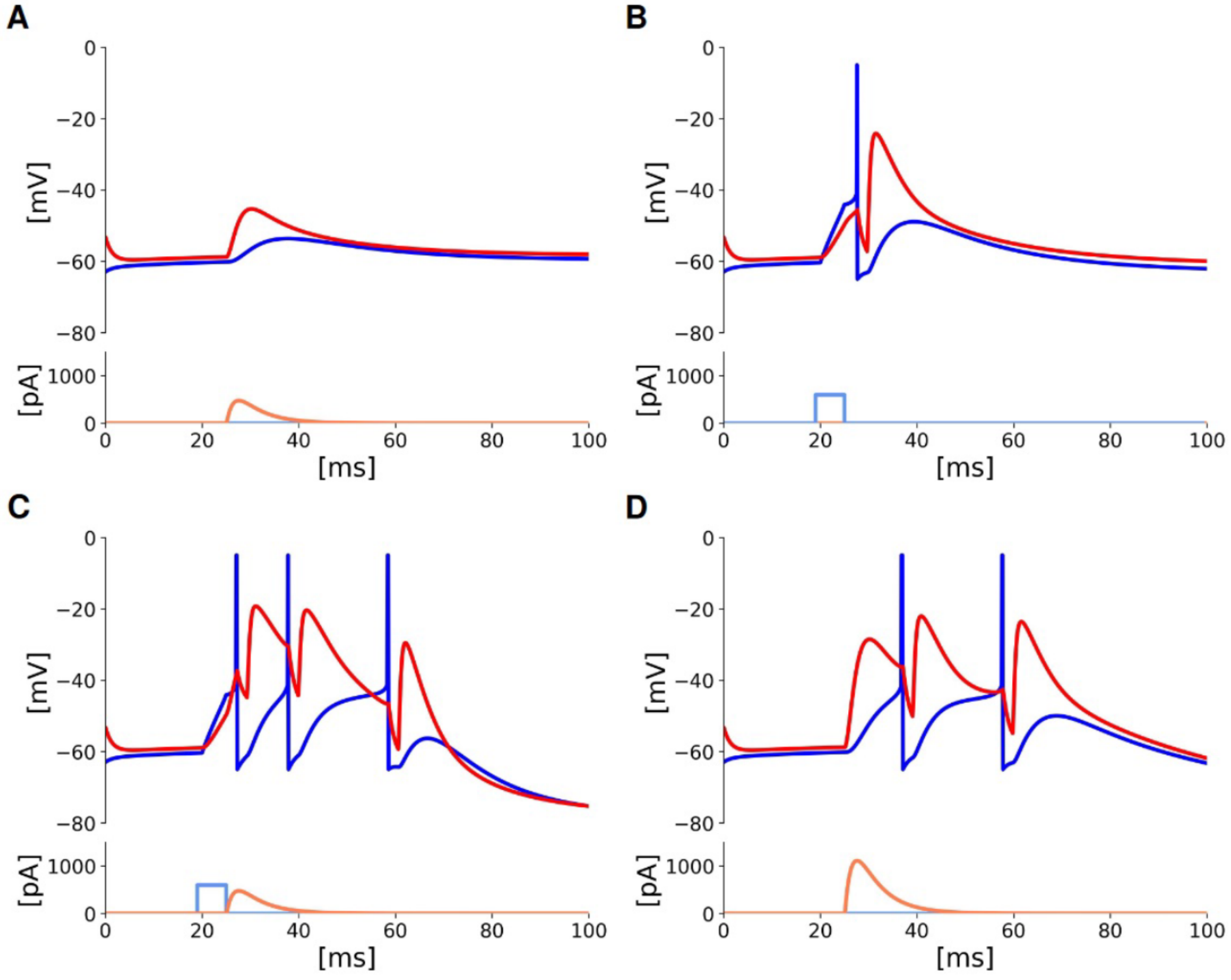


Figure 6. Response of the selected neuron to injected input currents of short duration, according to the *pulse stimuli* task outlined in 2.2, to reproduce experiments by Larkum et al. (1999). **(A)** a beta-shaped current injection of 950pA (peak amplitude) at the distal compartment produces a deflection of only 11mV at the soma without eliciting any spike; **(B)** a threshold current injection (550pA) at the soma evokes one single AP; **(C)** the combination of a threshold somatic current as in b) and a subthreshold distal current as in a), separated by an interval of 5 ms, activates the BAC firing mechanism and evokes a burst of three APs; **(D)** to obtain a burst using only distal injection, a current of at least 1350pA is required. All panels share scale bars and legend: in blue somatic membrane voltage; in red distal membrane voltage; in lightblue step somatic input; in orange beta-shaped distal input).

Neuron https://doi.org/10.1016/j.neuron.2024.02.004 CellPress OPEN ACCESS

Perspective

An integrative, multiscale view on neural theories of consciousness

Johan F. Storm,[1,*] P. Christiaan Klink,[2,3,4] Jaan Aru,[5] Walter Senn,[6] Rainer Goebel,[7] Andrea Pigorini,[8] Pietro Avanzini,[9] Wim Vanduffel,[10,11,12,13] Pieter R. Roelfsema,[2,4,14,15] Marcello Massimini,[16,17,18] Matthew E. Larkum,[19,20] and Cyriel M.A. Pennartz[21,22]

Our novel two-compartment neural model enables large scale simulations of spiking networks leveraging brain-state specific DIT (Dendritic Integration Theory) neural mechanisms.

This enables the investigation of models constructed according to different theories of consciousness all sharing DIT as “the” enabling cellular mechanism.

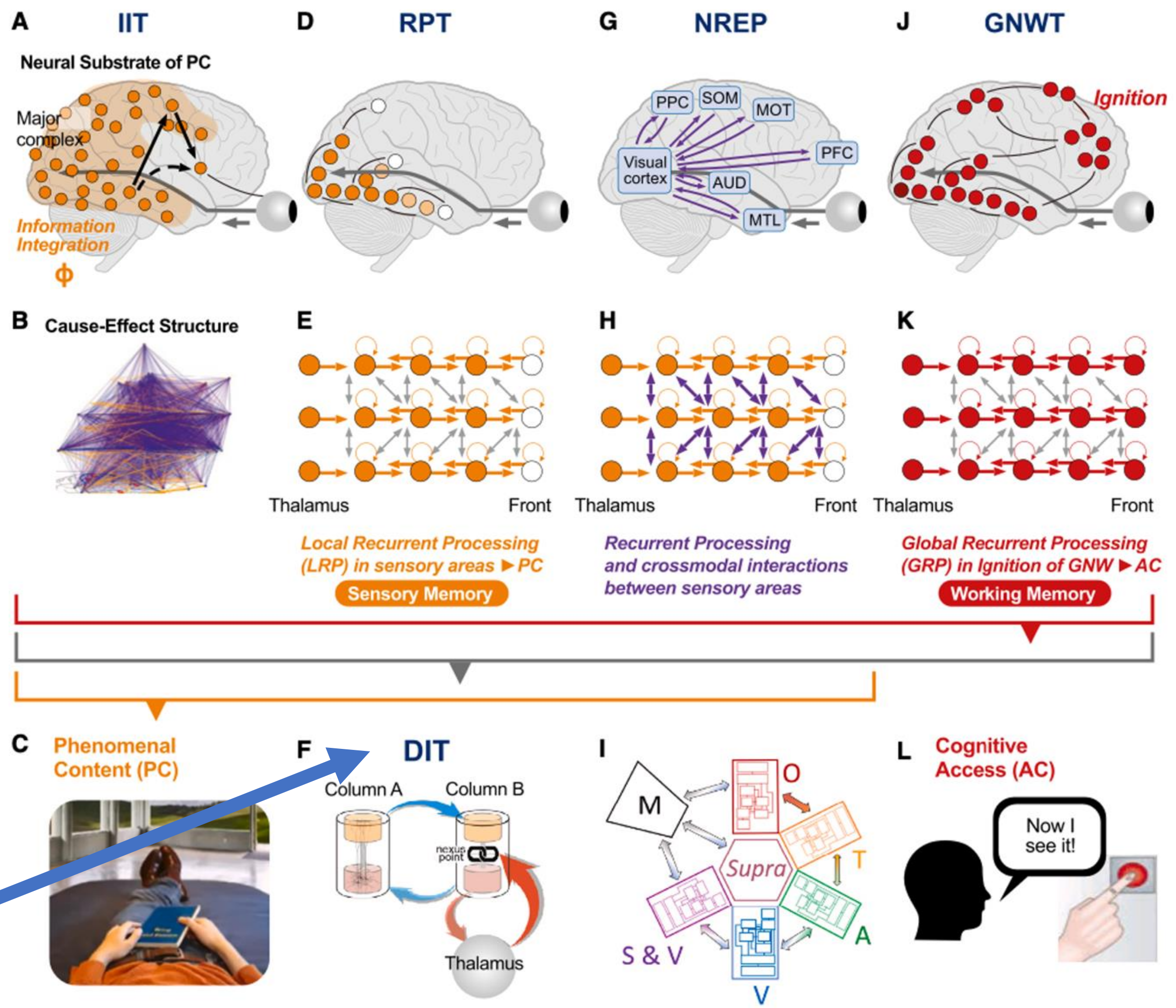


Figure 7. Comparing theories of consciousness

Summary figure illustrating how the five theories of consciousness discussed in this article are partly complementary, partly overlapping, and related to each other and to the core concepts and explananda: phenomenal consciousness (PC; orange elements and C) and access consciousness (AC; red elements and L), illustrated here mainly for vision.

(A and B) Integrated information theory (IIT), and its measure of integrated information (Φ), which quantifies P-consciousness according to IIT.

(C) PC illustrated by an image of a subjective visual experience from one eye (after Ernst Mach[186]).

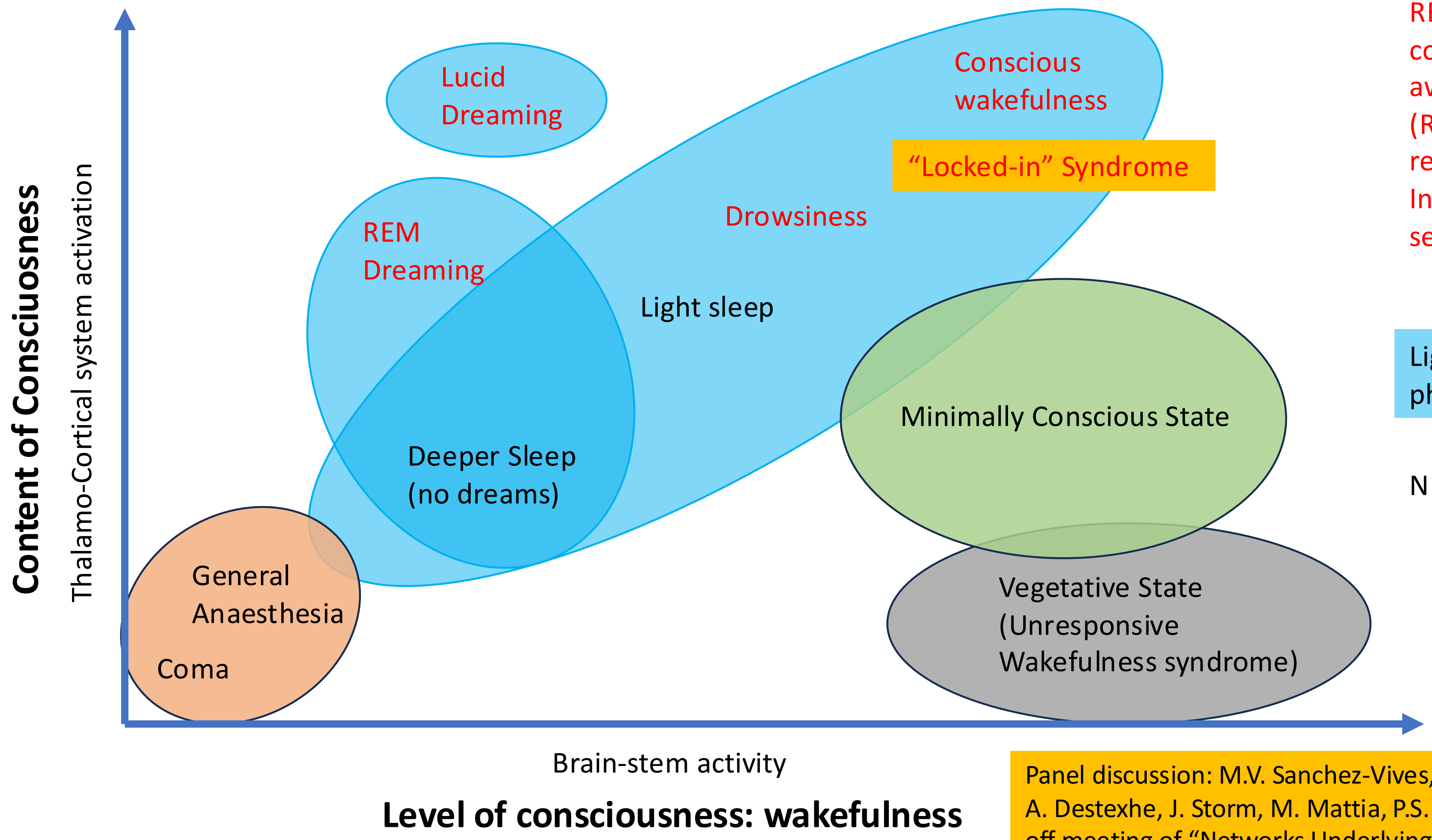
(D and E) Recurrent processing theory (RPT).

(F) Dendritic integration theory (DIT).

(G, H, and I) Neurorepresentationalism (NREP); see Figure 4B for abbreviations in (I).

(J and K) Global neuronal workspace theory (GNWT).

Brain States vs. Consciousness



REM Sleep considered a conscious state. Subjects awakened during REM (Rapid Eye Movement) report vivid dreams, Integrating multi-sensorial experiences,

Ligh blue, physiological states

NREM := Non REM Sleep

Panel discussion: M.V. Sanchez-Vives, M. Massimini, S. Laureys, A. Destexhe, J. Storm, M. Mattia, P.S. Paolucci et al. (2020) kick-off meeting of "Networks Underlying Cognition and Consciousness" Work-package, The Human Brain Project.

All animal species sleep, even though this exposes them to predation and may seem like wasted time because they cannot gather food, look for a mate for reproduction, or care for their offspring.

Newborns sleep most of the time.

Very young children sleep 10 hours a day.

I neonati ed i giovanissimi sono delle spugne che imparano ad una velocità impressionante in confronto alle altre età

An adult needs 6-8 hours of sleep to be efficient.

Elderly people often suffer from insomnia and cognitive problems.

Sleep deprivation: a terrible torture.

SLEEP in the brain and in artificial intelligence systems.

The spontaneous reorganization of brain connections during sleep optimizes energy consumption.

The brain's activity during sleep reorganizes memories and knowledge, creates art, new ideas, and new goals, solves pressing problems, and formulates plans to face the challenges that await us upon waking.

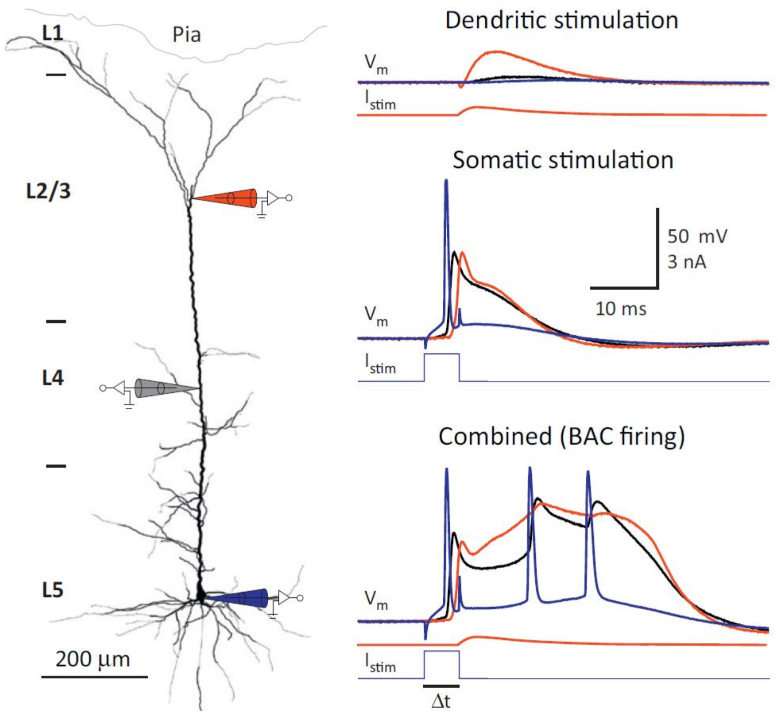
It is possible to create computer simulation models of brains that learn and sleep: networks of neurons and their connections (synapses) described with simple equations from which complexity, learning, dreaming, and deep sleep EMERGE.

It is possible to study the induction of sleep and dreams in artificial intelligence systems! A robot can sleep and dream.

It is possible to simulate the mechanisms of sleep disorders to understand how to treat them.

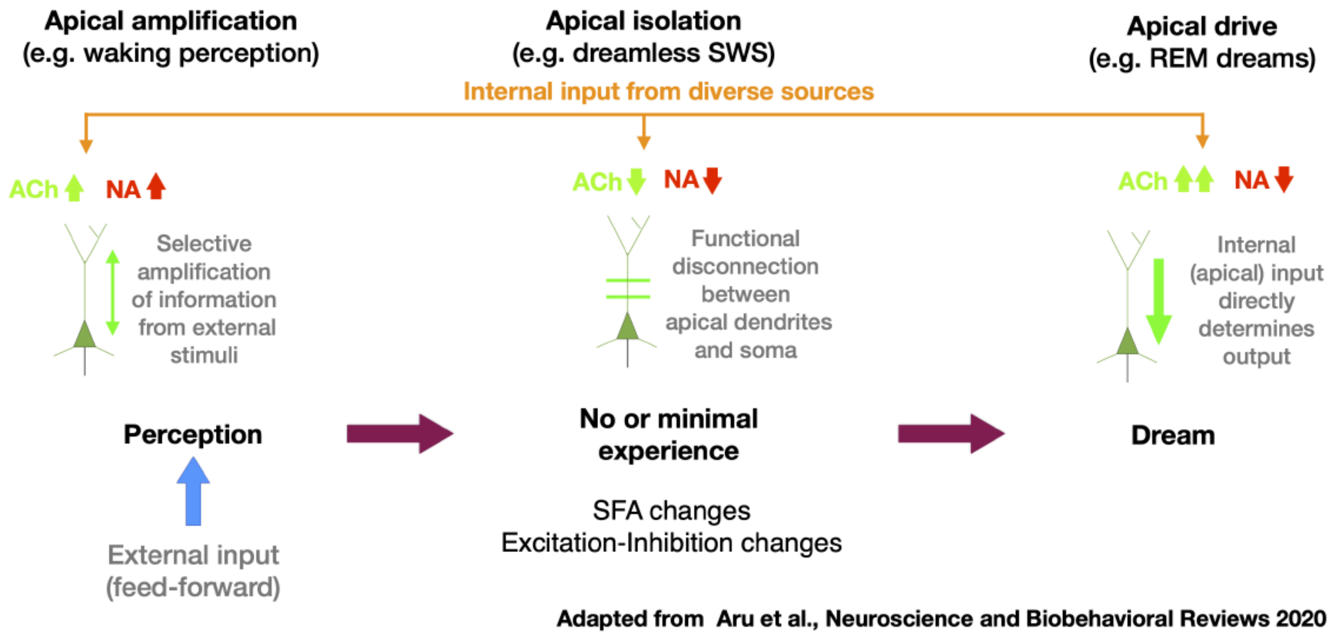
Desired features in a spiking neuron model supporting brain-state specific apical mechanisms

Coincidence of input to the distal compartment with a single back propagating spike at cell body triggers a burst of multiple action potentials



Larkum (2013) A cellular mechanism for cortical associations: an organizing principle for the cerebral cortex. ***Trends in Neurosciences***

Brain-state specific changes in neural dynamics



Aru, Siclari, Phillips, Storm (2020) Apical drive—A cellular mechanism of dreaming? ***Neuroscience & Biobehavioral Reviews***

Aru, Suzuki, Larkum (2020) Cellular Mechanisms of Conscious Processing. ***Trends in Cognitive Sciences***

Two-compartment neuron supporting brain state specific apical-mechanisms

Firing rate (Hz) in response to:

Horizontal axis: input to (peri-)somatic compartment (pA)

Vertical axis: Input to apical compartment (pA)

Note that "yellow" has an entirely different meaning in the three regimes

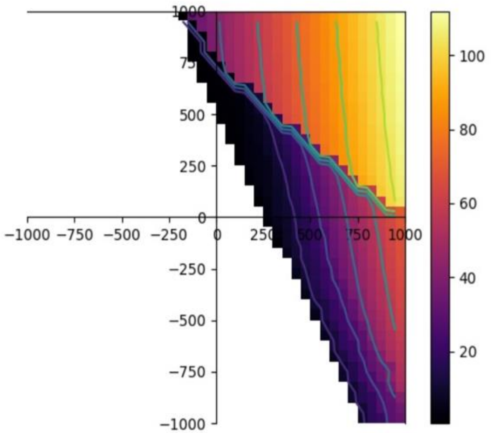
REM sleep

AWAKE

NREM sleep

Apical-drive

Ach ⇧⇧ NA ⇩

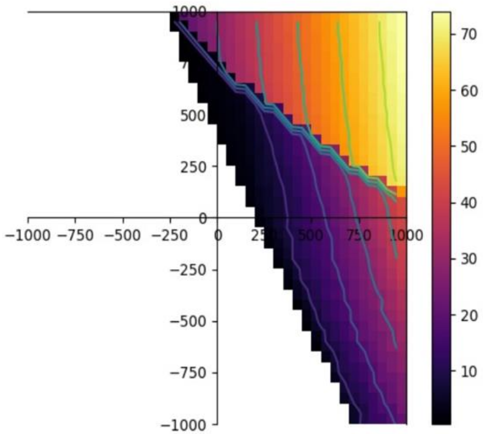


100 Hz

b=20, g=1,
El_d=-53, El_s=-68

Apical-amplification

Ach ⇧ NA ⇩

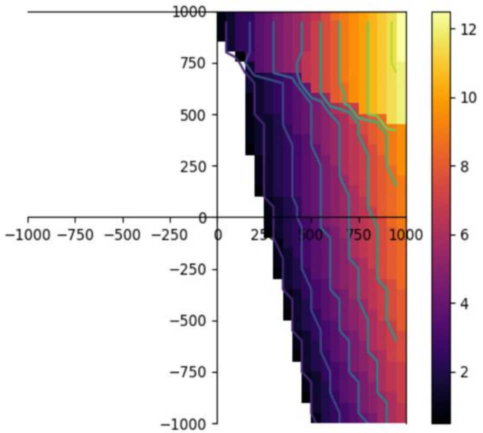


70 Hz

b=40, g=1,
El_d=-53, El_s=-63

Apical-Isolation

Ach ⇩ NA ⇩



12 Hz

b=200, g=0.3,
El_d=-58, El_s=-68

arXiv nest:: nest-simulator.org

doi: 10.48550/arXiv.2311.06074

Two-compartment neuronal spiking model expressing brain-state specific apical-amplification, -isolation and -drive regimes

E. Pastorelli, A. Yegenoglu, N. Kolodziej, W. Wybo, F. Simula, S. Diaz, J. F. Storm, and P. S. Paolucci

Thalamo-cortical spiking models showing the beneficial cognitive and energetic effects of the interplay among sleep and memories, learned by combining contextual and perceptual information

- Sleep essential, in all animal species
- Young humans pass the majority of time sleeping, when learning is faster
- Sleep deprivation detrimental for cognition

Sleep Functions (in brains)

Optimization of energy consumption / cognitive performance

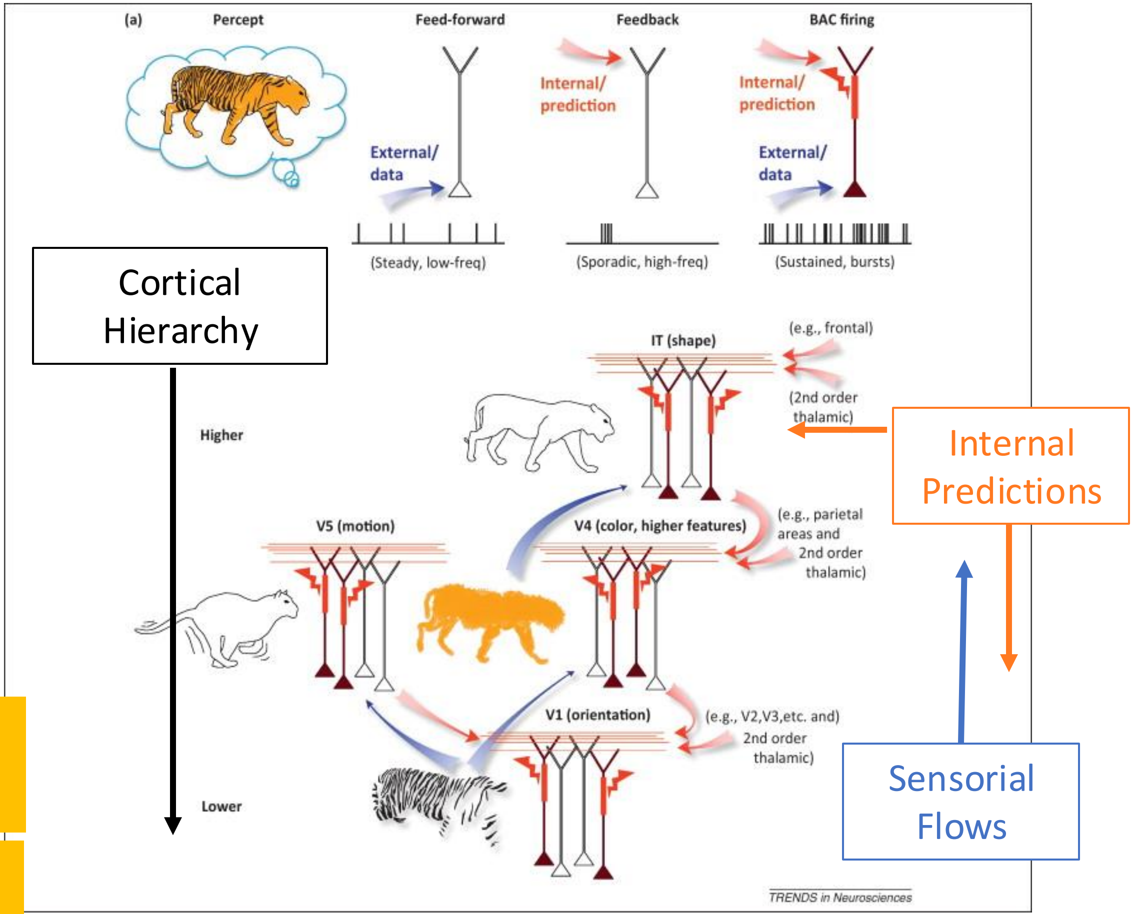
Homeostatic processes (normalization of representations)

Novel, creative associations and planning

Recovery / restorations of bio-chemical optimality

(our opinion) Sleep essential for bio-inspired artificial intelligence

Wakefulness



Thalamo-cortical spiking model of incremental learning combining perception, context and NREM-sleep ***PLoS Computational Biology*** (2021). *B.Golosio, C. De Luca, C. Capone, …, P.S. Paolucci*. https://doi.org/10.1371/journal.pcbi.1009045

Sleep-like slow oscillations improve visual classification through synaptic homeostasis and memory association in a thalamo-cortical model ***Scientific Reports*** (2019). *C. Capone, E. Pastorelli, B. Golosio, P.S. Paolucci*. https://www.nature.com/articles/s41598-019-45525-0

NREM and REM: cognitive and energetic effects in thalamo-cortical sleeping and awake spiking model ***arXiv:2211.06889*** (2022) ***(under review).*** *L. Tonielli, C. De Luca, E. Pastorelli, …, Golosio, P.S. Paolucci*.

Larkum, M. A cellular mechanism for cortical associations: an organizing principle for the cerebral cortex. ***Trends in Neurosciences***, 36 (2013), 141.

Apical-amplification simplifies incremental learning. Sleep spontaneously normalizes and associates memories

Key trick using single compartment AdEx neurons. Put them underthreshold when only bottom-up signals arrive.

Thalamo-cortical spiking model of incremental learning combining perception, context and NREM-sleep ***PLoS Computational Biology*** (2021*). B.Golosio, C. De Luca, C. Capone, …, P.S. Paolucci*.
https://doi.org/10.1371/journal.pcbi.1009045

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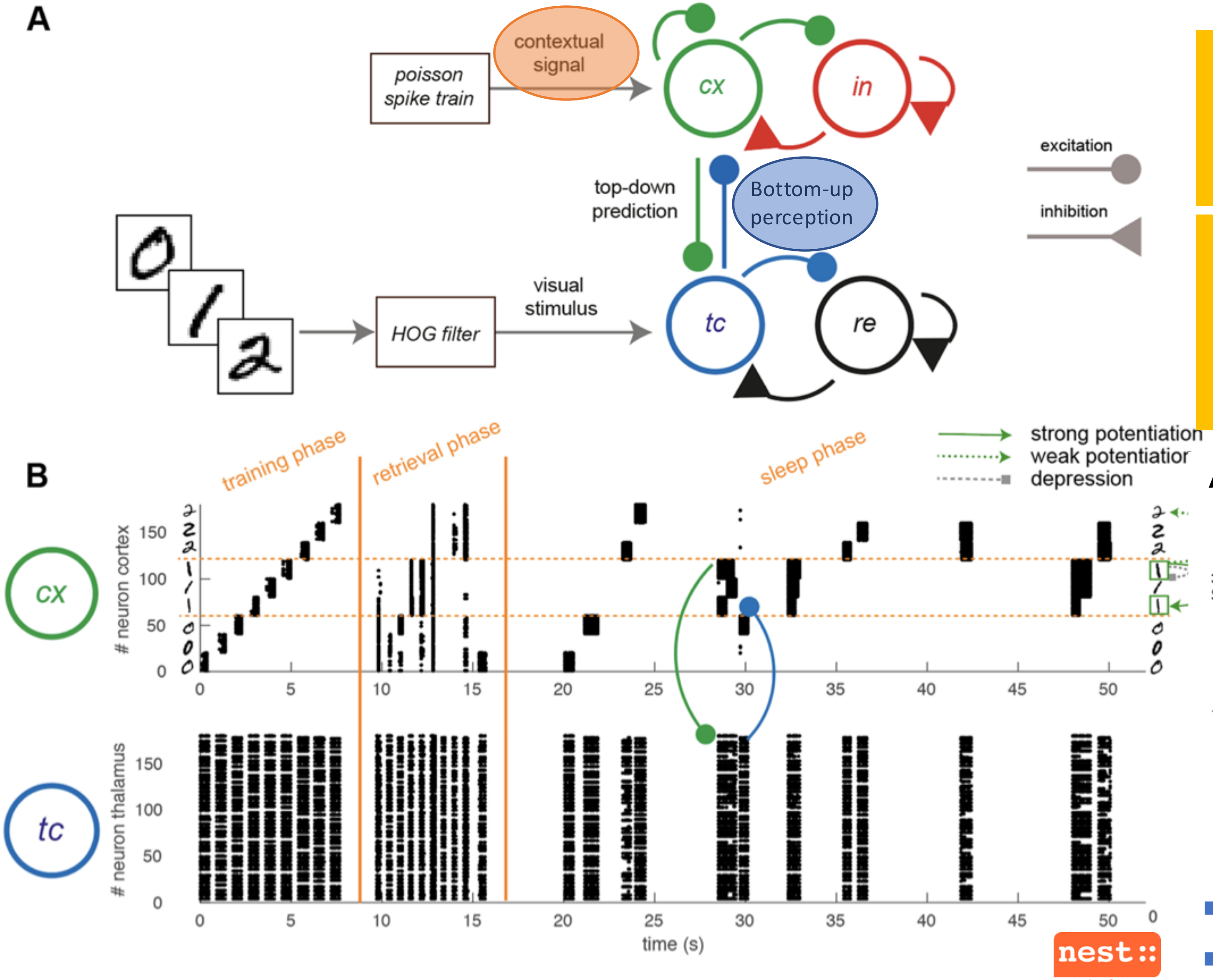
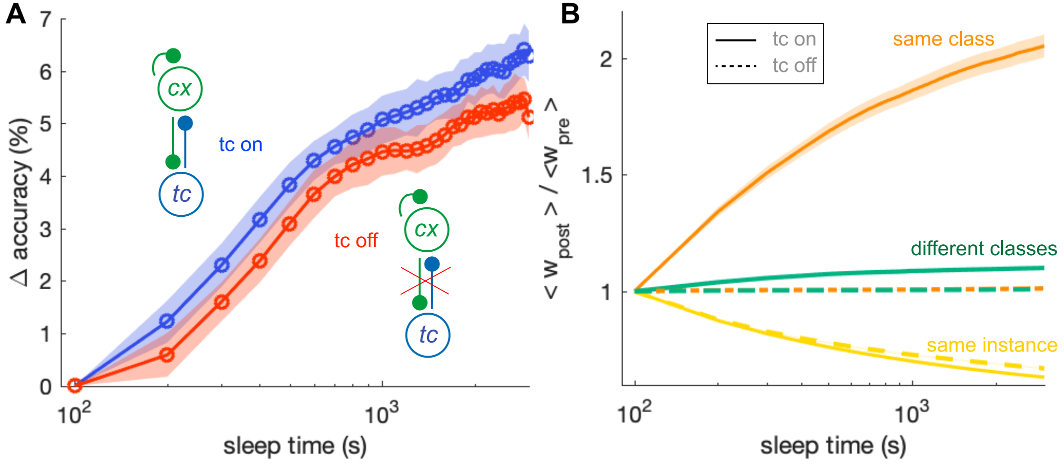
https://www.nature.com/articles/s41598-019-45525-0





- Classification accuracy improved by sleep (left).
- Differential synaptic homeostasis (right)

Other spontaneous features

C) Sleep reduces firing rates and energy consumption on next awakening

Synaptic matrices

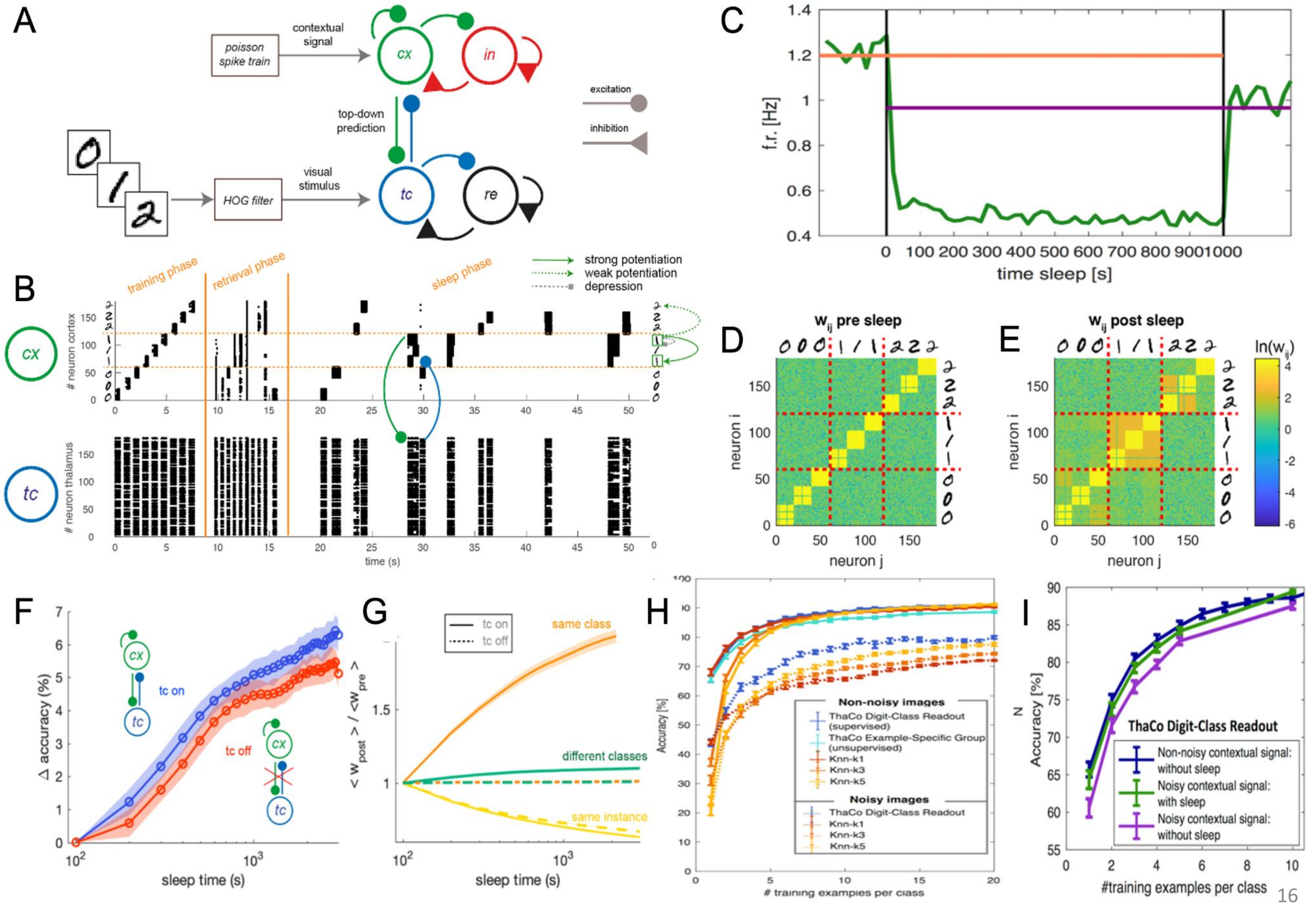
D) Before sleep:

Yellow squares: images learned by neural groups

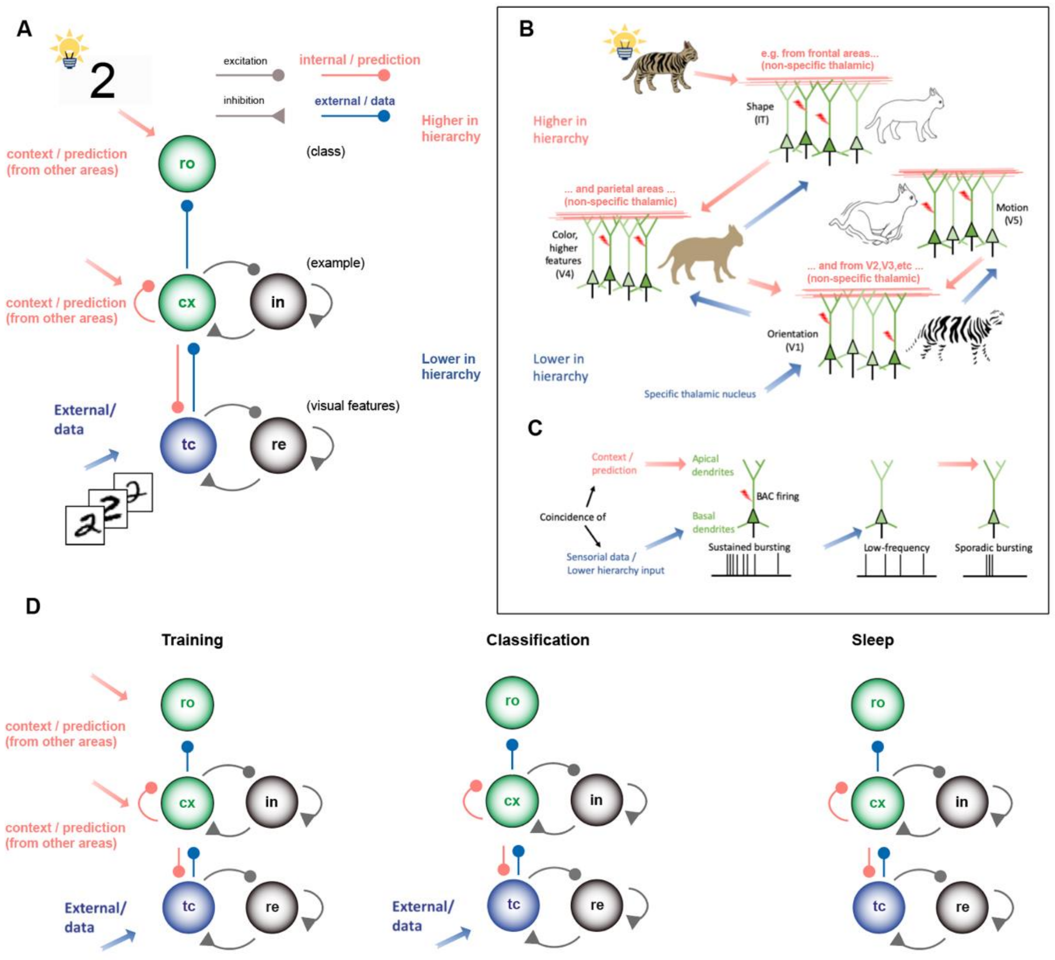
E) After sleep:

Orange blocks: spontaneous creation of classes

H) And I) Sleep benefits after training in presence of noise



Incremental awake deep-sleep cycle

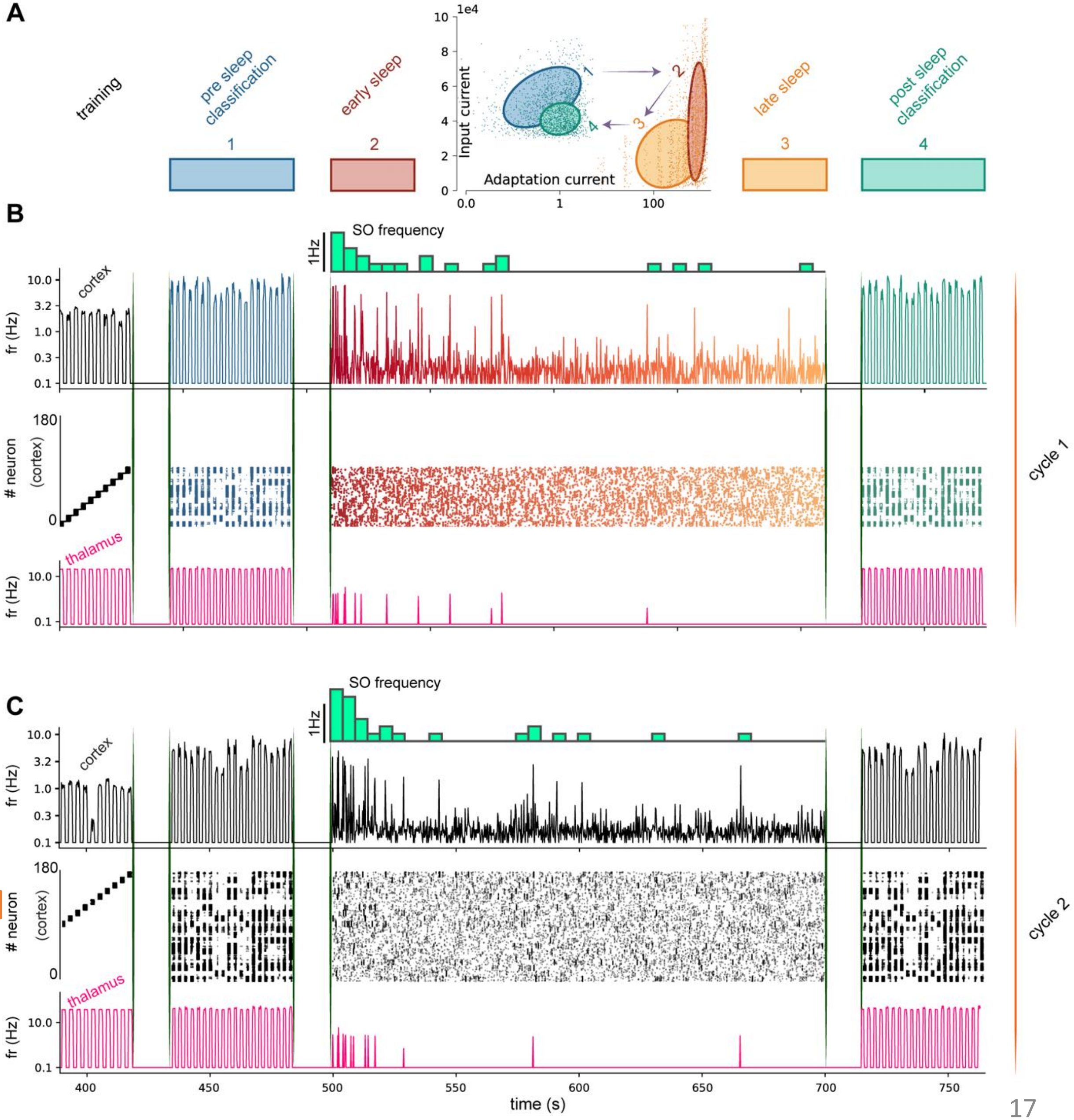


Thalamo-cortical spiking model of incremental learning combining perception, context and NREM-sleep ***PLoS Computational Biology*** (2021). *B.Golosio, C. De Luca, C. Capone, …, P.S. Paolucci*.
https://doi.org/10.1371/journal.pcbi.1009045

The cycle in the adaptation – current plane

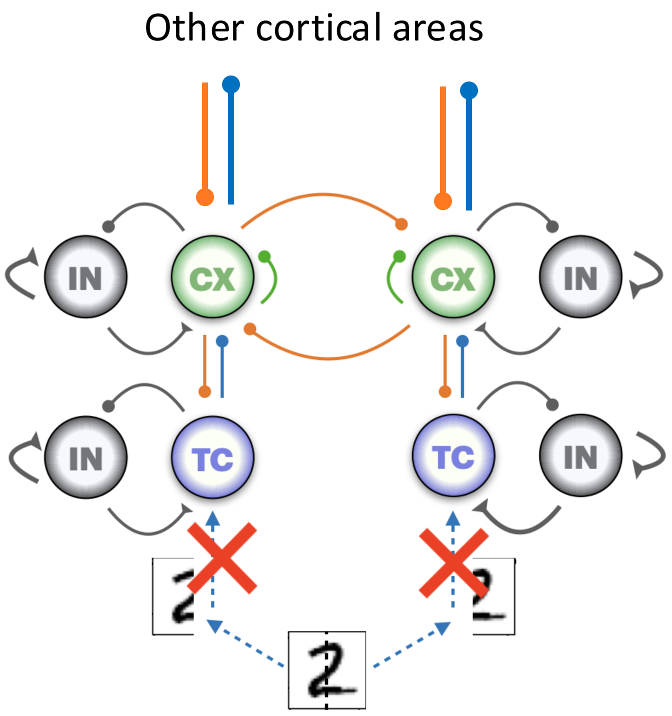
First Cycle

Second Cycle

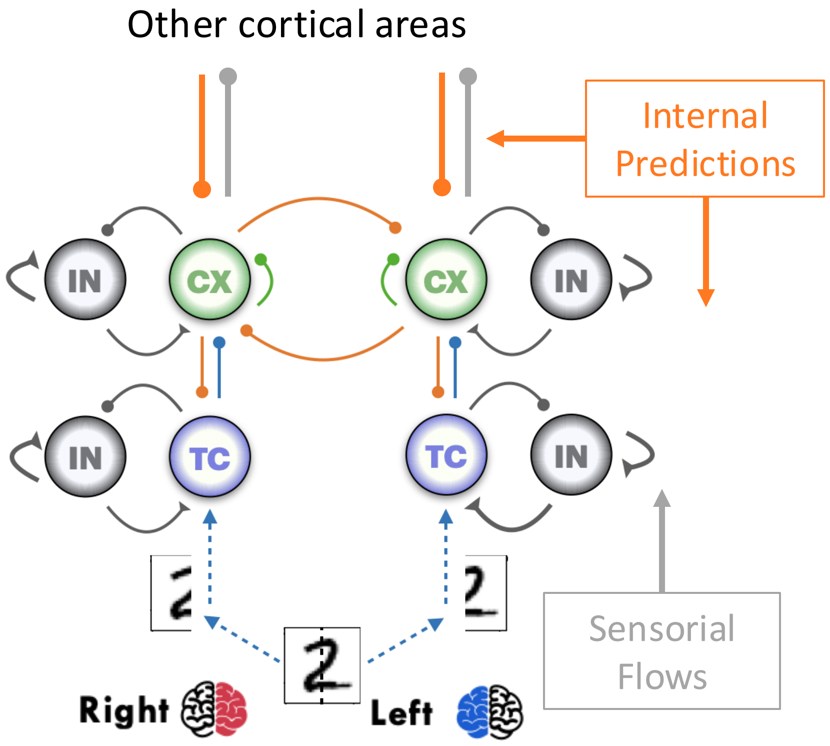


Modular multi-areal playground to investigate brain-state specific cognitive / energetic effects during AWAKE, NREM, REM cycles in thalamo-cortical plastic spiking models: ThaCo

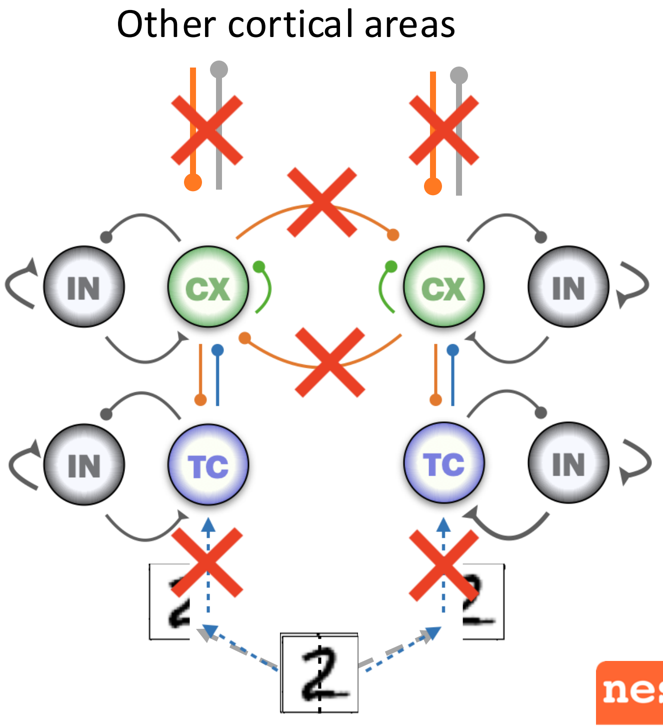
REM: endogenous activity of connected areas with STDP plasticity (block of external stimuli)



AWAKE: incremental STDP learning and classification of external stimuli



NREM: endogenous local activity with STDP plasticity (block of external stimuli and inter-areal information flow)



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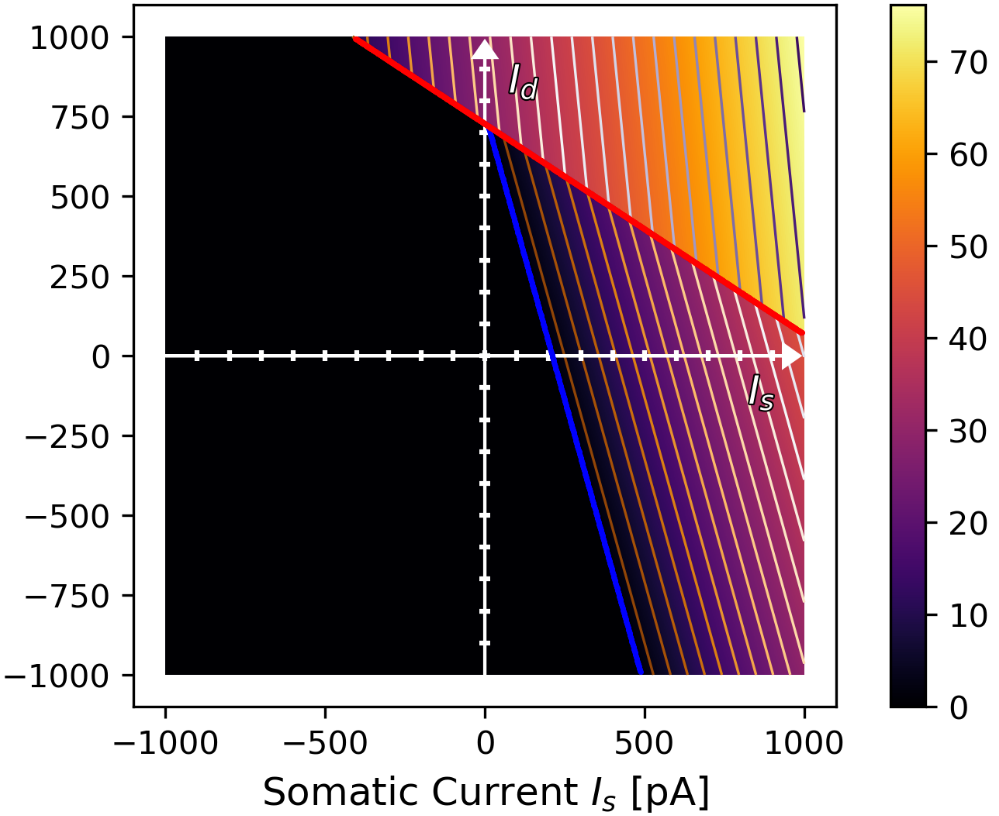
Change of Neuromodulation (through proxy parameters in simulations)

Simplified transfer function for application to bio-inspired artificial intelligence algorithm

ThetaPlanes piece-wise linear approximation

$$\nu_F(I_s, I_d; \nu) = \Theta_\rho(1 - \Theta_H) \cdot \nu_- + \Theta_H \cdot \nu_+$$

Identified by Montecarlo Algorithm.



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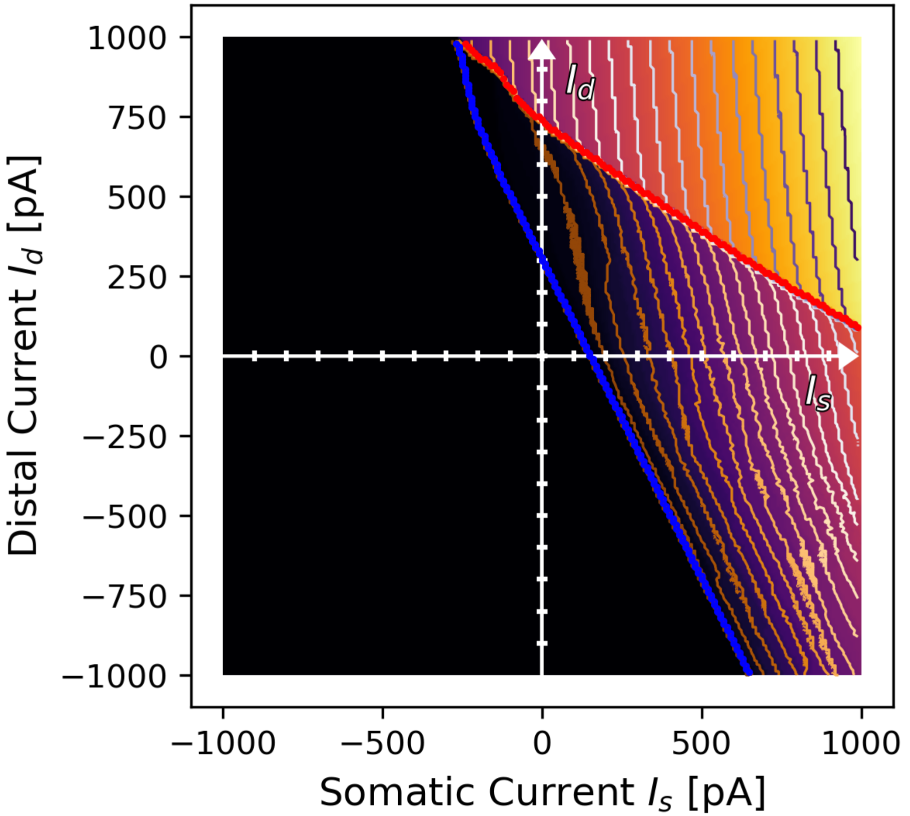
Transfer function of spiking neuron model with detailed integration of differential equations

nest-simulator.org



*current APE members (in **bold those directly involved** on neuroscience topics):*

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past members that contributed to the presented topic: C. Capone, C. De Luca, P. Muratore, N. Kolodziej, F. Marmoreo, I. Bernava, L. Rosati, D. Cipollini

Istituto Nazionale di Fisica Nucleare

https://apegate.roma1.infn.it/

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Disclaimer: the APE group, founded in 1984, is active on many other research topics, including: design of architecture for supercomputing, their interconnects and high-speed analysis of physical data, system software and parallel algorithms for physics simulations. Here in **bold** APE members that **more directly contributed exactly** to the **presented topics**. Other brain-related topics e.g. neural net simulations on GPU, or simulations inferred from data not considered.

Other institutions

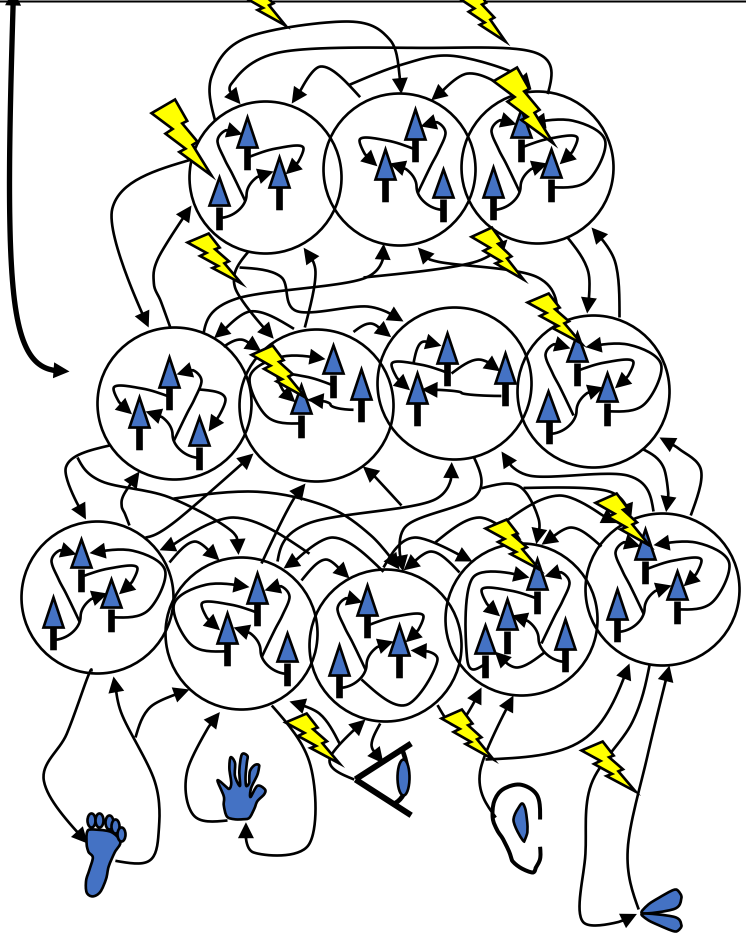
Università degli Studi di Cagliari	Bruno Golosio, Gianmarco Tiddia
Jülich Forschungszentrum	Sandra Diaz, Alper Yagenglu, Willem Wybo, Michael Denker, Robin Gützen
University of Oslo	Johan Frederik Storm
Istituto Superiore di Sanità	Cristiano Capone
Sapienza Università di Roma	*Several among the authors started as MSc and PhD students associated to INFN Roma*
EBRAINS	European research Infrastructure https://www.ebrains.eu/
HBP	Human Brain Project https://www.humanbrainproject.eu/

Human brain: one hundred billion neurons

… connected by one quadrillion synapses (10^15)

- Synapses internal to same cerebral areas
- Among cerebral areas at same abstraction level
- Synapses toward lower abstraction levels
- Toward higher abstraction level (feed-forward)

Alice' consciousness correlates* with:



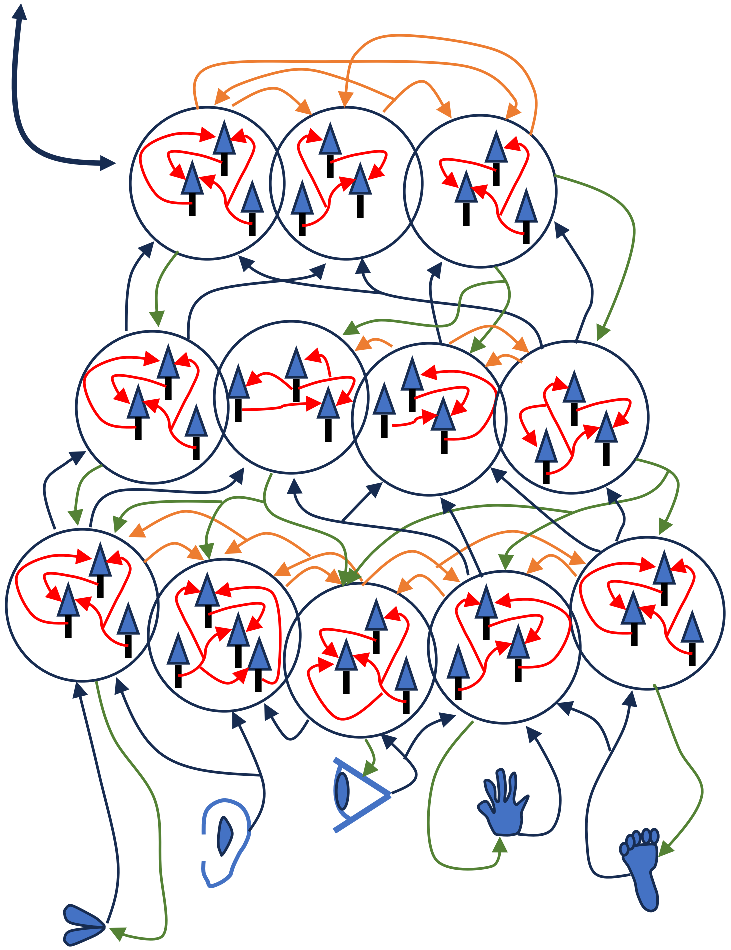
Brain areas at
Higher levels of abstraction

Each **conscious perception is correlated*** with the simultaneous activation of a perception specific – small minority of neurons and synapses representing ourself, Alice and Bob and the external world at different levels of abstraction

Brain areas nearer to sensorial receptors and motor actuation

Consciousness correlates* (disclaimer): in a biological brain

Bob' correlates with:



Alice interacting with the external world and with ……Bob? Or with a General Artificial Intelligence system?

Not a deep feed-forward architecture based on single point neuron

The brain as a controlled generator of hallucinations, and all our conscious perceptions as controlled hallucinations based on internal priors and context

Until now largely neglected in neural network models and artificial intelligence systems

The essential role of other brain-states (dreaming, day dreaming, deep sleep) for energetic and cognitive optimization of such controlled hallucinations generator

Until now largely neglected in neural network models and artificial intelligence systems

The single point neuron. An approximation to be improved to enable a better simulation of correlates of conscious perception, brain-states and learning

Until now,

- large scale simulations of brain activity and
- artificial intelligence system

have been based on “single point neurons”.

The neuron is modeled as a more or less complex single integrator.

A single transfer function that transforms the total synaptic input from incoming synapses into a spike (or a rate of activity) to be delivered to other point like neurons.

How to incorporate as internal priors information acquired through hundreds of millions of years of evolution and individual life-time

HPC simulations for Brain cognition and bio – inspired AI

Energy consumption for digital twins of the Human Brain

The brain consumes about 13 W. *For both the biological brain and their simulations* **Synaptic management** (i.e. transmission of events to post-synaptic neurons and delivery of synaptic inputs to post-synaptic neurons) dominates the energetic cost (and cognitive speed).

Power consumption: $P \propto N\ M\ f\ e_s\ R$ **where:**

P	:== Power consumption
N	:== Total Number of Neurons (about 100 billion in the human brain)
M	:== Average number of synapses per neuron (biological 10^4 - 10^5)
f = (1-3 Hz)	:== Average firing rate (emission of neural and synaptic spikes)
R	:== accepted slow down, i.e. Biological time / Wall clock time
e_b	:== biological joule/synaptic event (4 femtoJoule – 1 picojoule)
e_s	:== Simulation joule/synaptic event (currently, at least 10^8 higher than brain's)

However, interesting simulations for both foundational investigations, clinical applications and future AI principles can be performed using either 1) smaller spiking networks (i.e. less neurons, i.e. less brain areas) 2) simplified neural mass models 2) multi-scale hybrid neural mass – spiking models 3) higher abstraction models / theoretical approaches

INFN and Computing @CNS5: a leading role in European foundational and applied research on brain cognition, next gen bio-AI, related HPC systems and tools

Computational neuroscience (and its application to AI) is the realm of physicists, and specialists in parallel, distributed, and cloud computing. INFN Roma and INFN Cagliari played a leadership role in the **Human Brain Project** and now continue their work in the **EBRAINS** infrastructure, the **FAIR** (Future AI Research) partnership and the **CNS5 Brainstain** projects. See also **RED-SEA, TEXTAROSSA**, **DARE** (openHW/SW RISC-V based), **NET4EXA** (interconnect for EXASCALE).

During this workshop:

Mechanisms underlying **Brain Cognition and Consciousness** with a focus on those enabling **incremental learning and sleep** in Thalamo-cortico-hippocampal systems…towards **Bio – inspired next generation explicable Artificial Intelligence** (*this presentation*)

Analysis worflows for brain activity applicable to both experimental data acquired with multiple-methodologies and at multiple spatio-temporal scales and simulation outputs, and for their comparison (*see Cosimo Lupo presentation*)

Models of working memories, multi-area visual systems, and simulations engines for largest multi-area networks on thousands GPUs systems (NEST-GPU) (*see Gianmarco Tiddia presentation*)

Design of interconnection and acceleration technologies for simulations, analysis and bio-AI (*see Andrea Biagioni presentation)*