BIO: Leveraging Conscious Dynamics Enhancing ML Performance

Michiel van der Vlag[1,*], Alper Yegenoglu[1], Cristian Jiminez-Romero[2], Sandra Diaz[1] and Jennifer Goldman[3]

[1] SDL Neuroscience, Forschungszentrum Jülich GmbH, Institute for Advanced Simulation, Jülich Supercomputing Centre (JSC), 52428 Jülich, Germany

[2] ETIS Lab, ENSEA, CNRS, UMR8051, CY Cergy-Paris University, Cergy, France

[3] Paris Saclay University, Institute of Neuroscience, CNRS, Gif-sur- Yvette, France

[*] Correspondence: **m.van.der.vlag@fz-juelich.de**.

Reservoir computing (Jaeger, 2001) in ML has the purpose of projecting its input into higher-dimensional space, making it easier to extract relevant features. Endowed with fading memory (Maass et al., 2004), it allows the system to store and capture information. Columns in the neocortex have similarities, and conscious processing may result from adaptable neural circuits (Buonomano et al., 2009; Seoane, 2019). Intriguingly, biophysical models of the brain also represent a form of reservoir computing. **Criticality** may optimally support effective neural computation (Bak et al., 1987; Toker et al., 2022).

Bio-realistic reservoirs have not yet been optimized using metrics of criticality and complexity while performing cognitive tasks. This research aims to determine the influence of complexity on the performance of simulated biological networks when given specific tasks. **Hypothesis**: Tuning a TVB reservoir to exhibit increased complexity observed in conscious states, while solving a simulated behavioral task, will lead to improved performance. This approach will be contrasted with a TVB reservoir tuned to complex patterns associated with minimally conscious brain states, such as during sleep.

Mean-field dynamics
Adaptive Exponential

- Biologically plausible mean-field model
- For large-scale brain network simulations
- Adaptive Exponential intergrate-and-fire
- Captures adaptation (W), spiking behaviour
- Connects micro to macroscales
- Populations of regular excitatory (RS) and fast inhibitory spiking (FS)
- Modeling human sleep and wake states

Mean-field dynamics
Montbrió - Paxin - Rosin

- Based on dynamics of populations of coupled neurons
- r(t): mean firing rate
- V(t): mean membrane potential
- Captures essential collective dynamics (oscillations, synchronization)
- Modeling resting state vs cognitive task
- Exploration of brain stimulation techniques

Metric
Detrended Fluctuation Analysis

- Quantify fractal-like scaling properties
- Analyzing longe range connections
- Indicating trend or memory or reservoir
- Computes the RMS fluctuation for each segment (F(s))
- Fractal properties if $F(s) \propto s^{\alpha}$ exhibits power law (Ihlen, 2012)

The virtual brain as a reservoir

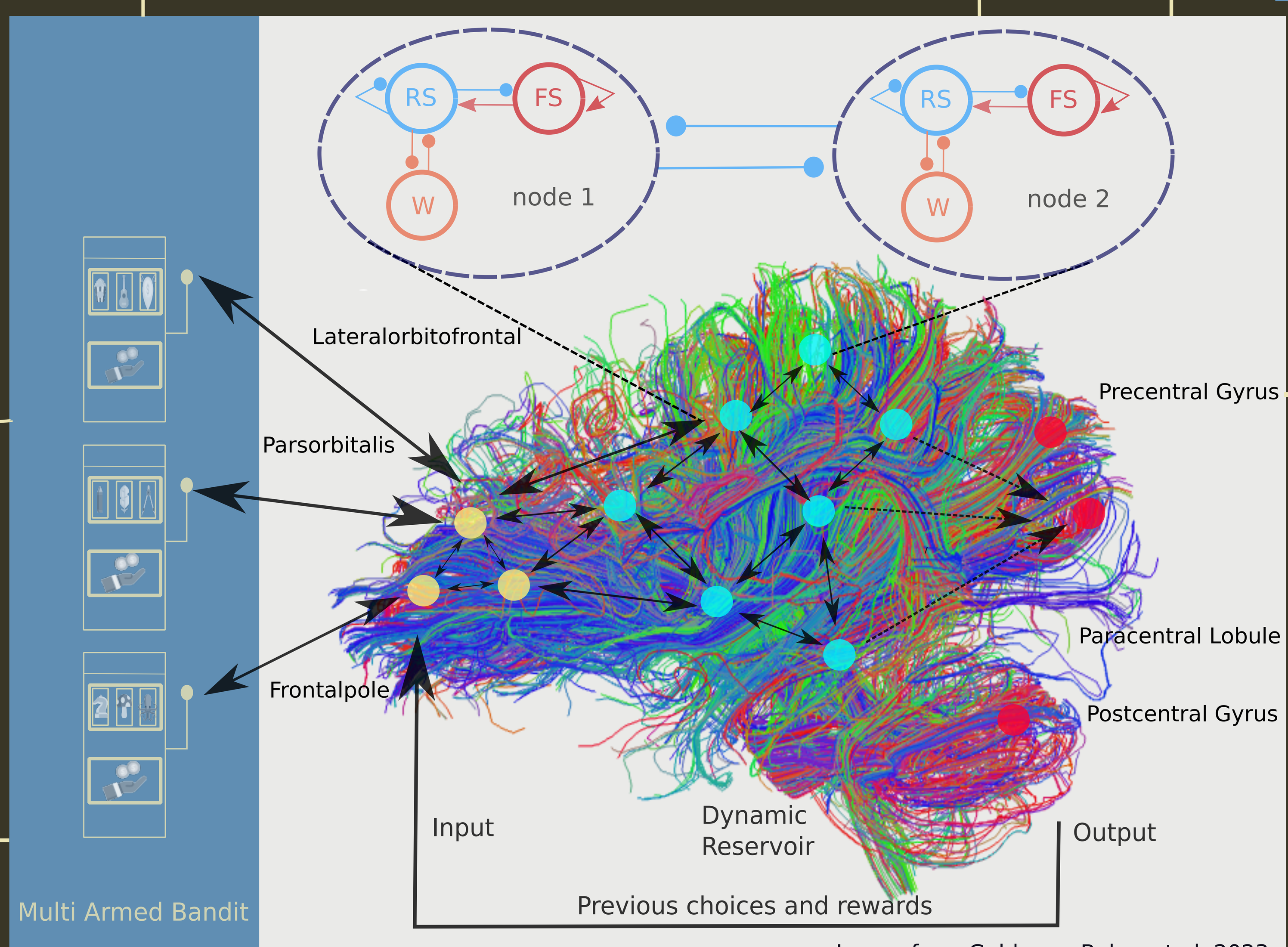


Image from Goldman, Bahar et al, 2023

Task
Multi Armed Bandit

- A classic dilemma in decision theory
- The agent must decide between exploiting known good options (arms) and exploring potentially better options to maximize cumulative reward over time
- Reward distributions of arms may change over time
- Epsilon-Greedy strategy

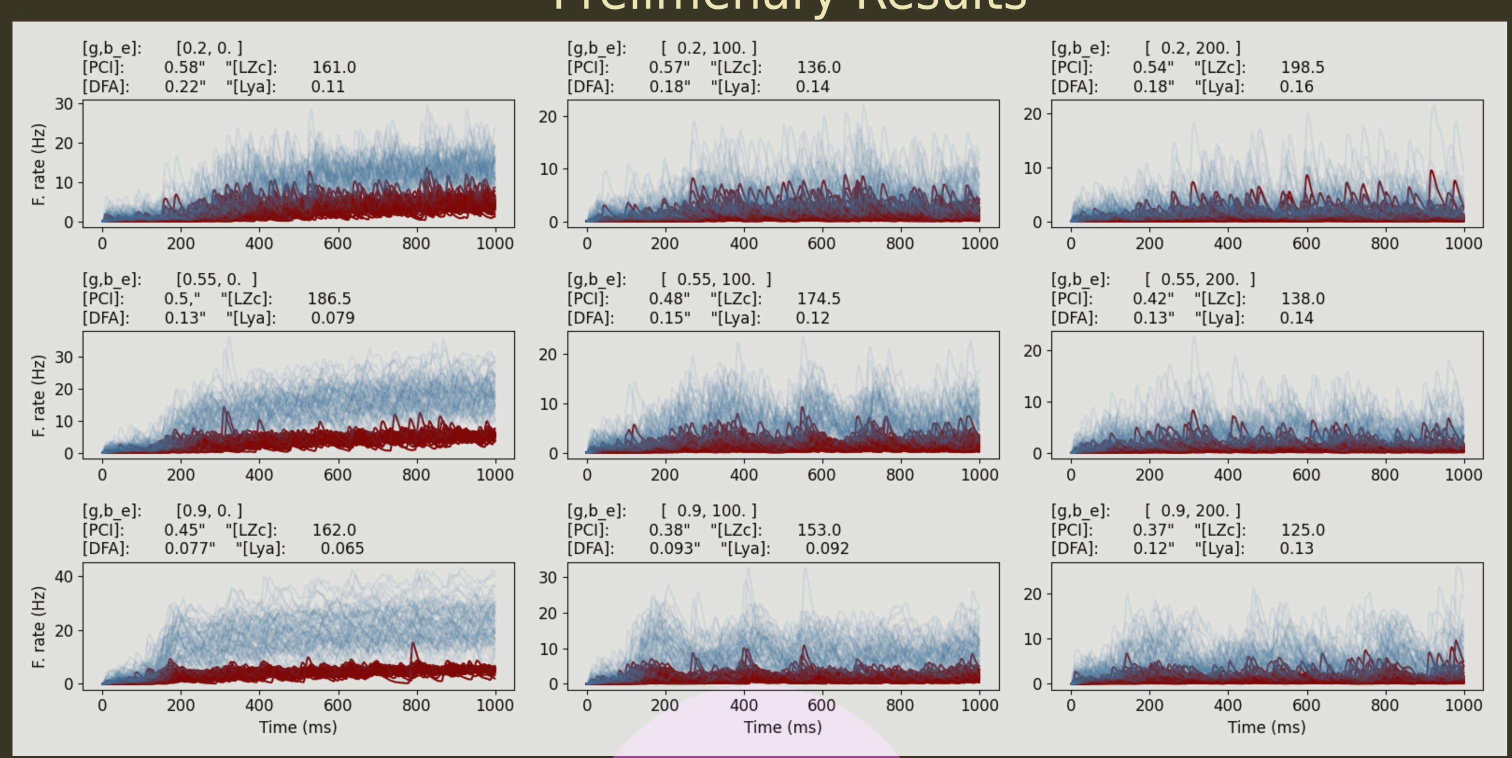
Metric
Lyapunov Exponent

- Quantify divergence or convergence rate of nearby trajectories
- Insight in chaotic behaviour
- Eigenvalues of Jacobian Matrix
- Peturbations of initial condition over time
- Metric for information propagation, detailing the system's behavior over time
- (Toker et al. 2018)

Metric
Complexity Index and Lempel Ziv

- Consciousness is integration and differentiation of neural activity (Casali et al 2013)
- Leveraging response to transcranial magnetic stimulation (TMS)
- Capturing richness of spatiotemporal patterns with Perturbational Complexity Index (PCI)
- < PCI indicating conscious response
- > PCI associated with unconscious states
- Lempel-Ziv complexity (LZC)

Prelimenary Results



Firing rate and metrics for multi-armed bandit task encoded (>250 ms) for AdEx. The global coupling and adaptation are explored, setting the model from wake behavior (left) to sleep like behavior (right). Red: exhibitory, blue: inhibitory firing rate.

In this work we treat **The Virtual Brain** (Sanz-Leon et al., 2013, TVB) simulator as a reservoir system and train it to perform a cognitive task: the **Multi-Armed Bandit** (Molano-Mazon et al., 2022), comprised of mean-field models describing different types of dynamics, delineating firing rates through the **Adaptive Exponential** (AdEx) model (Goldman et al., 2023) and membrane potential changes via the **Montbrió-Pazo-Roxin** (MPR) model (Montbrió et al., 2015). While performing the task, we monitor the complexity and criticality of the reservoir, with the aim to map its dynamics. The **outlook** of the results is twofold. They can be used to drive reservoir computing efficiently, comprehending its learning. On a biological scale, this research may contribute to a better understanding of the information processing of the neocortex.

References

Bak, Per, Chao Tang, and Kurt Wiesenfeld (1987). “Self-organized criticality”.
Buonomano, Dean V and Wolfgang Maass (2009). “State-dependent computations: spatiotemporal processing in cortical networks”
Casali, Adenauer G. et al. (2013). “A theoretically based index of consciousness independent of sensory processing and behavior”.
Goldman, Jennifer S., Lionel Kusch, David Aquilue, Bahar Hazal Yalçınkaya, Damien Depannemaecker, Kevin Ancourt, Trang-Anh E. Nghiem, Viktor Jirsa, and Alain Destexhe (2023b). “A comprehensive neural simulation ofslow-wave sleep and highly responsive wakefulness dynamics”
Ihlen, Espen A. (2012). “Introduction to Multifractal Detrended Fluctuation Analysis in Matlab”
Jaeger, Herbert (2001). “The “echo state” approach to analysing and training recurrent neural networks-with an erratum note”.
Maass, Wolfgang, Thomas Natschläger, and Henry Markram (2004). “Fading memory and kernel properties of generic cortical microcircuit models”.
Molano-Mazon, Manuel et al. (2022). “NeuroGym: An open resource for developing and sharing neuroscience tasks”.
Montbrió, Ernest, Diego Pazó, and Alex Roxin (2015). “Macroscopic description for networks of spiking neurons”.
Seoane, Luís F. (2019). “Evolutionary aspects of reservoir computing”.
Toker, Daniel et al. (2022). “Consciousness is supported by near-critical slowcortical electrodynamics”

Contact me:

Funding

The research has received funding from the European Union’s Horizon 2020 Framework Program for Research and Innovation under the Grant Agreements No. 101058516 (eBRAIN-Health). This research was also supported by the Helmholtz Joint Lab “Supercomputing and Modeling for the Human Brain”.