Neuromodulation robustly tunes rhythmic patterns in a fixed connectome: application to gait control

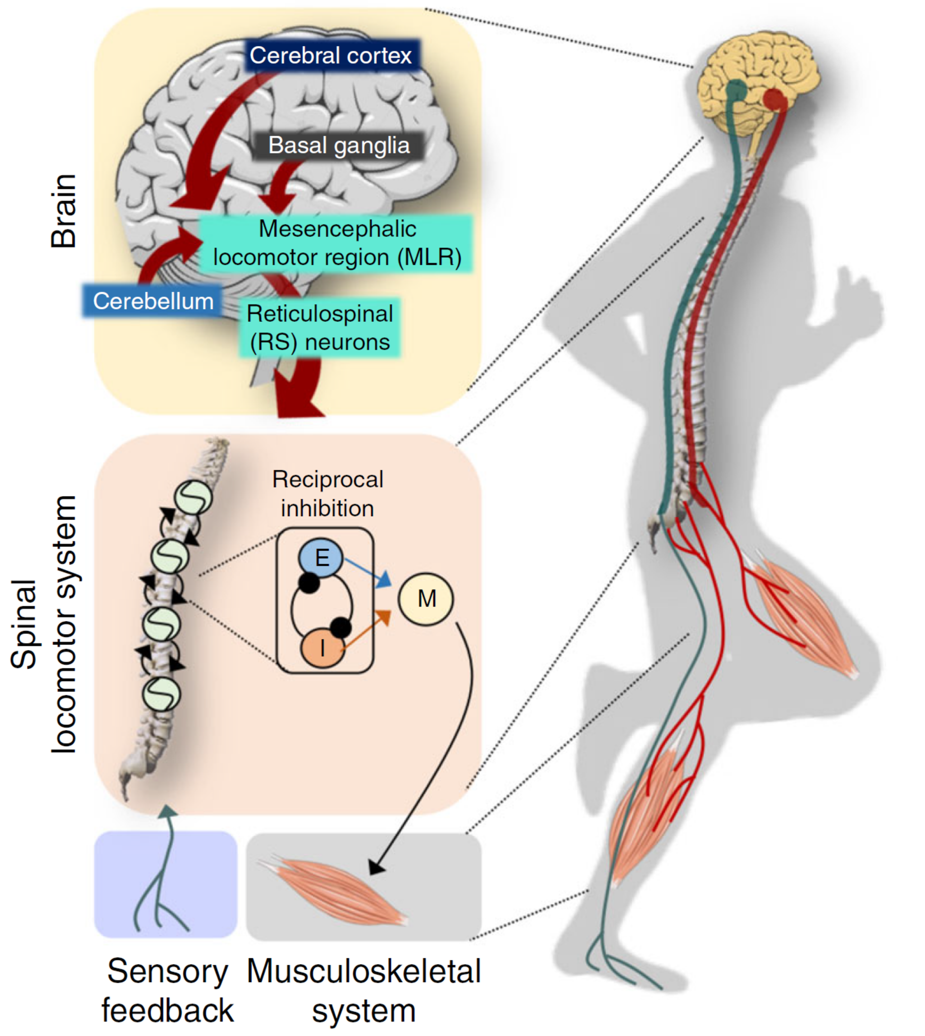
Arthur Fyon Guillaume Drion

Montefiore Institute of Electrical Engineering and Computer Science, University of Liège

Background and Motivations

Central pattern generators (CPGs):

- *What:*
  → Self-organized biological neural circuits
  → Produce rhythmic outputs in the absence of rhythmic input
- *Purpose:*
  → Generate coupled patterns of neural activity
  → Drive rhythmic, stereotyped motor behaviors (*e.g.*, walking, swimming, breathing, chewing)
- *How:*
  → Interconnections of bursting neurons using inhibitory synapses
  → These CPG neurons project to motor neurons
- *Key features:*
  → Robust to neuronal degeneracy
  → Great flexibility in their rhythmic output



Adapted from *Dutta et al. 2019*.

In modern **computational neuroscience**:
→ CPGs are fragile to perturbations in neuronal properties
→ CPGs lack flexibility; modifying the rhythmic pattern requires remodeling the CPG connectome

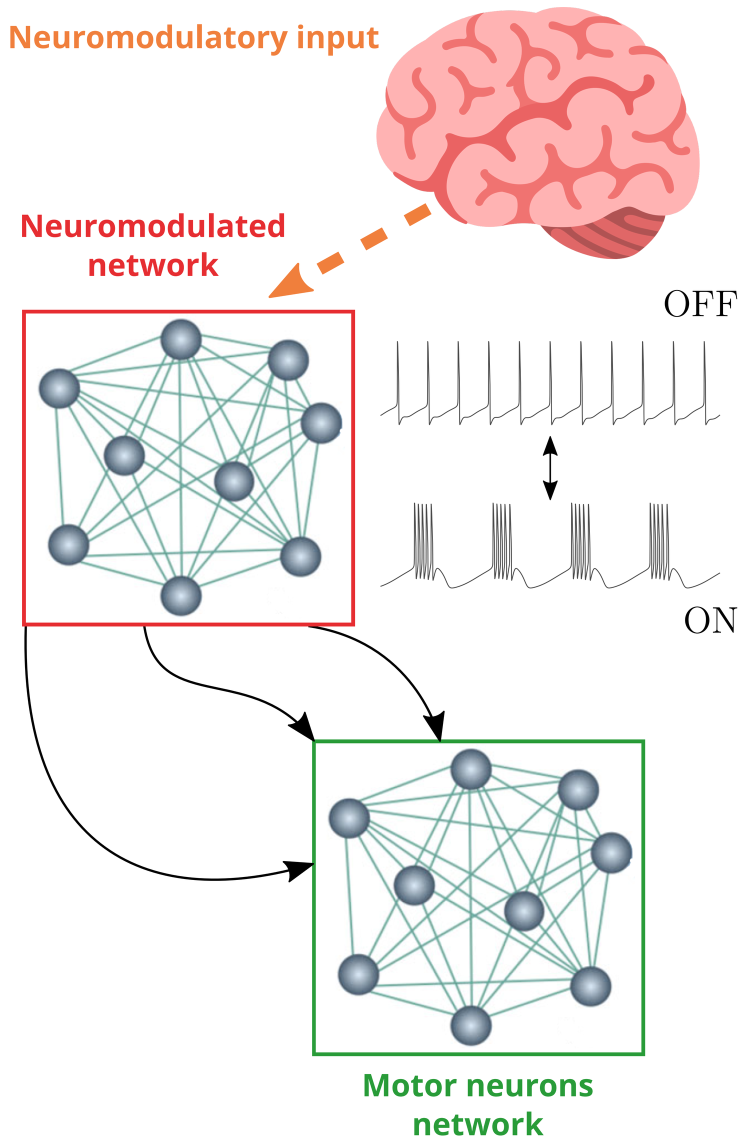
However, **living organisms** require rapid and localized transitions in rhythmic patterns:
→ Cannot rely on synaptic connectivity changes through plasticity
→ Triggered by neuromodulatory input in invertebrates [*Marder et al. 2014*]

In this poster: a novel approach to address this challenge by using neuromodulation to dynamically reconfigure fixed connectome networks of conductance-based models.

Neuromodulation in central pattern generators

Proposed top-down architecture:

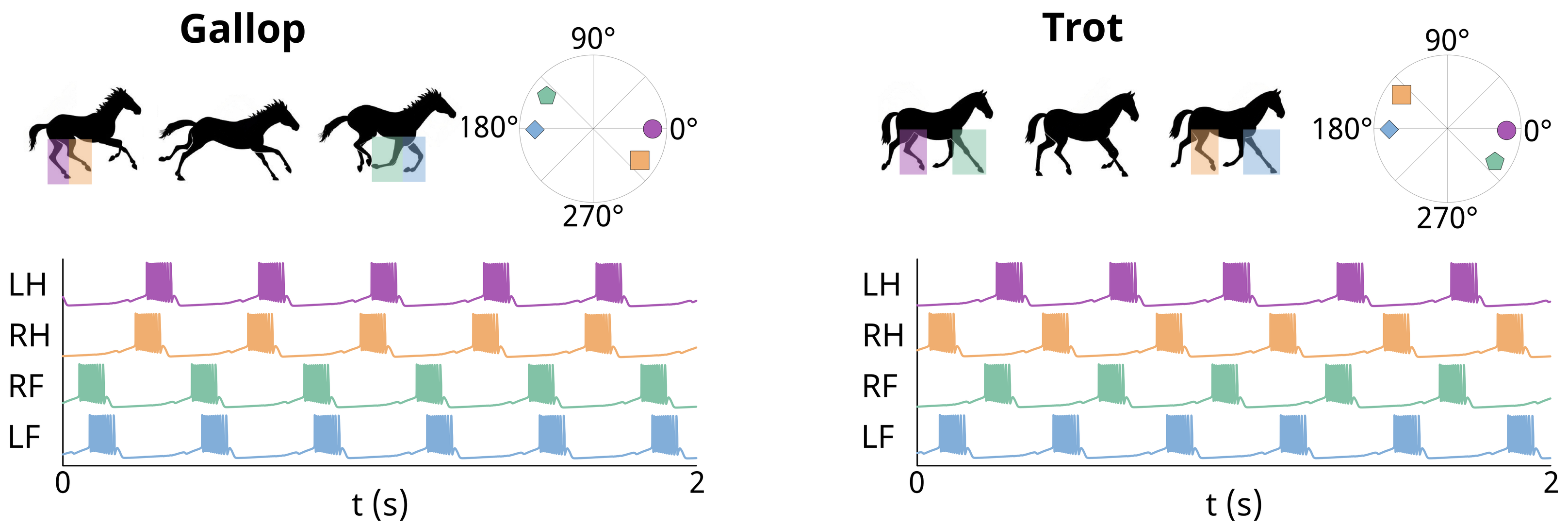
- The **neuromodulatory input**:
  → Projects to a **neuromodulated network**
  → Enables neurons in this network to switch between tonic spiking and bursting modes using a controller from *Fyon et al. 2023*
- The **neuromodulated network**:
  → Connects to the **motor neurons network** using inhibitory synapses
  → Induces rhythmic patterns in the **motor neurons network**
- The **motor neurons network**:
  → Consists of bursting neurons that activate muscles
  → Contains inhibitory synapses that regulate muscle activation patterns



The **neuromodulatory input** alters the rhythmic patterns by changing the behavior of the **neuromodulated network**, tuning the inhibitory input to the **motor neurons network**.

Example of a neuromodulated central pattern generator

We demonstrated our neuromodulated CPG architecture using a simple quadruped model with two rhythmic patterns: gallop and trot.

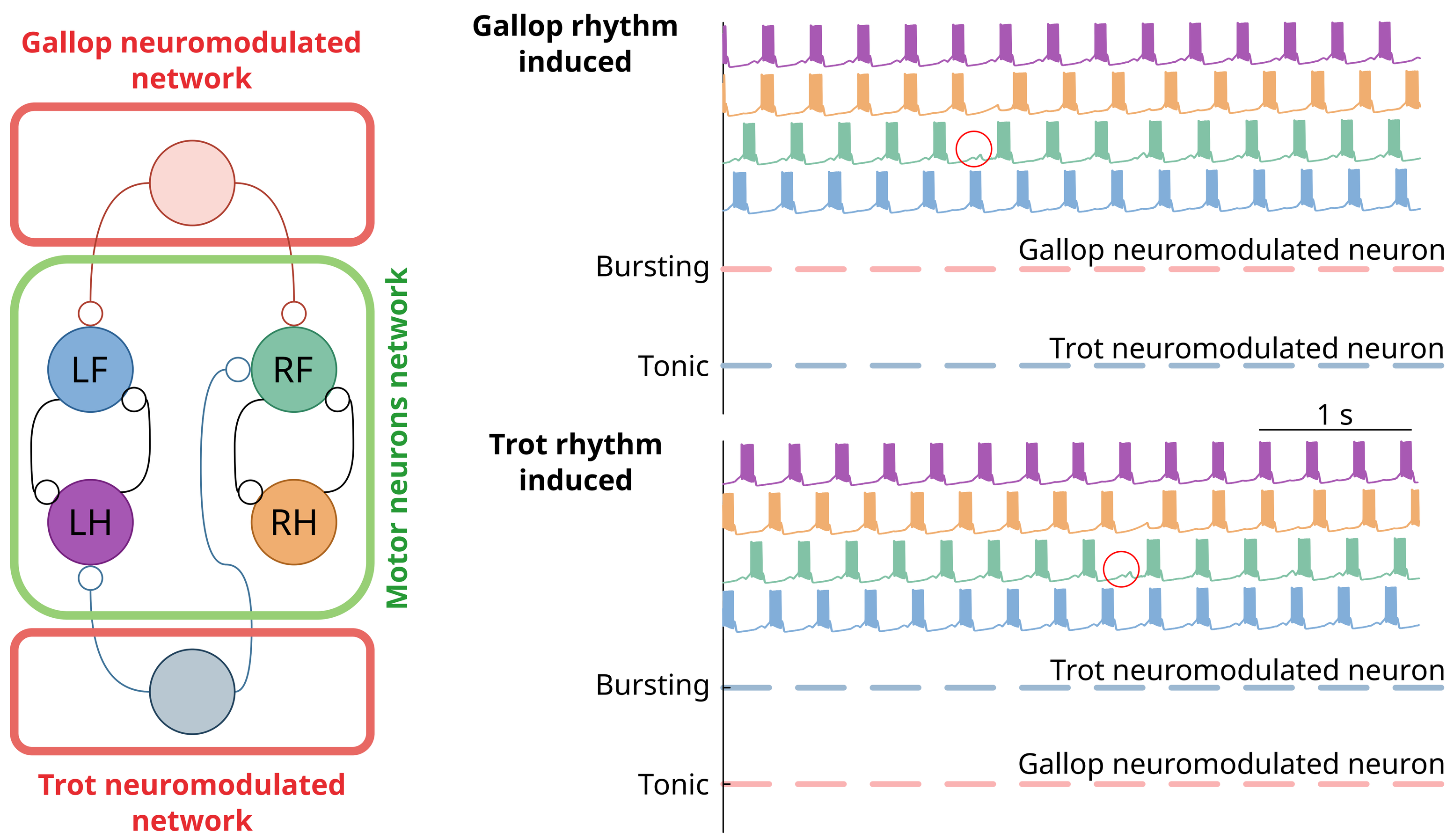


L stands for left, R for right, H for hip and F for front.

→ The **motor neurons network** is composed of 4 bursting neurons, one activating each leg
→ As the left and right legs are never activated at the same time, neurons activating both left and right legs can be placed in mutual inhibition loops.

Asymmetry in the neuromodulated network leads to unreliable behaviors

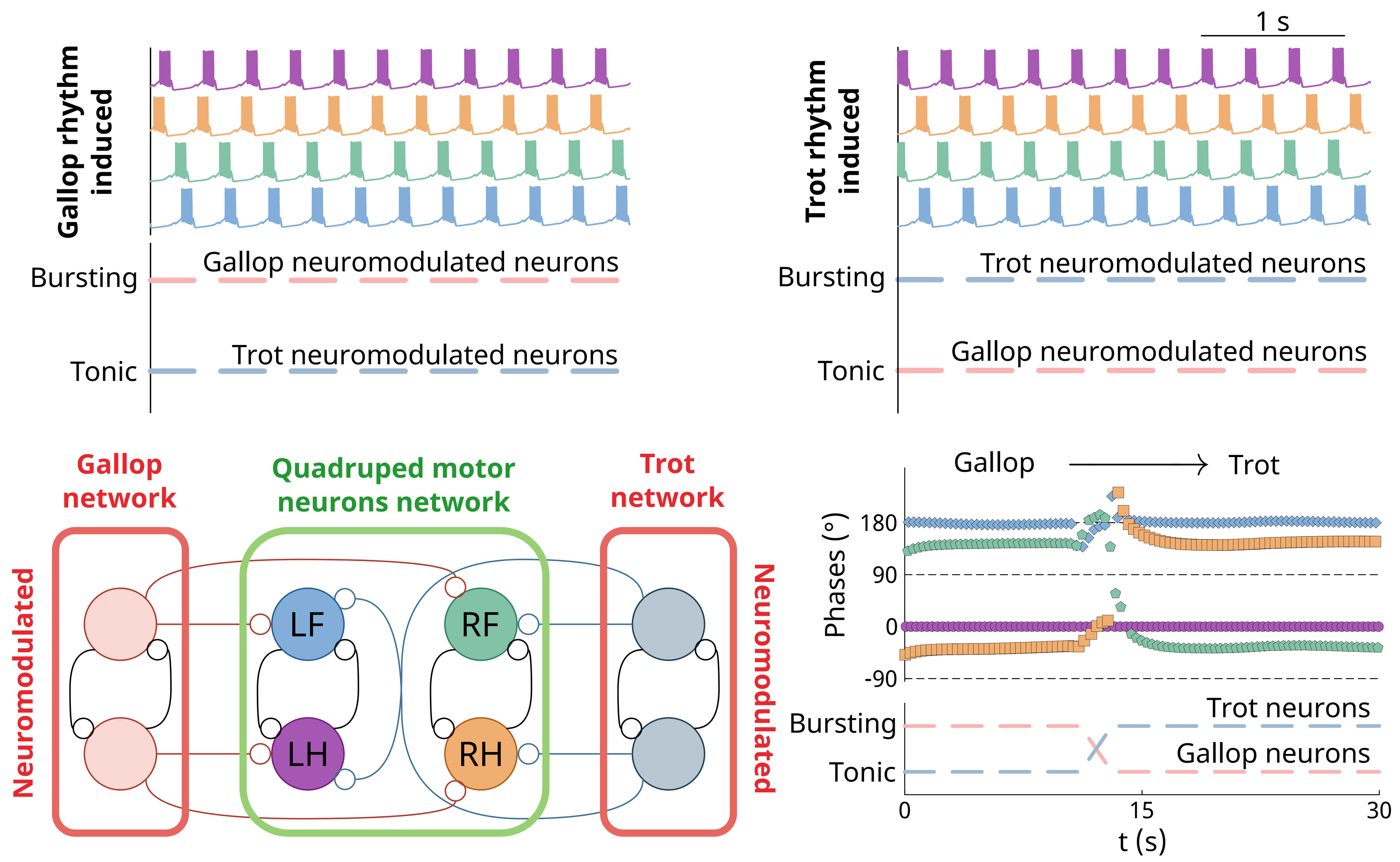
A minimal solution: **one** neuron per rhythm in the **neuromodulated network**.



→ Unreliable because of the asymmetric inhibitory projections from the **neuromodulated network** to the **motor neurons network**: the RF neuron receives too much inhibition.

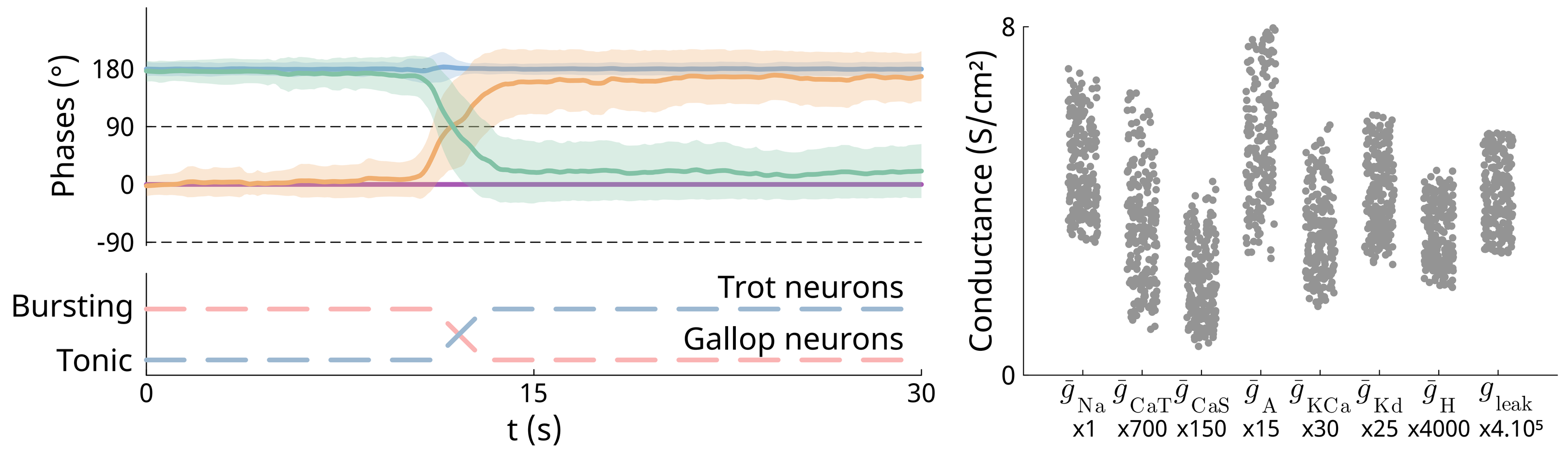
A symmetric neuromodulated network leads to reliable switches in rhythmic patterns

Symmetry in the inhibitory projections from the **neuromodulated network** to the **motor neurons network** is required:
→ **two** neurons per rhythm in mutual inhibition loop within the **neuromodulated network**.



→ Both rhythmic patterns are sustained.
→ Transitions from one pattern to the other are smooth and quick.
→ For both rhythmic patterns, only neuromodulation is involved as the connectome is unchanged.

The pattern transition is **robust** to **neuronal parameter variability**.



→ Despite a conductance variability up to five folds in all neurons, the rhythmic patterns are robust.
→ The transition from one pattern to another is robustly achieved without modifying the connectome, hence without involving synaptic plasticity.

Conclusions and perspectives

- Using only **a simple neuromodulatory input**, our central pattern generator architecture can robustly change between **neuronal rhythmic patterns** in the quadruped example.
- **Aim at generality** → this architecture is applicable to any central pattern generator that requires rhythmic switches and is **biologically plausible** as only neuromodulation is involved.

Future work

- Validation on several central pattern generators, such as the stomatogastric ganglion in crustaceans.
- Development of an automatic method to find the minimal architecture of both the **neuromodulated** and the **motor neurons networks**.
- Tests on neuromorphic robots

References

Dutta, Sourav et al. (2019). "Programmable coupled oscillators for synchronized locomotion". In: *Nature communications* 10.1, p. 3299.
Fyon, Arthur et al. (2023). "Reliable neuromodulation from adaptive control of ion channel expression". In: *IFAC-PapersOnLine* 56.2, pp. 458–463.
Marder, Eve et al. (2014). "Neuromodulation of circuits with variable parameters: single neurons and small circuits reveal principles of state-dependent and robust neuromodulation". In: *Annual review of neuroscience* 37, pp. 329–346.

Acknowledgments: *This work was supported by the Belgian Government through the FPS Policy and Support (BOSA) grant NEMODEI.*
Arthur Fyon is a FNRS Research Fellow.

 afyon@uliege.be