Oscillatory adaptive networks in cognition-like processes: from slime moulds to brain organoids

Keywords: Biological Networks, Network Neuroscience, Minimal cognition, Brain organoids, Oscillations, Adaptive networks

Extended Abstract

Understanding the origin of cognition is a central challenge across biology, neuroscience, and psychology. To address this, we must ask both how cognition first arose through evolution and how it develops within an individual. Progress requires identifying the mechanisms by which living systems process information, and mathematical models provide one way to uncover such mechanisms. Yet, building full models of the brain is difficult because of its complexity.

Simpler systems can therefore provide valuable insights. Oscillations and adaptation are two well-established mechanisms underlying cognition. For example, oscillatory processes are crucial for coordination in the human brain [1], while adaptation through synaptic plasticity is central to learning and memory [2]. Network science, with its focus on how structure and dynamics interact, offers a natural framework to study these processes in both evolutionary and developmental contexts.

In this talk, I will present two complementary examples where oscillatory adaptive networks are used as a basis for cognition-like processes. The first, from an evolutionary perspective, builds on recently published modelling work [3] on slime moulds and demonstrates how oscillations reinforce adaptive transport networks. The second, from a developmental perspective, introduces ongoing work on brain organoids, where we study how oscillatory activity emerges as neural networks grow. Together, these examples illustrate how adaptive oscillatory networks can serve as a unifying principle across systems that differ widely in scale and organization.

From an evolutionary perspective, basal organisms without nervous systems exhibit behaviours often described as minimal cognition. The slime mould *Physarum polycephalum* is a widely studied model organism for this purpose [4]. Despite being a single cell, it can solve shortest path problems [5], anticipate periodic events [6], and demonstrate forms of habituation [7]. To understand its adaptive behaviour, network adaptation models based on current-reinforcement have been proposed, most notably by Tero et al. in their formulation of feedback rules for tube growth [8]. However, these models do not incorporate the increasing evidence that spontaneous oscillations play a central role in sustaining learning processes [4]. To address this gap, we have recently presented a mechanistic model of *Physarum* that combines oscillatory dynamics with current-based reinforcement, showing how such processes generate adaptive networks capable of efficient resource allocation and problem-solving [3]. This model shows how oscillations enable efficient resource allocation, shortest-path formation, and problem-solving. By varying phase, amplitude, and frequency differences, we demonstrate that oscillatory inputs can sustain adaptive network growth, produce long-range synchronization, and generate robust solutions even under environmental variation.

From a developmental perspective, brain organoids provide a promising model of early neural development. These three-dimensional self-organizing tissues exhibit spontaneous oscillations as neural connections form [9]. However, the interplay between network growth, adaptation, and the onset of oscillations has not been systematically studied. In ongoing work with collaborators in experimental neurology, we combine multielectrode array (MEA) recordings with network analysis and modelling to investigate how oscillations emerge in growing organoid networks and how structural development shapes synchronous activity. Our aim is to investigate how network topology and oscillatory dynamics interact during organoid development, and whether comparable principles emerge to those seen in simpler biological systems.

Taken together, these two examples – *Physarum* as an evolutionary case and organoids as a developmental one – illustrate how oscillatory adaptive networks can generate cognition-like processes. In my talk, I hope to show how studying adaptive networks in both evolutionary and developmental contexts can contribute to our understanding of how cognition emerges.

Ethical Considerations

Modelling slime mould behaviour involves no human or animal data and poses no ethical concerns. The study of brain organoids, carried out with experimental collaborators, considers these systems solely as models of neural development, in line with current consensus that they do not possess features of consciousness. We acknowledge that analogies between basal and neural systems can be overinterpreted and therefore present them cautiously. Oversight of biomaterial sourcing follows institutional review processes and international stem cell guidelines, while my role focuses on data analysis, modelling, and theoretical interpretation.

References

[1] E Başar et al. “Brain oscillations in perception and memory”. In: *International journal of psychophysiology* 35.2-3 (2000), pp. 95–124.

[2] Simon D Fisher et al. “Reinforcement determines the timing dependence of corticostriatal synaptic plasticity in vivo”. In: *Nature communications* 8.1 (2017), p. 334.

[3] Anonymous. *Blinded for review*. 2025.

[4] Aurèle Boussard et al. “Adaptive behaviour and learning in slime moulds: the role of oscillations”. In: *Philosophical Transactions of the Royal Society B* 376.1820 (2021), p. 20190757.

[5] Madeleine Beekman and Tanya Latty. “Brainless but multi-headed: decision making by the acellular slime mould Physarum polycephalum”. In: *Journal of molecular biology* 427.23 (2015), pp. 3734–3743.

[6] Tetsu Saigusa et al. “Amoebae anticipate periodic events”. In: *Physical review letters* 100.1 (2008), p. 018101.

[7] Romain P Boisseau, David Vogel, and Audrey Dussutour. “Habituation in non-neural organisms: evidence from slime moulds”. In: *Proceedings of the Royal Society B: Biological Sciences* 283.1829 (2016), p. 20160446.

[8] Atsushi Tero, Ryo Kobayashi, and Toshiyuki Nakagaki. “Physarum solver: A biologically inspired method of road-network navigation”. In: *Physica A: Statistical Mechanics and its Applications* 363.1 (2006), pp. 115–119.

[9] Ranmal A Samarasinghe et al. “Identification of neural oscillations and epileptiform changes in human brain organoids”. In: *Nature neuroscience* 24.10 (2021), pp. 1488–1500.