Nonlocal Coupling Effects on a Network of Neurons

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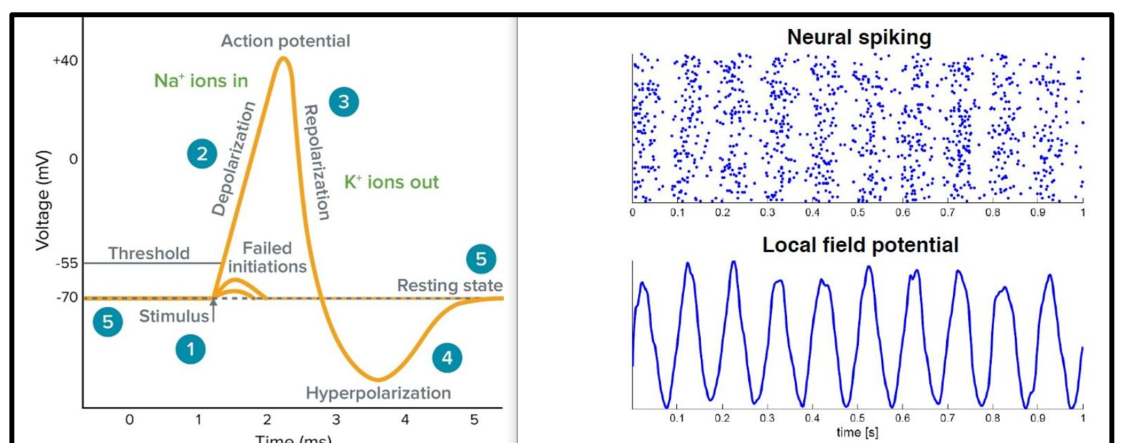
Objective

The objective of this research was to study how nonlocal coupling affects the formation of patterns and chimera states in networks of neurons.

Background

- **Systems of neurons can exhibit excitatory and oscillatory behavior. An example of excitatory behavior is a neuron's action potential, and an example of oscillatory behavior is the firing of neurons in a periodic manner.**
- **We use Wiener-Rosenblueth (WR) and FitzHugh-Nagumo (FHN) models to study how nonlocal coupling (the connection between neurons) affects pattern formation in excitatory and oscillatory systems, respectively.**
- **We model a network of neurons with a square grid, and apply WR and FHN equations to it.**
- **In excitatory systems, we will explore how nonlocal coupling affects spiral wave formation. In oscillatory systems, we will determine how the Levy walk model and a two layer network affect the formation of chimeras.**



Left: neuron action potential; right: neural oscillators

Left: *What is an action potential?*, (Molecular Devices), https://www.moleculardevices.com/applications/patch-clamp-electrophysiology/what-action-potential#gref
Right: *Neural oscillation*, (Wikipedia), https://en.wikipedia.org/wiki/Neural_oscillation

Motivation

- **Experiments have found that in the brain there are mixed regions of synchronous and asynchronous neural activity. These states, called chimeras, have been found to increase efficiency in the brain [4].**
- **Research suggests that epileptic seizures occur when chimera states form in synchronous regions and then collapse [1].**
- **It is believed that stabilizing chimera states in the brain can reduce epileptic seizures.**
- **Here we study simple models describing network of neurons that are capable of reproducing chimera states. We explore the role of nonlocal coupling in stabilizing these patterns, with the hope that our results can guide research into epileptic seizures.**

FitzHugh-Nagumo Model

- **The FHN model is a simplified, dynamical, two-dimensional version of the Hodgkin-Huxley model, which models neuron behavior as an electrical circuit.**
- **FHN consists of a voltage-like variable, u, that exhibits excitatory behavior and a recovery variable, v, that provides a negative feedback.**
- **Based on the parameters, the FHN model can exhibit excitatory or oscillatory behavior. However, we will only look at the oscillatory case. This occurs when the parameter *a* in the equations below is less than 1.**
- **Using the Poincaré-Bendixson Theorem, we can prove that when *a* < 1, the system has a limit cycle and therefore displays oscillatory behavior.**

$$\epsilon\frac{du_{ij}}{dt} = u_{ij} + u_{ij}^3 - v_{ij} + \frac{\sigma}{N_r - 1}\sum_{(mn)\in B_r(i,j)} bxx(u_{ij} - u_{mn}) + bxy(v_{ij} - v_{mn})$$

$$\frac{dv_{ij}}{dt} = u_{ij} + a + \frac{\sigma}{N_r - 1}\sum_{(mn)\in B_r(i,j)} byx(u_{ij} - u_{mn}) + byy(v_{ij} - v_{mn})$$

Schmidt, Kasimatis, Hizanidis, Provata, and Hovel, *Chimera patterns in two-dimensional networks of coupled neurons*, (2017)

Excitatory System

Wiener-Rosenblueth Nonlocal Coupling Model

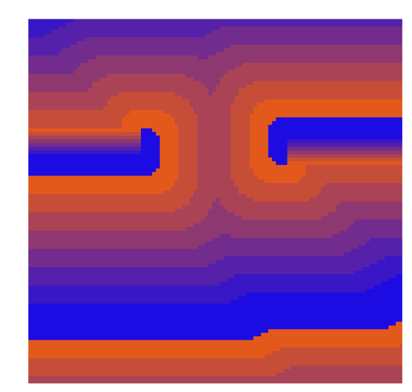
$$\Phi_{ij}^{n+1} = \begin{cases} \Phi_{ij}^n + 1, & \text{if } 0 < \Phi_{ij}^n < \tau_e + \tau_r \\ 0, & \text{if } \Phi_{ij}^n = \tau_e + \tau_r \\ 0, & \text{if } \Phi_{ij}^n = 0 \text{ and } u_{ij}^{n+1} < h \\ 1, & \text{if } \Phi_{ij}^n = 0 \text{ and } u_{ij}^{n+1} \geq h \end{cases} \qquad I_{ij}^n = \begin{cases} 1, & \text{if } 0 < \Phi_{ij}^n < \tau_e \\ 0, & \text{if } \tau_e < \Phi_{ij}^n \leq \tau_e + \tau_r \text{ or } \Phi_{ij}^n = 0; \end{cases}$$

$$u_{ij}^{n+1} = g u_i^n j + \sum_{k,l} C(k,l) I_{i+k,j+l}^n \qquad C(k,l) = \begin{cases} 1, & \text{if } |k| \leq 1 \ and \ |l| \leq 1 \\ 0, & \text{otherwise} \end{cases}$$

- **Early research found that people's brains exhibited spiral wave like patterns when hallucinating [8].**
- **We chose to extend the coupling range of the Weiner-Rosenblueth model to see how this would affect pattern formation.**
- **Overall the spacing between spiral wave arms decreased proportionally to the range of coupling.**

τe = 5, τr = 7, g = 0, h = 3, R = 1

τe = 5, τr = 7, g = 0, h = 3, R = 3



τe = 5, τr = 7, g = 0, h = 3, R = 5

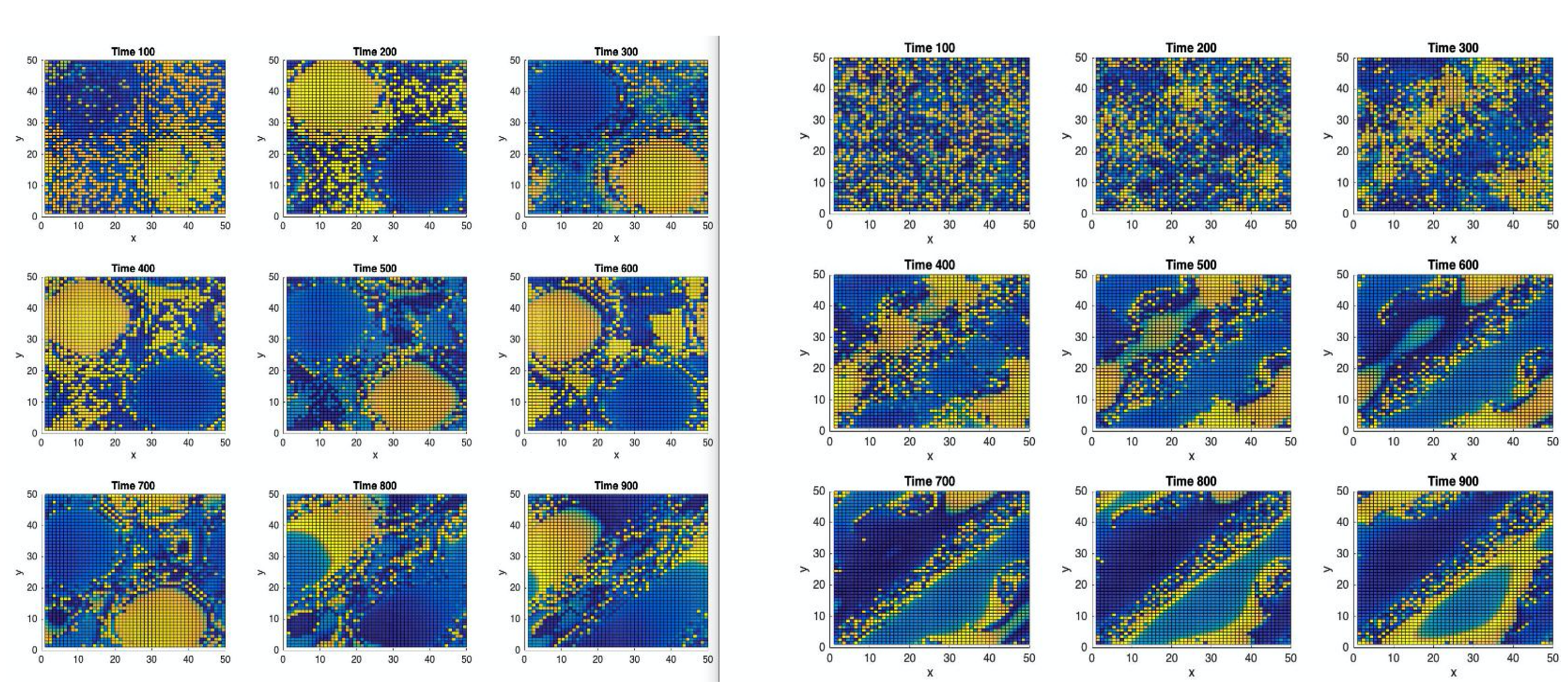
Oscillatory System

Levy-Type Coupling

- **We will use a Levy distribution to determine the coupling strength between different neurons.**
- **Levy distributions are heavy-tailed probability distributions use to describe the step lengths of a particle undergoing a Levy flight.**
- **Levy distributions follow a power law, so long length steps are less likely to occur than short steps. Similarly, for the FHN model shown below, neighbors that are farther away from a cell do not influence it as much as neighbors that are closer to it.**

$$\epsilon\frac{du_{ij}}{dt} = u_{ij} + u_{ij}^3 - v_{ij} + \frac{\sigma}{N_r - 1}\sum_{(mn)\in B_r(i,j)} \frac{bxx(u_{ij} - u_{mn})}{((i-m)^2 + (j-n)^2)^{\mu} l^{\mu}} + \frac{bxy(v_{ij} - v_{mn})}{((i-m)^2 + (j-n)^2)^{\mu} l^{\mu}}$$

$$\frac{dv_{ij}}{dt} = u_{ij} + a + \frac{\sigma}{N_r - 1}\sum_{(mn)\in B_r(i,j)} \frac{byx(u_{ij} - u_{mn})}{((i-m)^2 + (j-n)^2)^{\mu} l^{\mu}} + \frac{byy(v_{ij} - v_{mn})}{((i-m)^2 + (j-n)^2)^{\mu} l^{\mu}}$$



Grid on the left: nonlocal coupling in the original FHN system; grid on the right: FHN model with Levy-type coupling. For both models, N = 50, a = 0.5, σ = 0.1, φ = π/2 - 0.15, r = 19, dt = 0.02.

Oscillatory System

Two Layer FHN Model

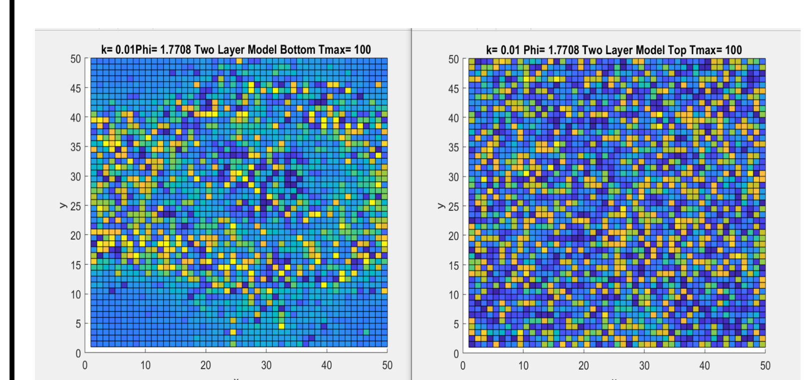
$$\epsilon\frac{du_{ij}}{dt} = u_{ij} + u_{ij}^3 - v_{ij} + \frac{\sigma}{N_r - 1}\sum_{(mn)\in B_r(i,j)} bxx(u_{ij} - u_{mn}) + bxy(v_{ij} - v_{mn}) + \kappa u_{ij}^b$$

$$\frac{dv_{ij}}{dt} = u_{ij} + a + \frac{\sigma}{N_r - 1}\sum_{(mn)\in B_r(i,j)} byx(u_{ij} - u_{mn}) + byy(v_{ij} - v_{mn}) + \kappa v_{ij}^b$$

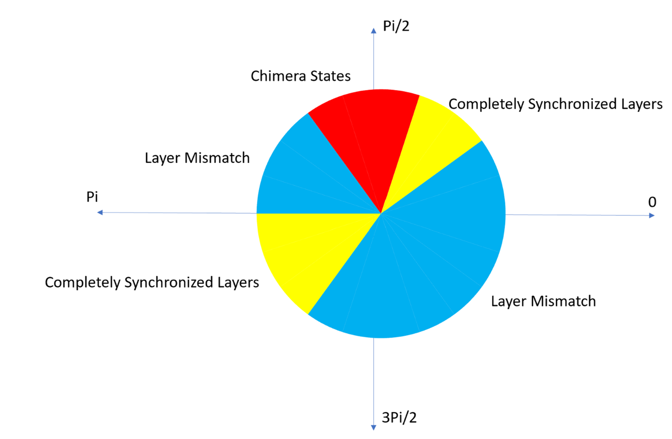
$$\epsilon\frac{du_{ij}^b}{dt} = u_{ij}^b + {u_{ij}^b}^3 - v_{ij}^b + \kappa u_{ij}$$

$$\frac{dv_{ij}^b}{dt} = u_{ij}^b + a + \kappa v_{ij}$$

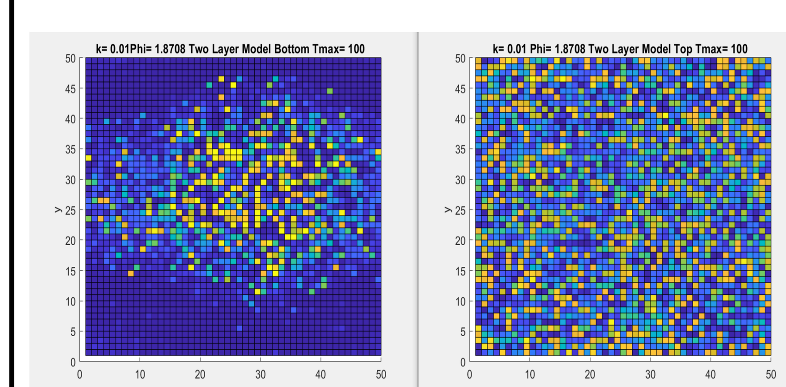
- **Recent research has found that chimera states can be synchronized in different regions of the brain using the corpus callosum as a medium [6].**
- **We chose to create a two layer grid of FHN oscillators which acts similar to the corpus callosum. The bottom layer has nonlocal interlayer and intralayer coupling, while the top layer contains only nonlocal interlayer coupling.**
- **We found that chimera states emerged when φ is approximately in the range (1.3,1.9) & κ =.01 in the case (R=19, N=50, σ =.10, T = 100).**



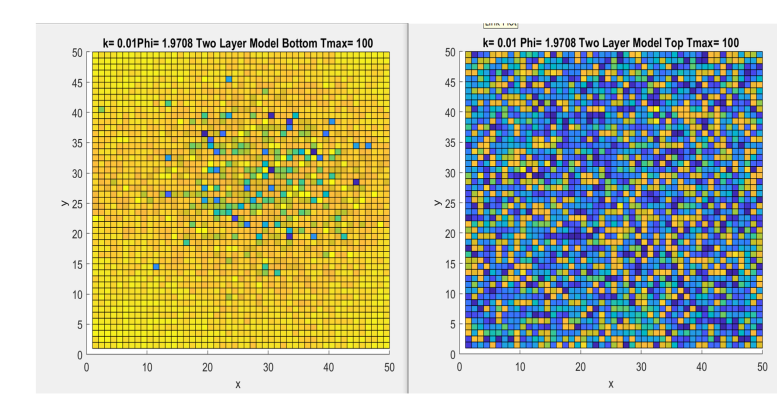
φ = 1.77, N= 50, σ=.1, R=19, T= 100, κ =.01



Different Types of Patterns observed



φ = 1.87, N= 50, σ=.1, R=19, T= 100, κ =.01



φ = 1.97, N= 50, σ=.1, R=19, T= 100, κ =.01

Conclusion/Future Works

- **In the Wiener-Rosenblueth model, nonlocal coupling changed the spacing between spiral arms.**
- **Compared to the results we got from the original FHN model, we found that Levy-type coupling changed the type of chimera patterns observed: oscillating spot chimeras were replaced by striped chimeras. Meanwhile the Two Layer FHN model was able to stabilize and create chimeras when the original FHN model could not.**
- **In the future, more cases should be tested and at longer times.**

References and Acknowledgements

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