Pattern formation and criticality in the developing retina

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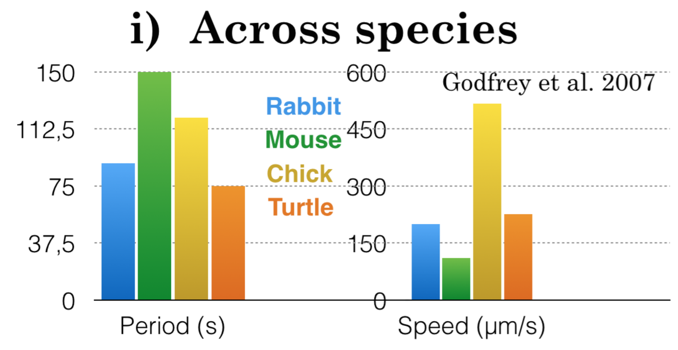
Abstract

In the early retina, spontaneous collective network activity emerges as propagating waves, playing a central role in shaping the visual system. Elucidating how the characteristics of such waves depend on biophysical parameters, would help us understand the underlying mechanisms of spatio-temporal patterns formation in the developing retina and their role in shaping the visual system. We have elaborated a set of detailed biophysical equations for a network of retinal cells coupled with excitatory lateral cholinergic connections, close enough to reality to reproduce and predict experimental results. From bifurcation theory, we predict that there exists a regime of parameters for which the network of cells in the developing retina is a critical system. This property is manifested via power law distributions for the waves characteristics (i.e. waves size), meaning that waves statistics could exhibit maximal variability. This critical regime is analytically characterized, predicting the exact form of the critical coupling strength of cells. Away from this regime of parameters, no power-law like distributions are observed. This theoretical result is in agreement with our experimental recordings in perinatal mice, revealing power-laws as well, suggesting that there exists a mechanism setting the retinal cells close to this critical regime.

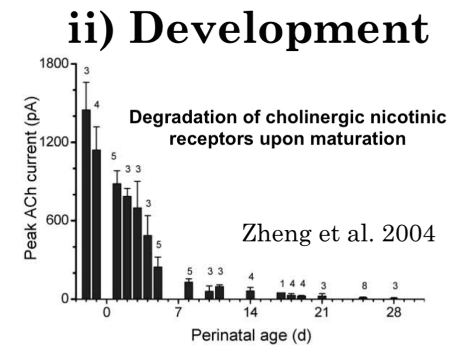
Context & Motivation

Retinal waves characteristics exhibit a vast variability:

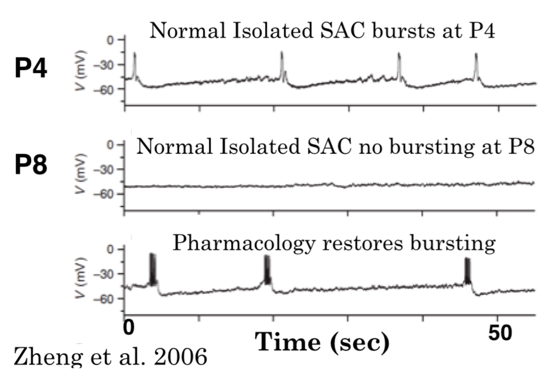
i) Across species



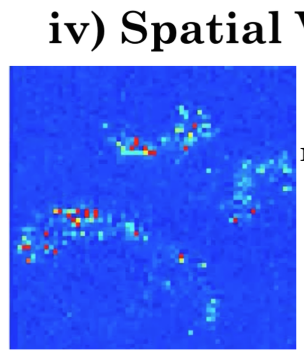
ii) Development



iii) Pharmacology



iv) Spatial Variability



Maccione et al. 2014

Waves have variable shapes due to a refractory mechanism which controls their borders. It is called sAHP (slow AfterHyper Polarization) for stage II.

Questions:

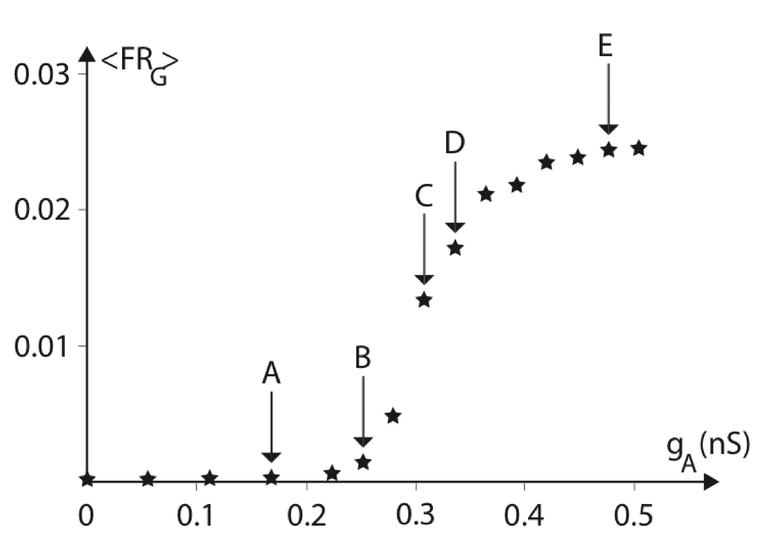
1. How do the variable characteristics of retinal waves depend on **few** biophysical parameters?
2. How can we **characterize** quantitatively the **different dynamical regimes** and the transitions between them?
3. Why is it important for the early retinal network to exhibit **large variability** in the characteristics of **spatiotemporal patterns**?
4. What are the biophysical **mechanisms** of the spatiotemporal **patterns formation** in the early retina?

Patterns vary upon parameters variation

Having proposed a biophysical model for retinal waves [1], we use our equations to understand the underlying mechanisms of waves apparition and propagation:

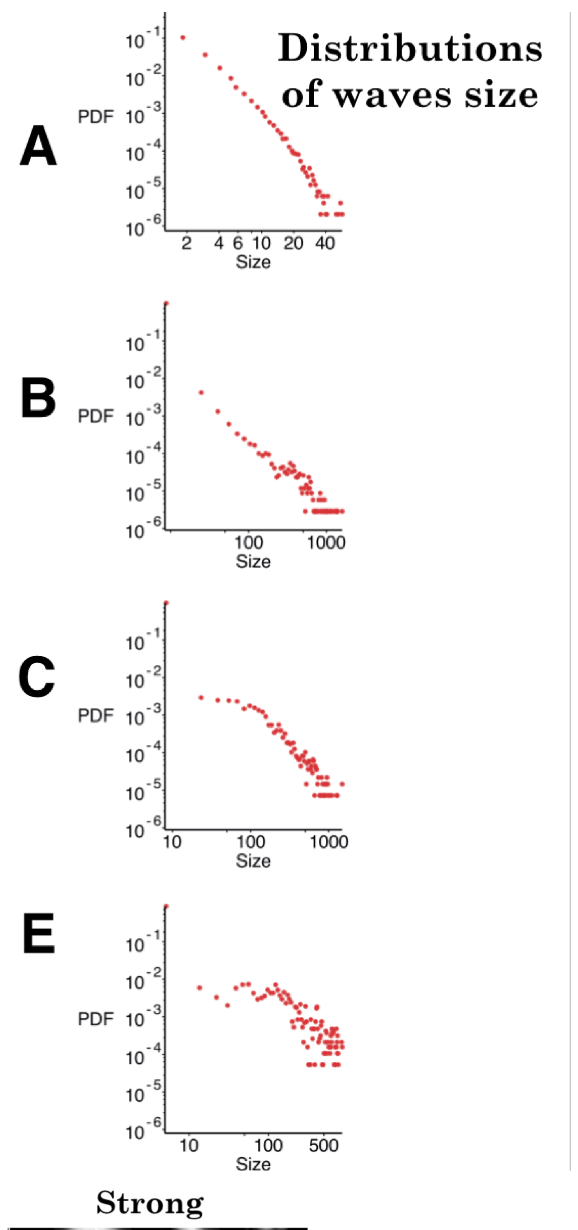
Classifying patterns on 2D

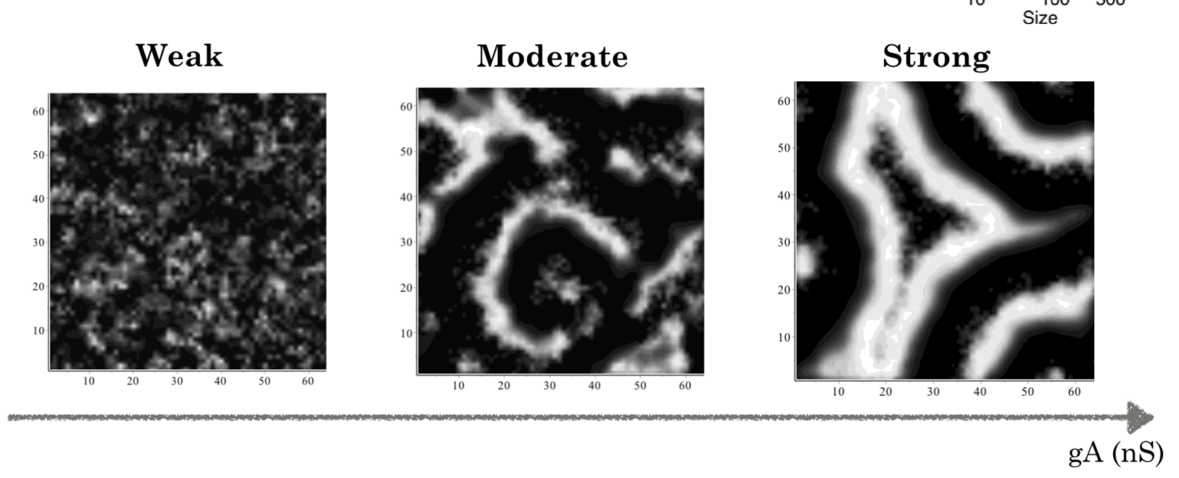
Average population firing rate



The average population firing rate undergoes a transition at a specific range of cholinergic coupling

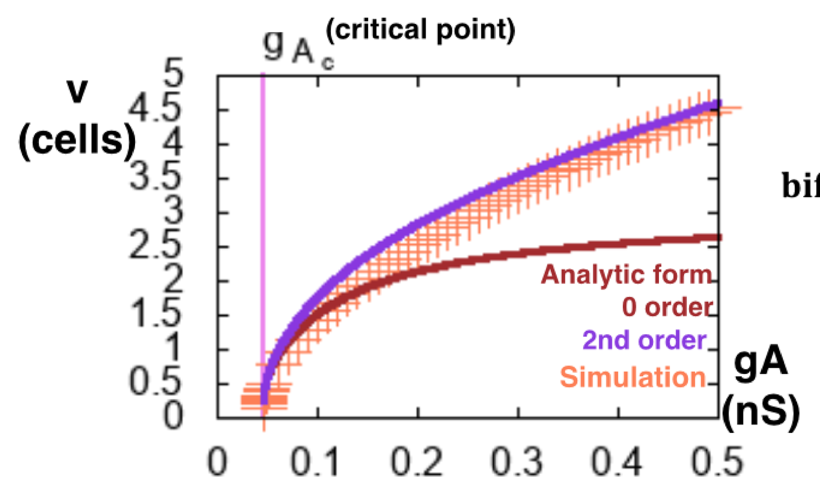
Distributions of waves size





Analytic condition for wave propagation

Waves propagation analytic condition for a critical threshold of cholinergic coupling



Based on our model, where wave propagation is <u>only possible</u> when the **total current received by a neighbouring cell exceeds the** (saddle-node) **bifurcation threshold**, we extract the analytic form for the waves propagation coupling threshold (1D case).

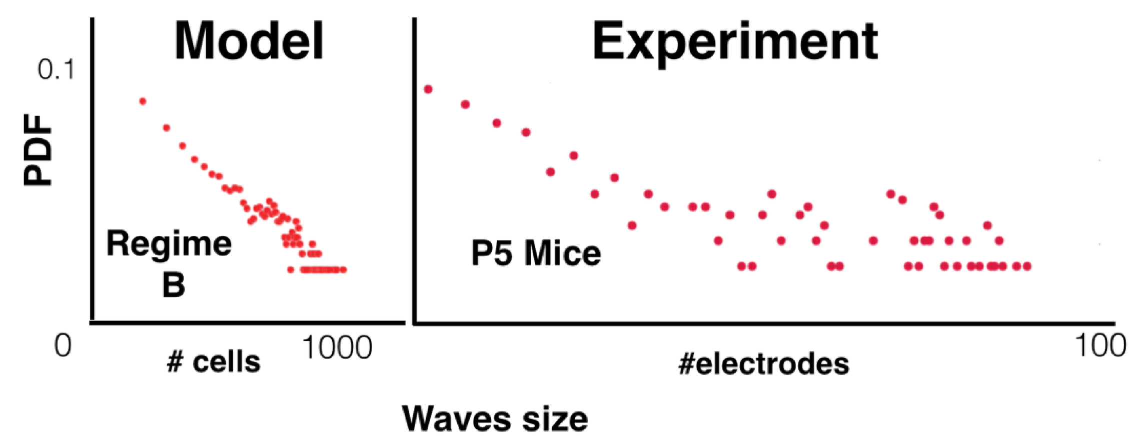
$$g_{A_c} = -\frac{2\mu\sqrt{\gamma_A}}{n_i \beta \Omega} \frac{I_{SN} + g_S R^4 (V_- - V_K)}{V_- - V_A}$$

Based on bifurcation theory:

1. We derive **analytic forms** for a critical **waves propagation threshold** of coupling strength among cells g_{A_C}, and for the **waves speed** (not shown).
2. We propose a possible mechanism of how power-law distributions could appear near this propagation threshold, where the cell is in fact **close to a** (saddle-node) **bifurcation point**. At this point, dynamics are driven mainly by noise fluctuations, leading to maximum variance in the patterns characteristics (e.g. waves size), manifesting power-law like distributions, and therefore indicating possible links to criticality.

Finding power-laws in experiments

We performed MEA (256 electrodes) **experiments on P5 mice** (stage II retinal waves) at Vision Institute, Paris.



- A power-law distribution for the waves size is computed at the regime where the transition occurs in our model (B), matching our experimental data on P5 mice.
- This indicates that maybe the network of SACs is naturally set close to a critical state by a possible **homeostatic mechanism**, yet to be identified.

Conclusions and Perspectives

- Our model allows us to anticipate how biophysical parameters variations (e.g. conductance) may impact the characteristics of waves.
- We predict that SACs are close to a bifurcation point, leading to explaining the different types of variability of retinal waves as well as proposing encouraging, although still primary links to criticality.
- Further analysis is needed to characterize critical systems, such as studying in detail possible phase transitions, and computing critical exponents on the theoretical side.
- On the experimental side, new and more precise methods should be proposed for the exact characterization of power-law distributions in experimental recordings.
- Extend our phenomenological model in order to identify the possible homestatic mechanism that drives the network to a critical state.
- Explore the role of the indicated criticality in the early retina, possibly related to an optimizing the response sensitivity to multi-scale stimuli upon maturation, enhancing the dynamical range of the early network (Steven's law).

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