Waves4AI

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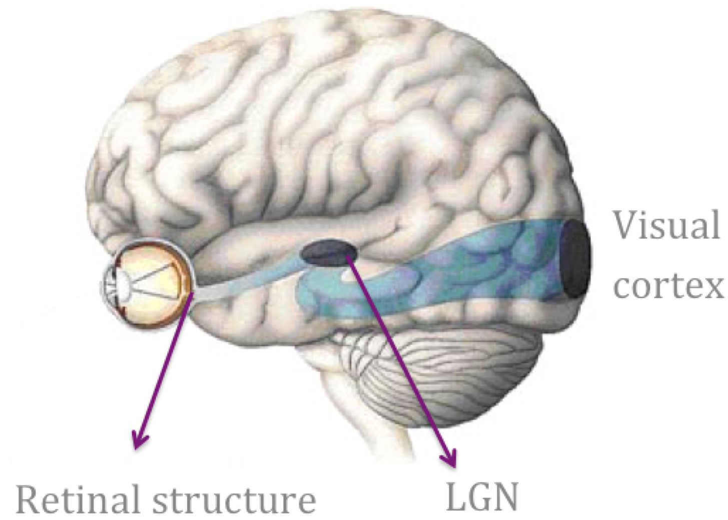
Sophia Antipolis, France

Context

The visual system



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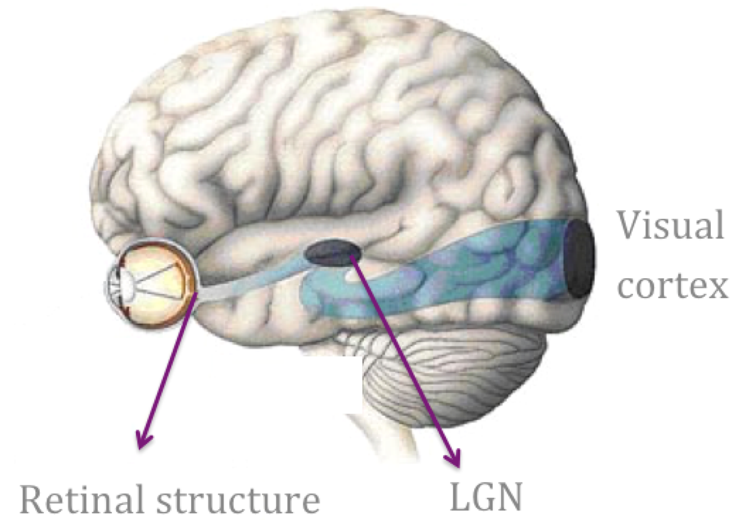
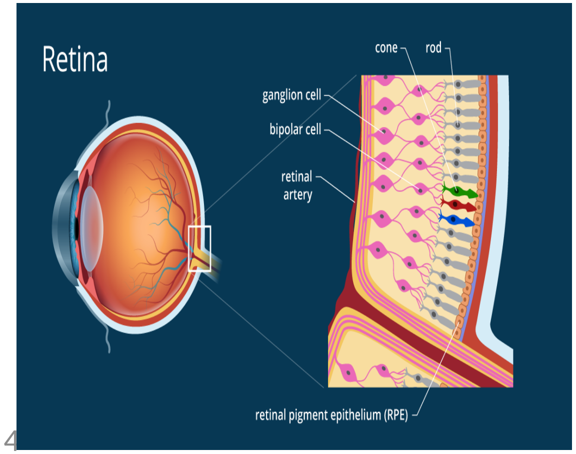
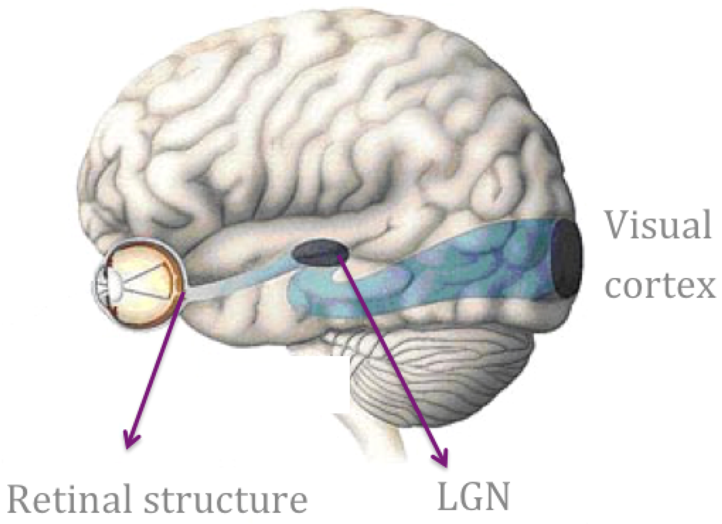
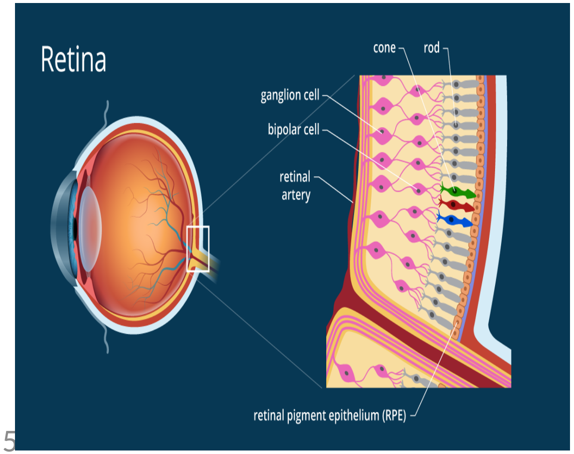




The visual system

Retinal processing: What the visual cortex receives as information from the external world.





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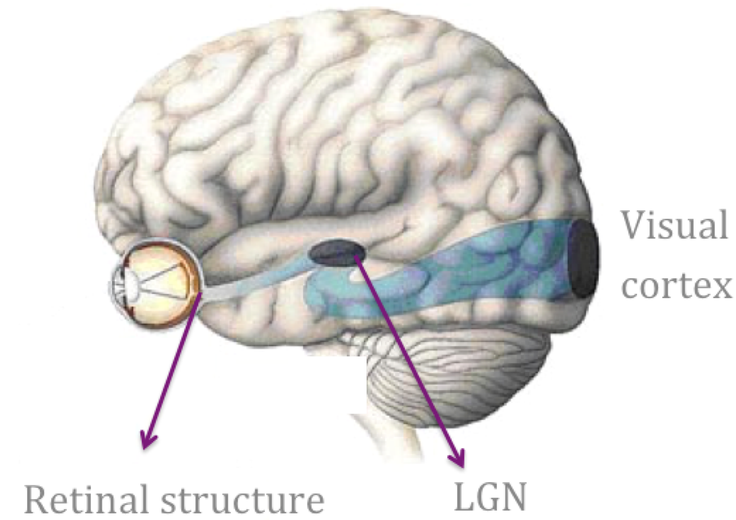
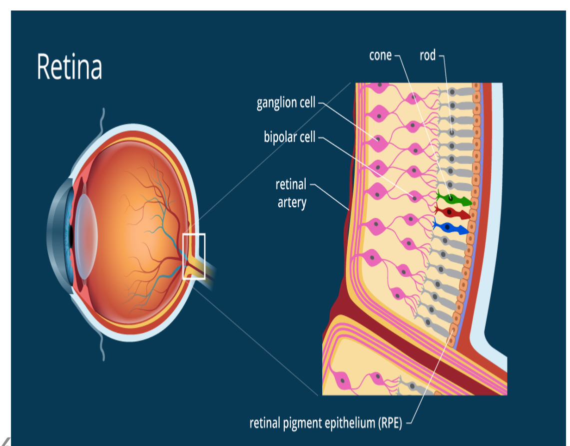
The external world is made of **motion** generating an ever changing (**non stationary**) flow of information.





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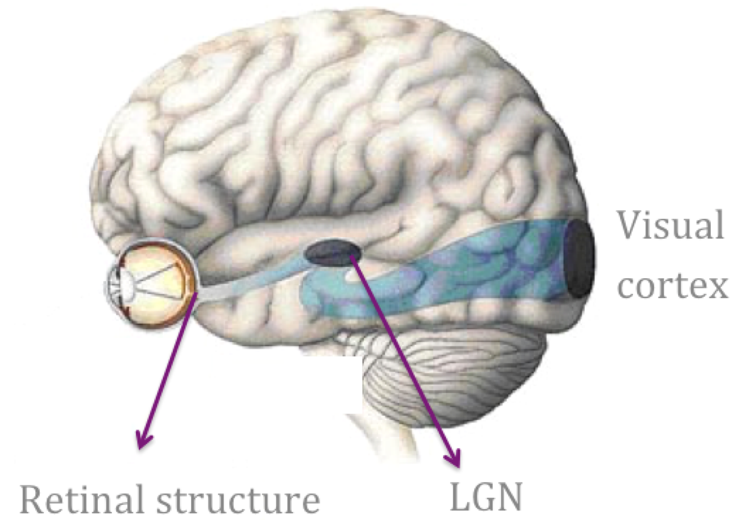

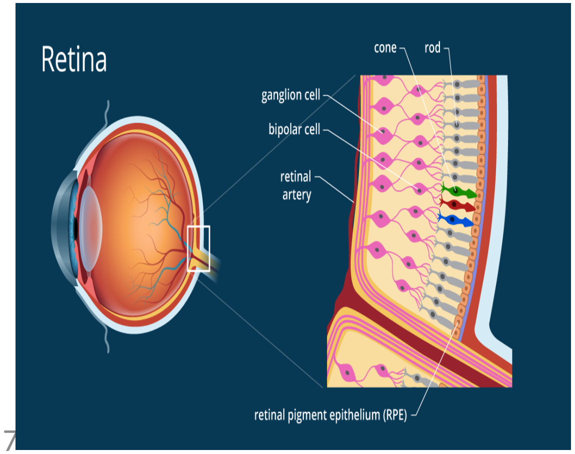

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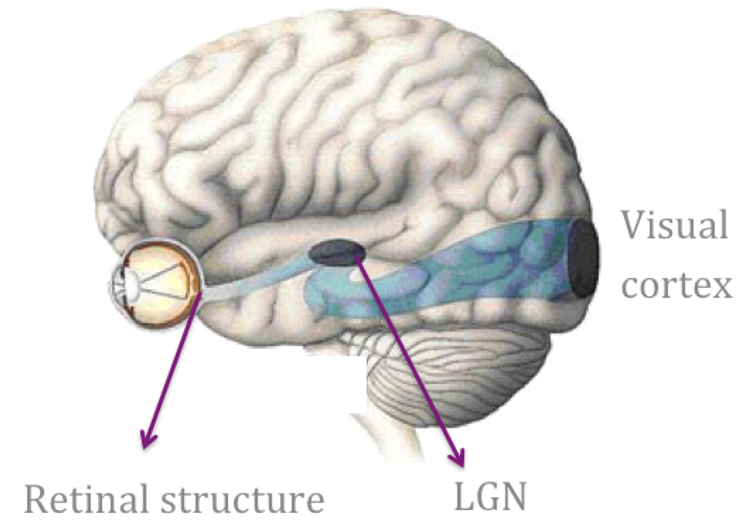

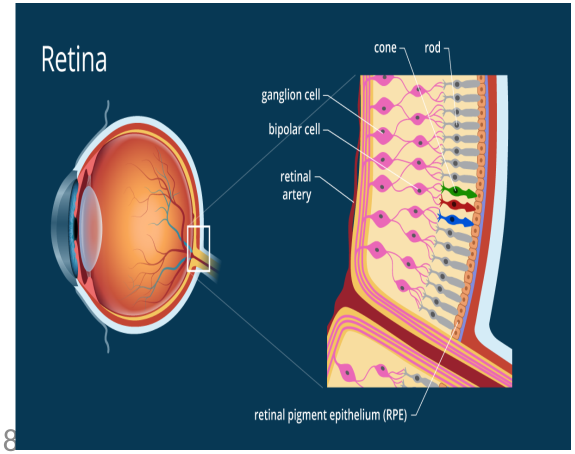

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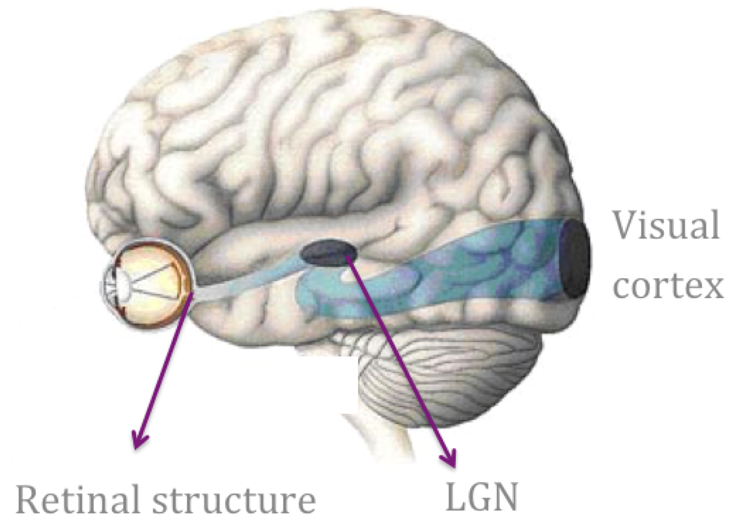

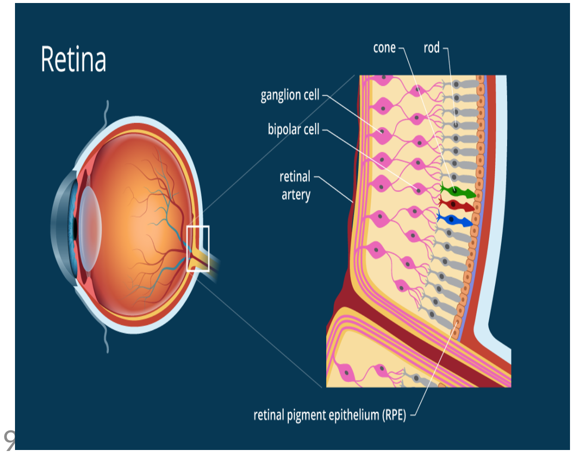

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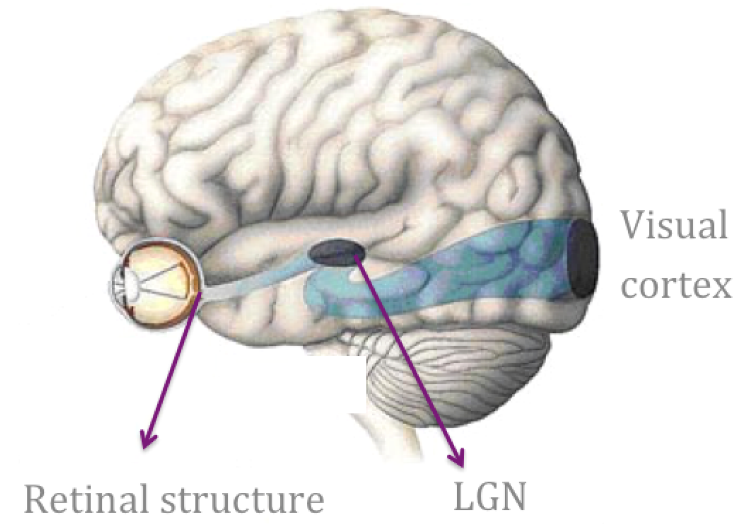
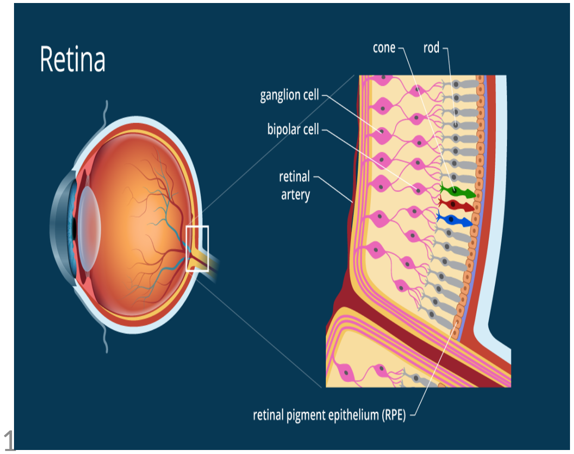
What can we learn from retinal waves activity that could be helpful to improve AI systems ?

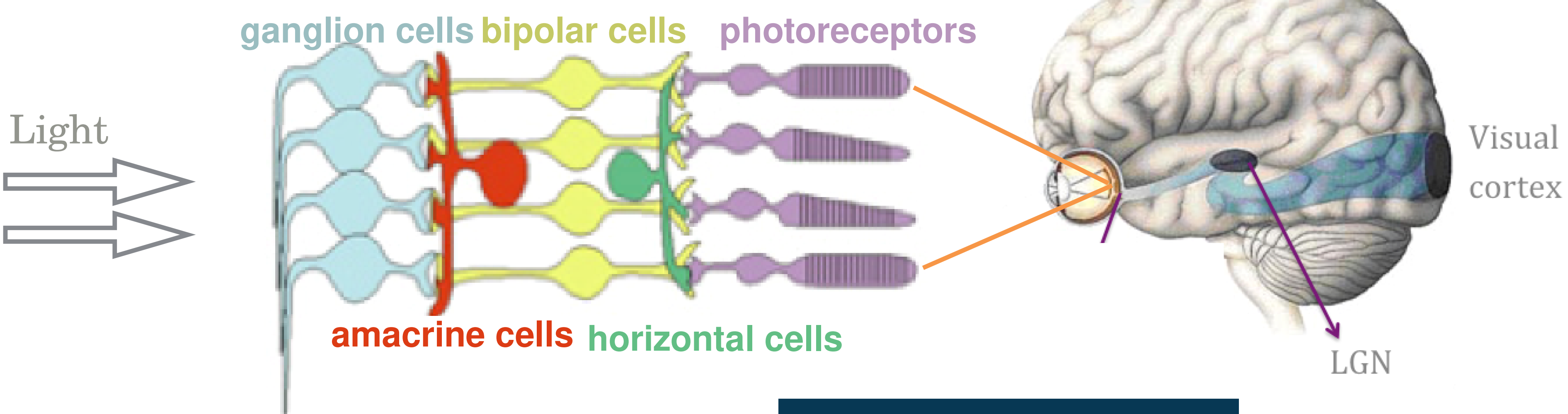


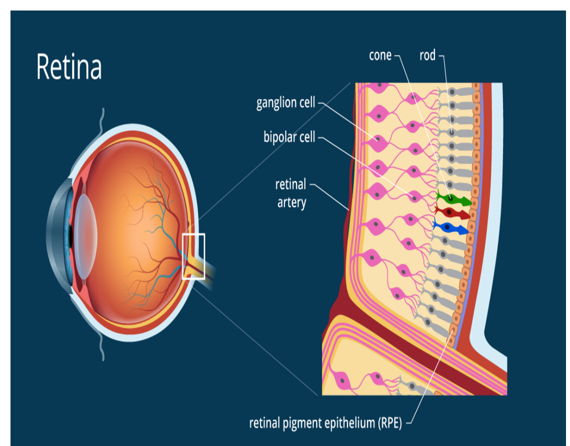


The retina and its dynamics

The visual system

Retina's layered structure





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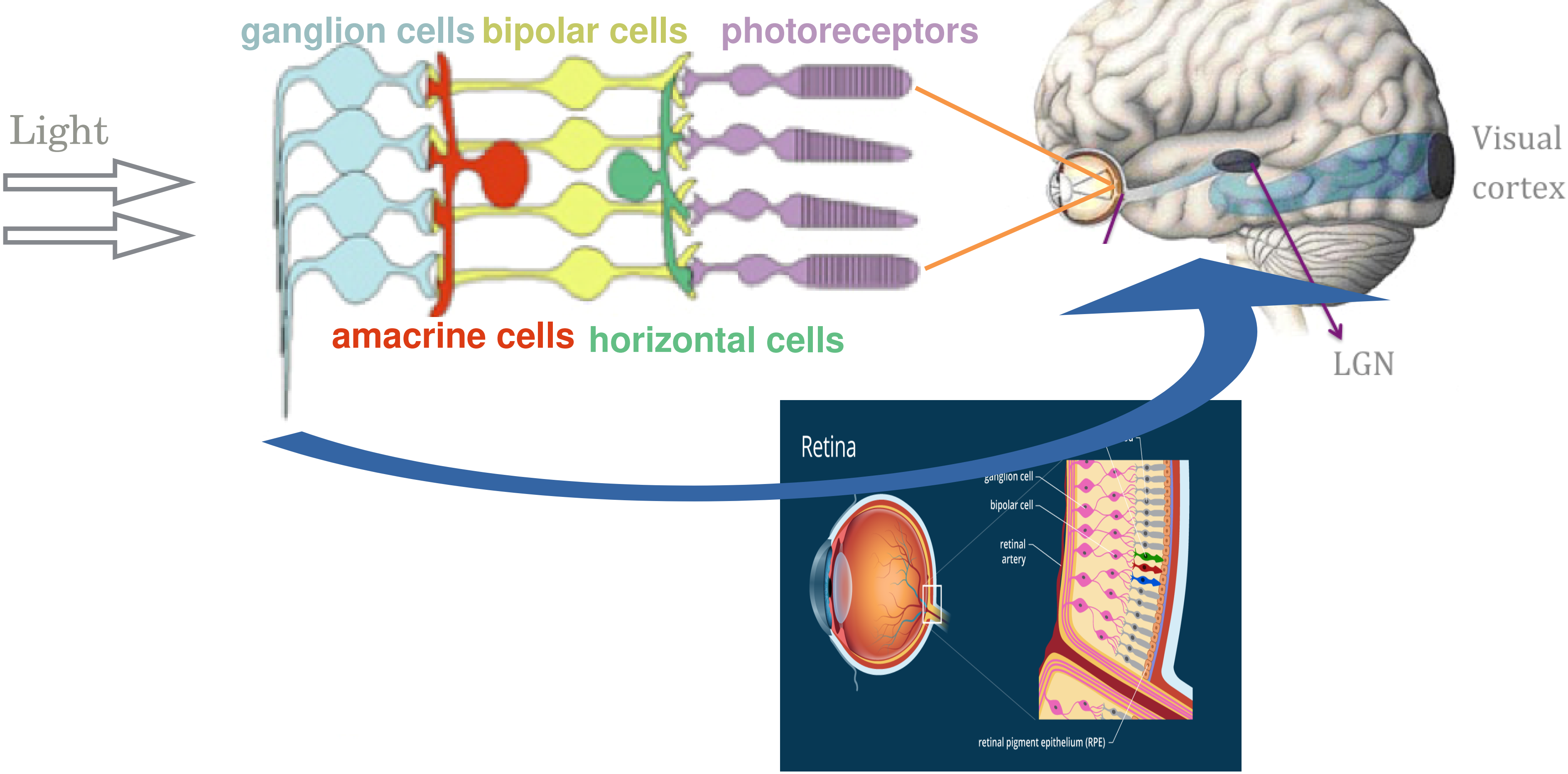

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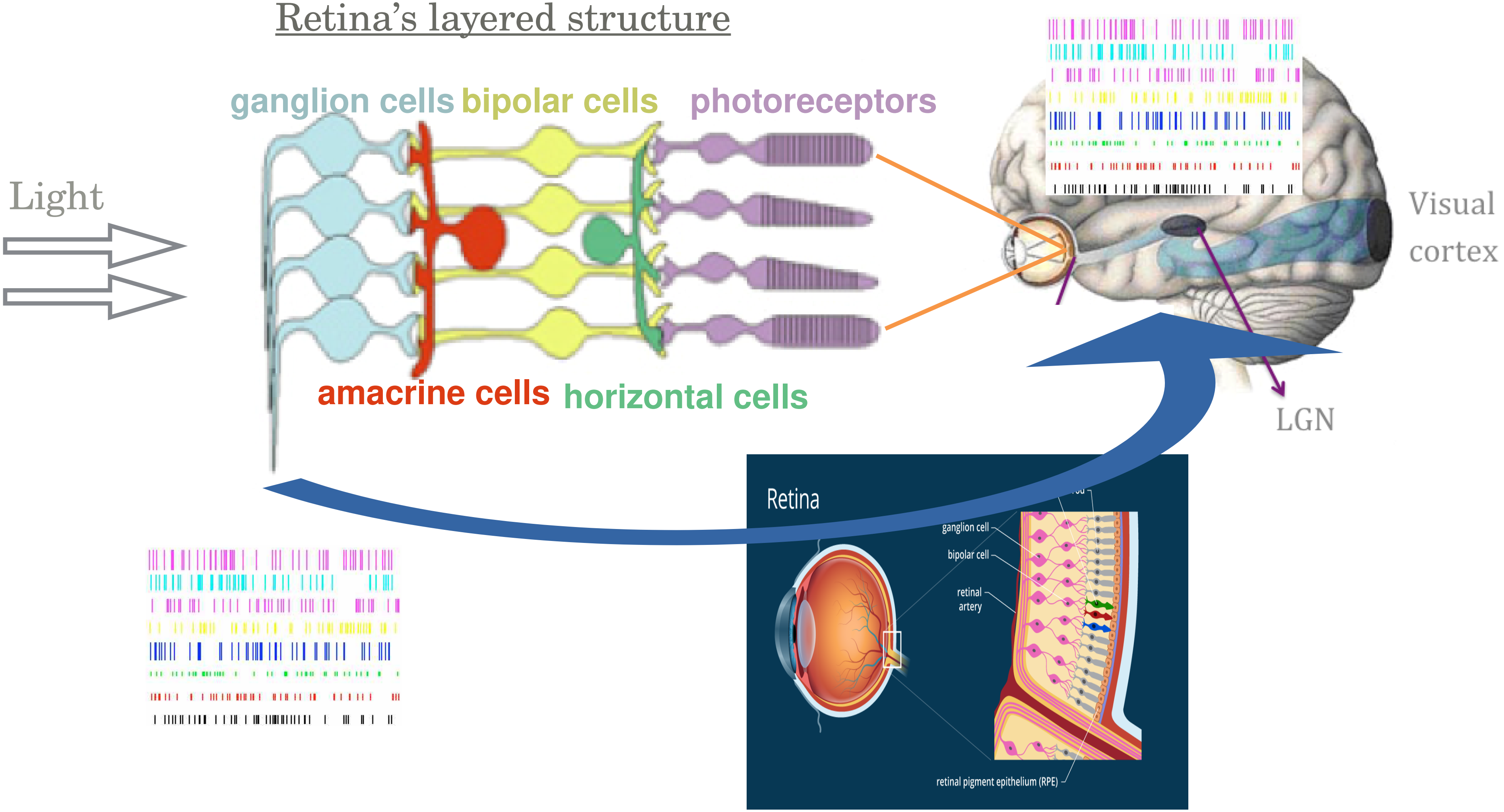

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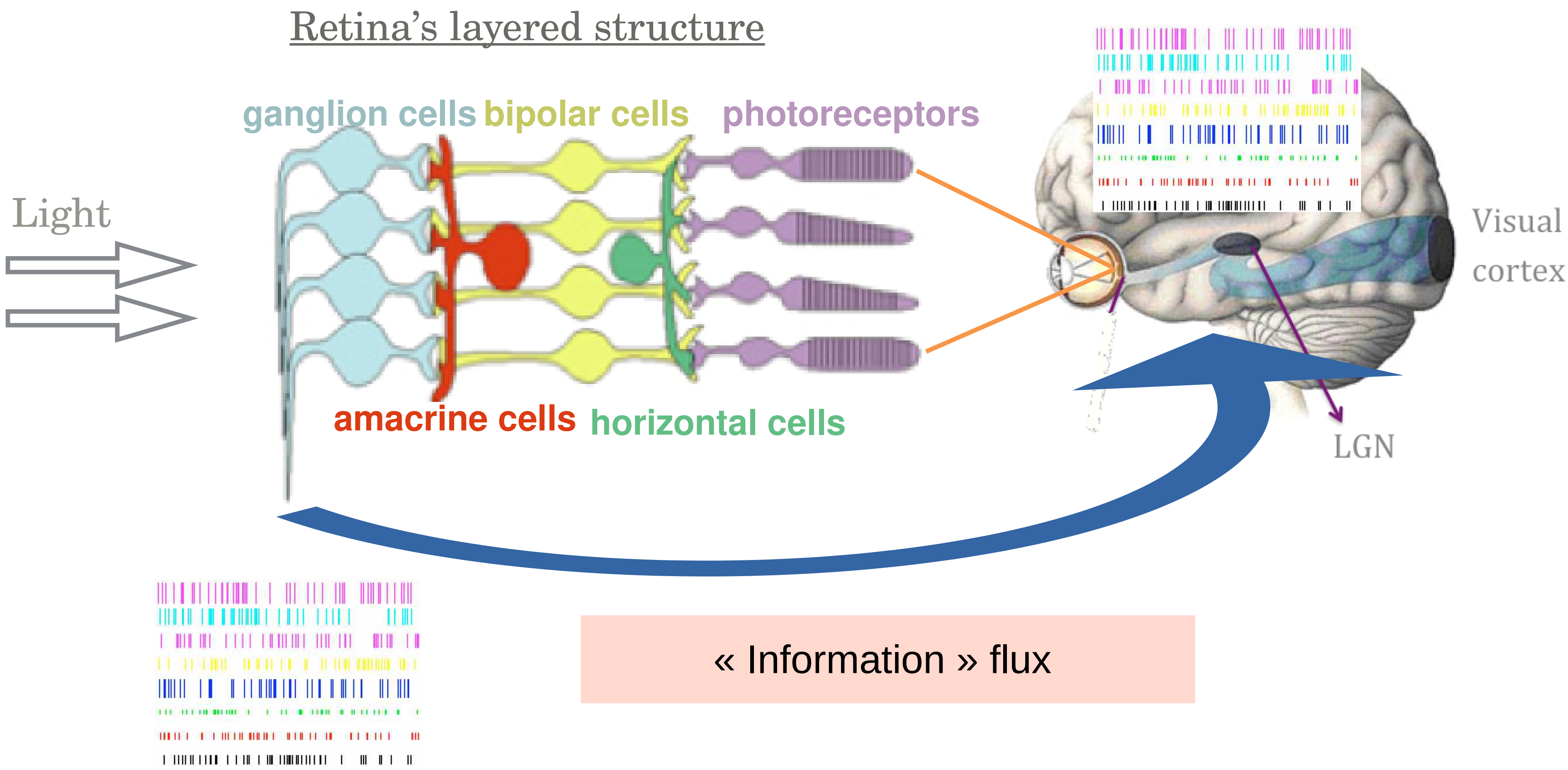

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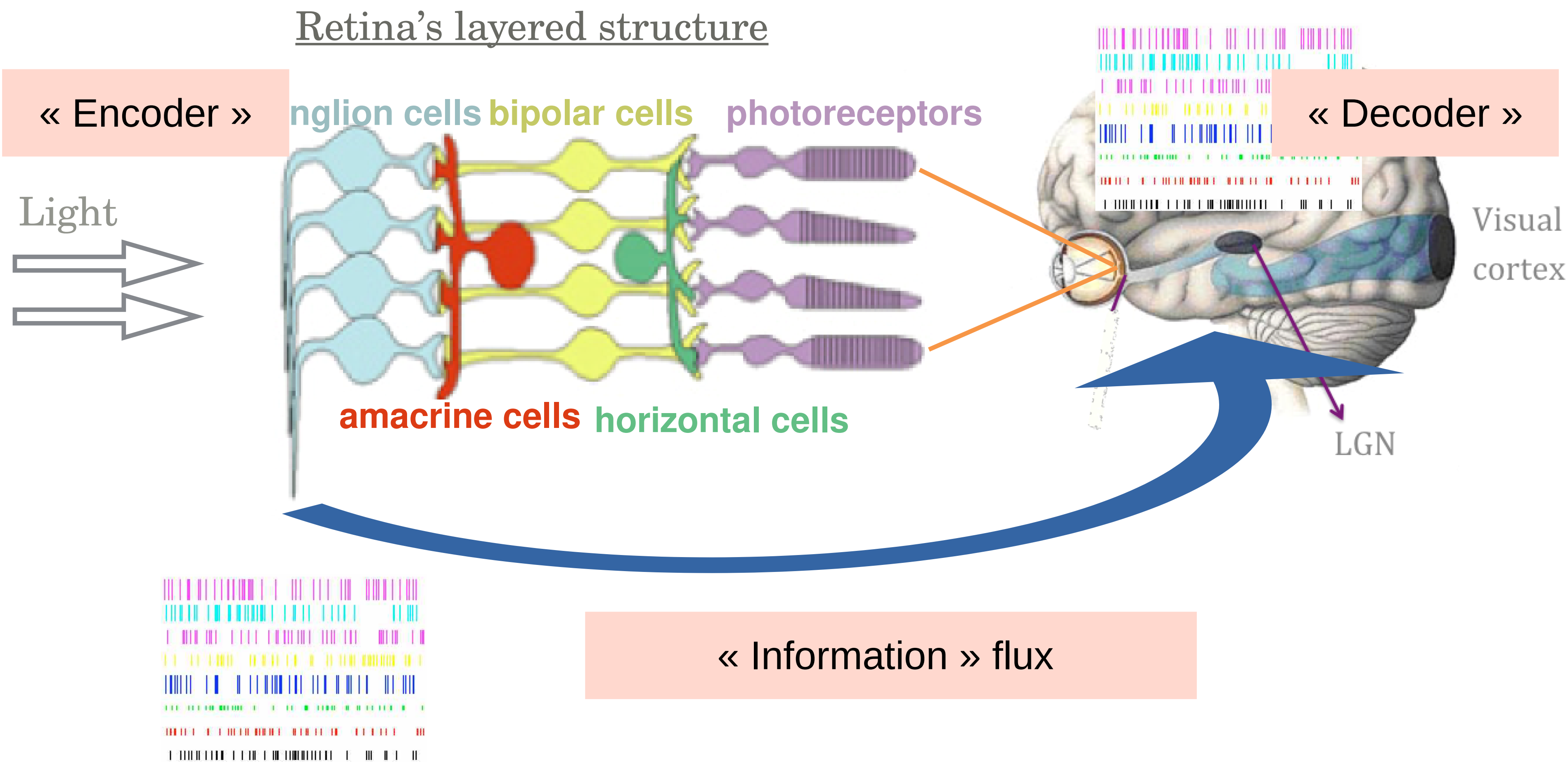

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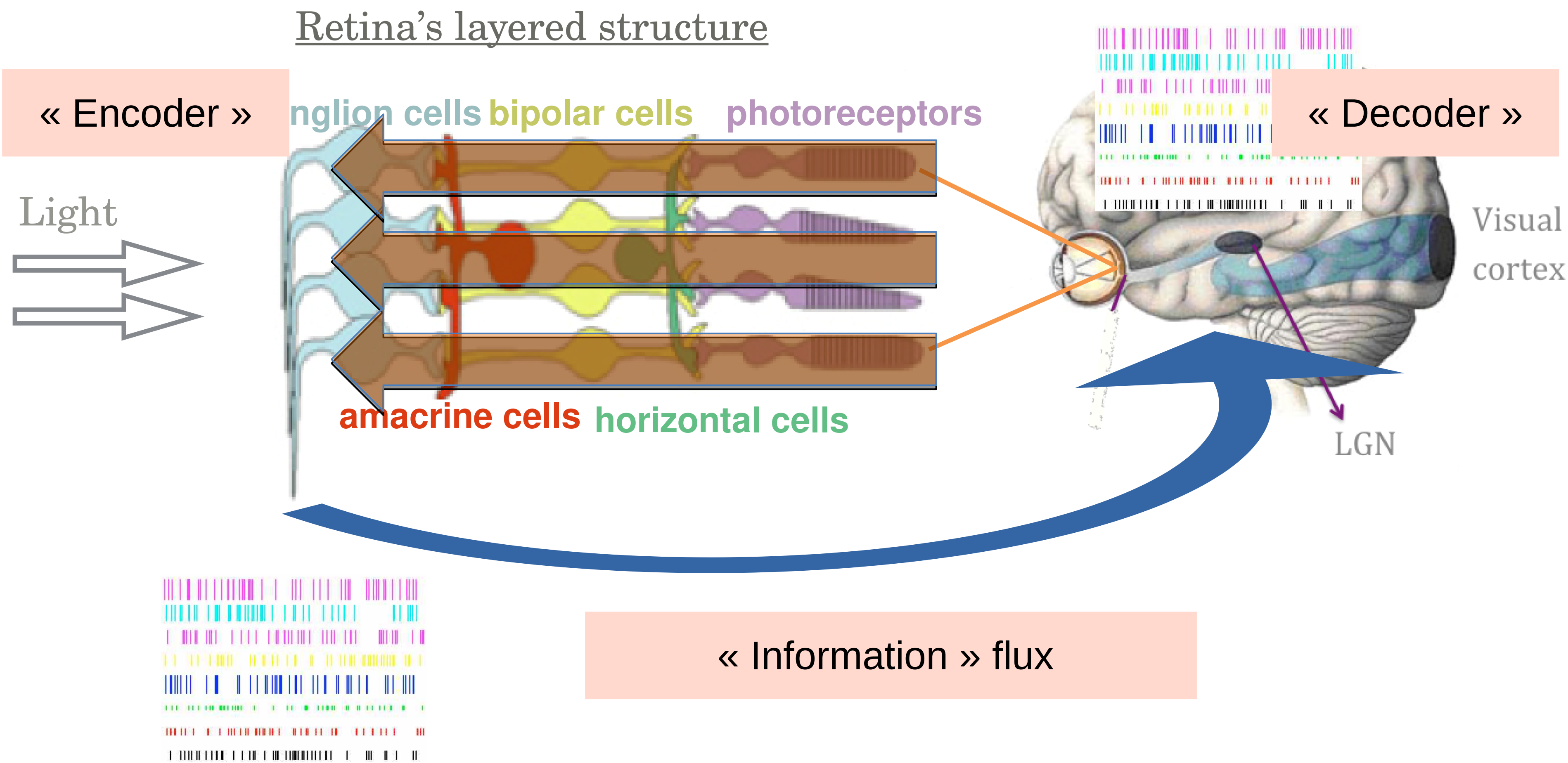

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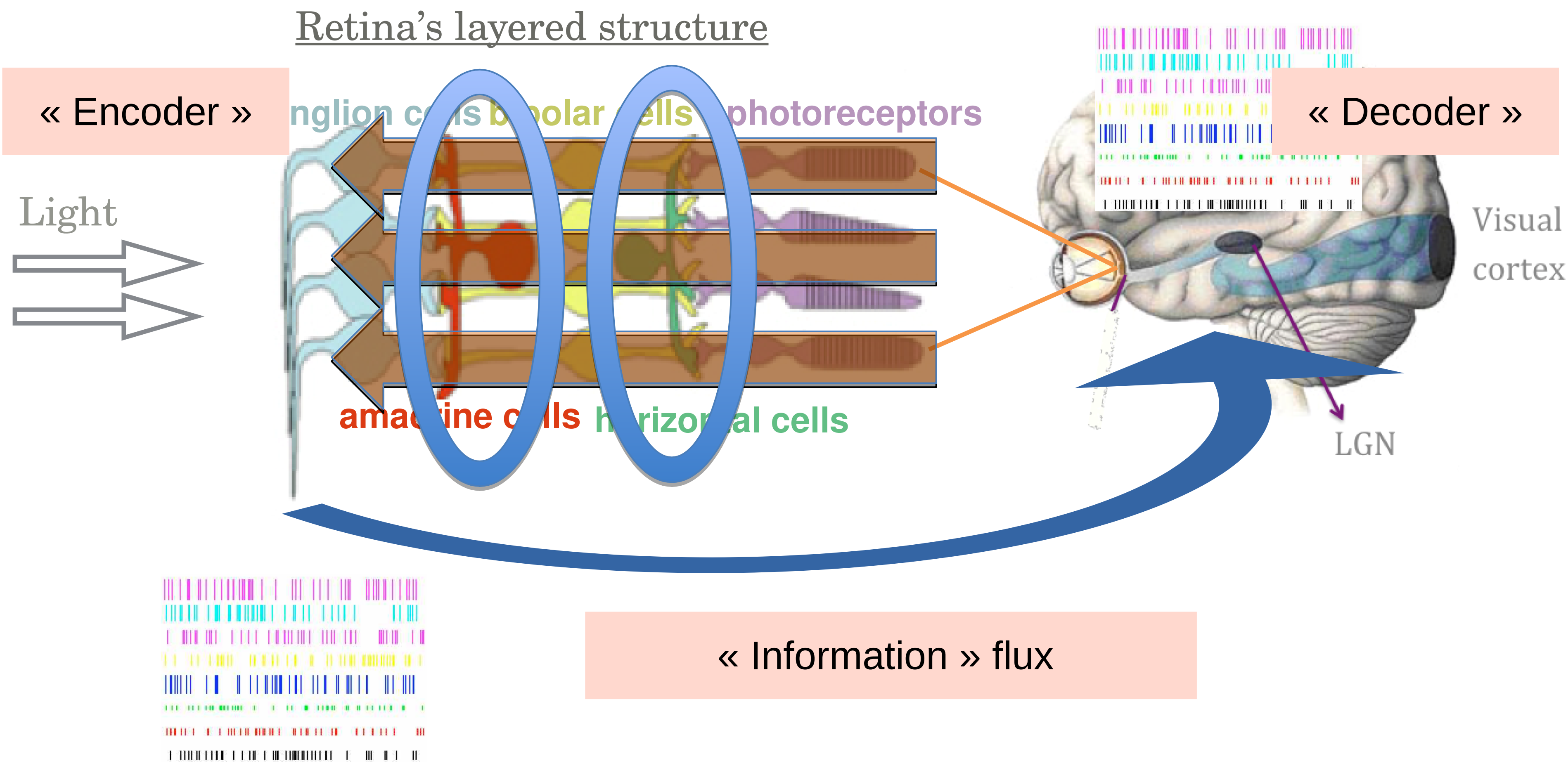

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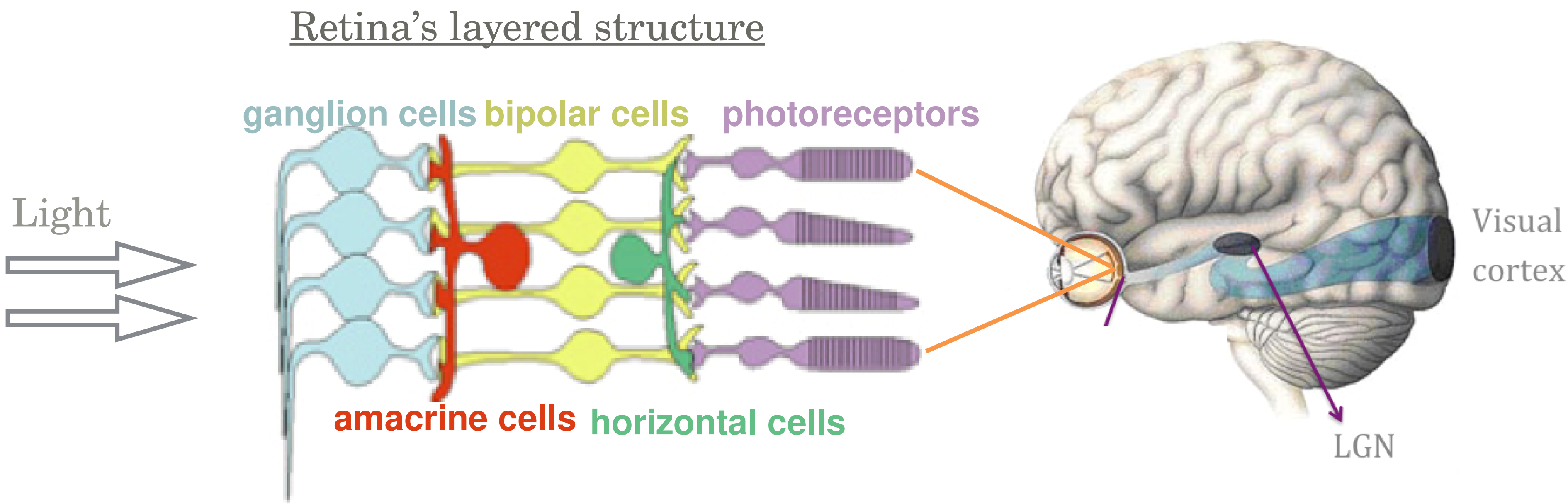
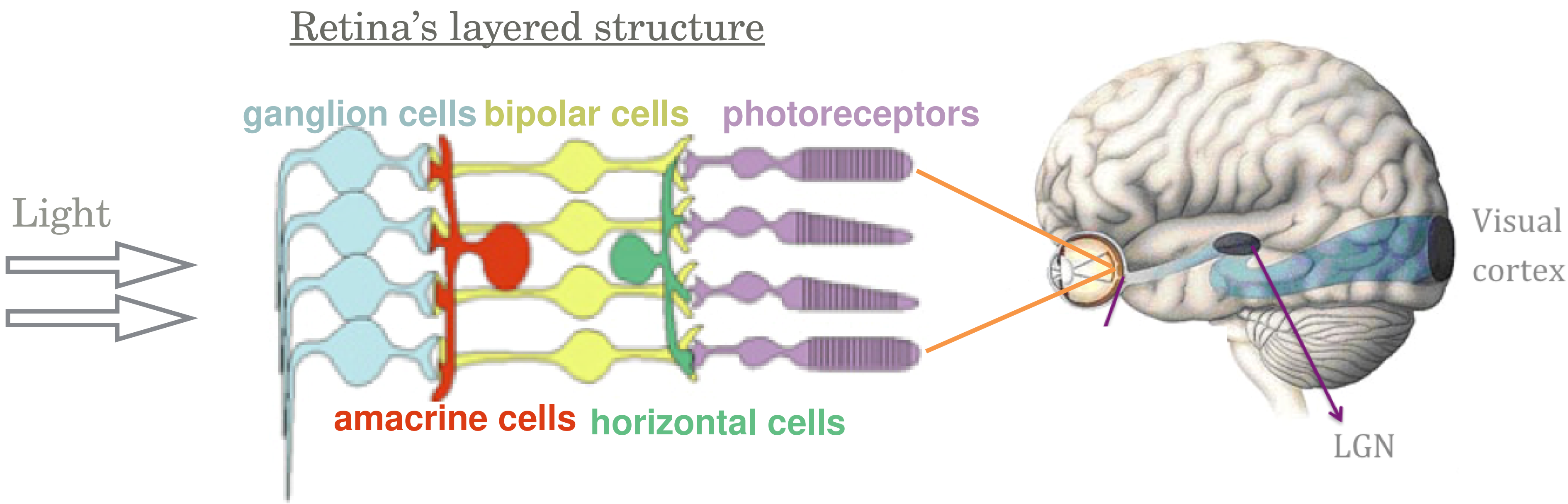


« Information » is processed by spikes.

Individual neurons and individual synapses do not matter.

Population dynamics, cortical columns, neural fields.

The visual system



Analogic computing.

No spikes except at GCells

Individual neurons and synapses DO matter.

Dedicated circuits made of a few neurons and synapses process the local visual information.

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Population dynamics, cortical columns, neural fields.

A modeller point of view

1. The retina is a ***high dimensional***, ***non autonomous and noisy*** dynamical system, layered and structured, with ***non stationary and spatially inhomogeneous entries*** (visual scenes).

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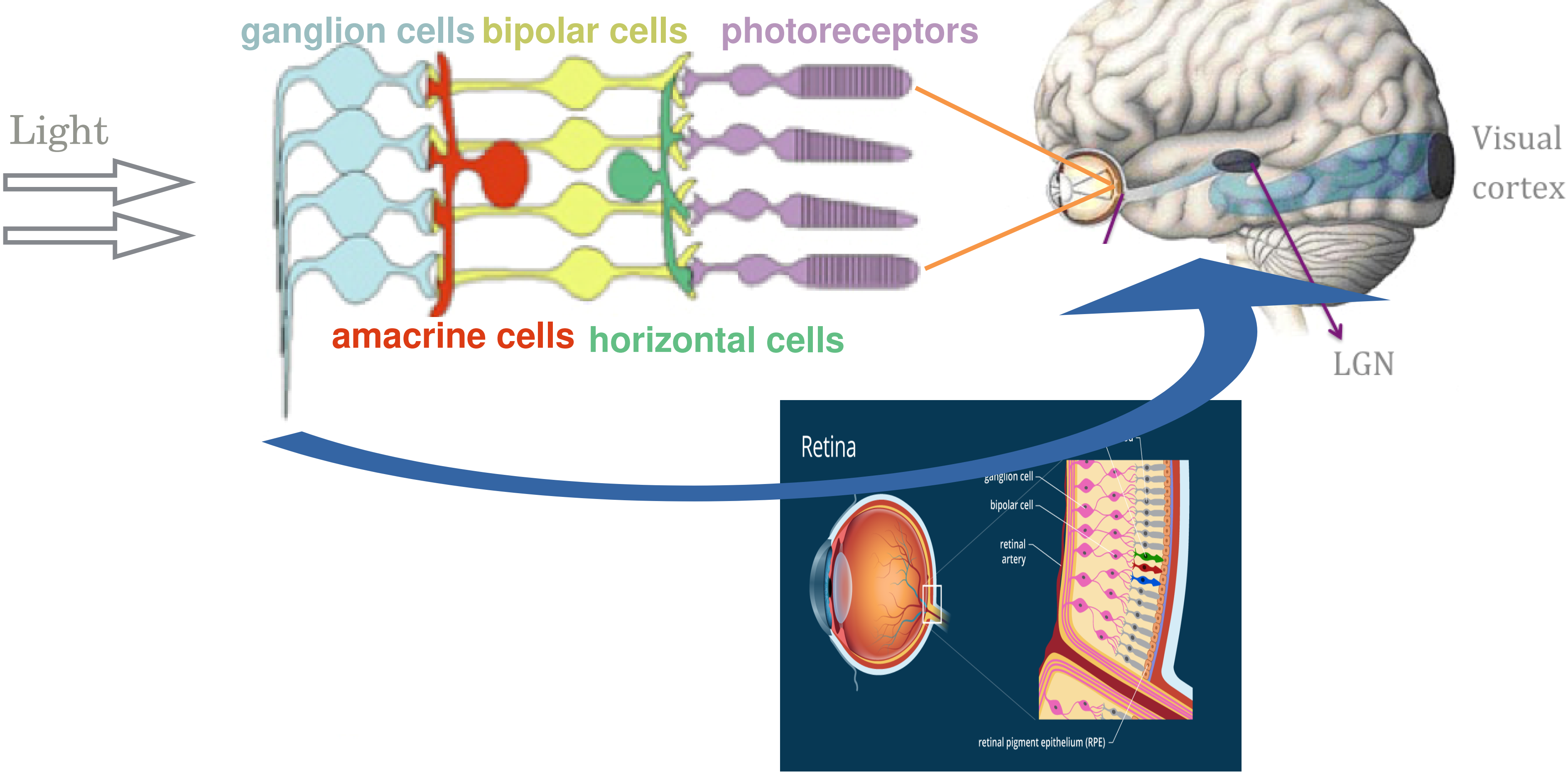
4. The retinal network naturally produces **waves** : spontaneous (developmental) or stimulus induced.

Why can we play tennis ?

Motion anticipation

Retina's layered structure



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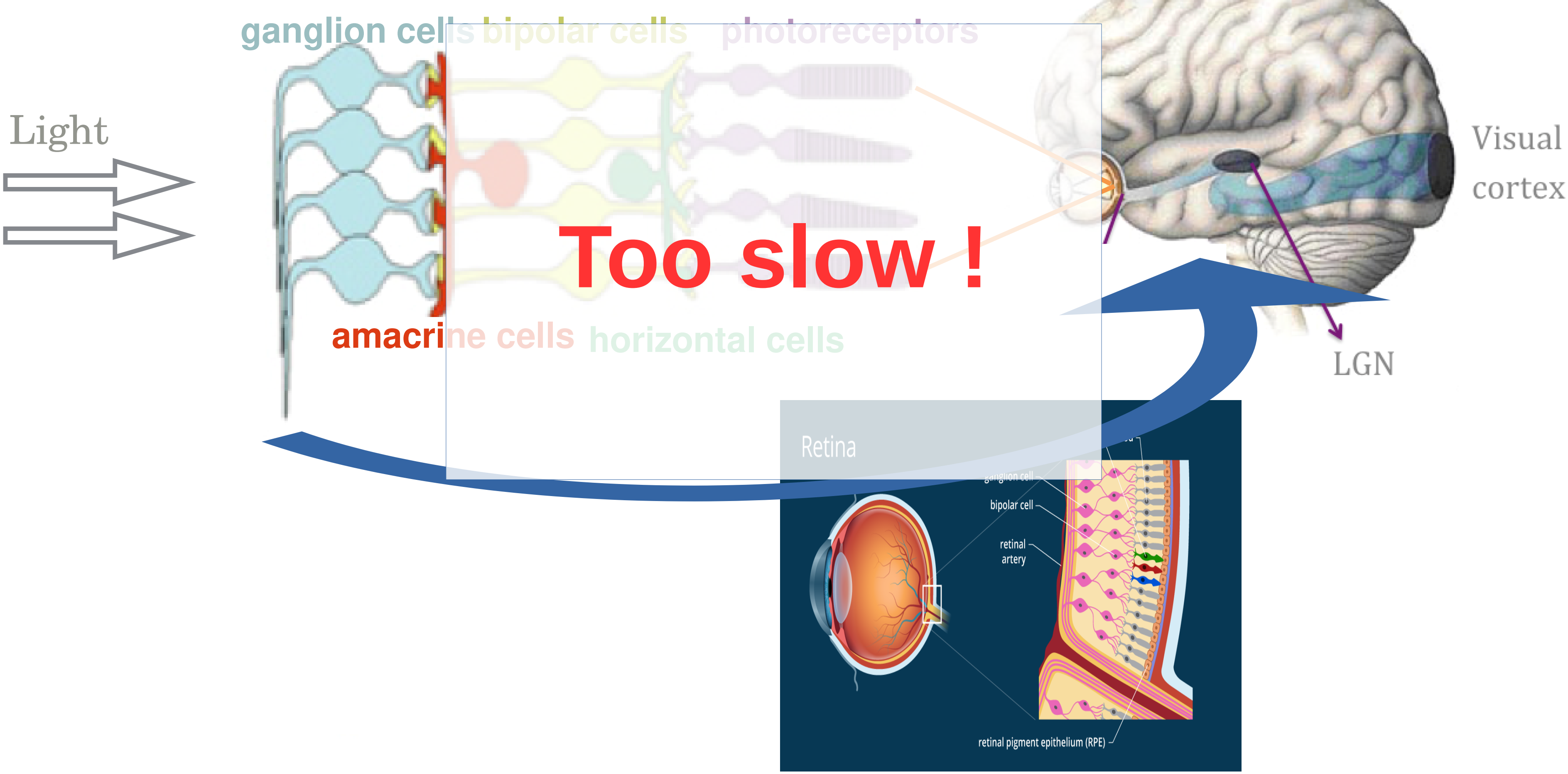


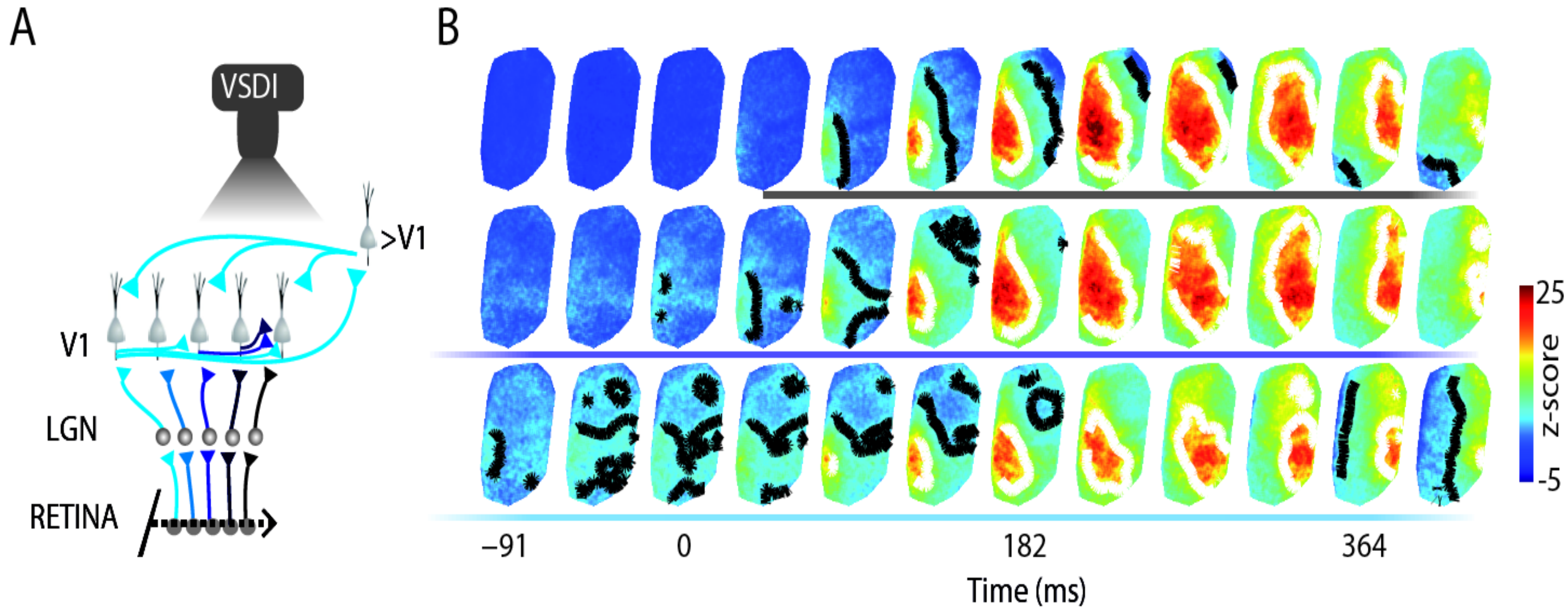
Motion anticipation

Transmission delay eye-visual cortex~ **100** ms.

Average speed of a tennis ball (stroke) : 170 km/h ~ 47 m/s => **4.7** m in 100 ms

Motion anticipation

Anticipation is carried out by the primary visual cortex (V1) through an activation wave



G. Benvenuti, S. Chemla, A. Boonman, L. Perrinet, G. S. Masson, and F. Chavane. Anticipatory responses along motion trajectories in awake monkey area v1. bioRxiv, 2020.

Motion Anticipation

Anticipation also takes place in the retina

M.J. Berry, I.H. Brivanlou, T.A. Jordan, and M. Meister. Anticipation of moving stimuli by the retina. Nature, 398(6725):334—338, 1999.

Jamie Johnston Leon Lagnado (2015) General features of the retinal connectome determine the computation of motion anticipation, eLife 4:e06250.

S. Souihel and B. Cessac. On the potential role of lateral connectivity in retinal anticipation. J. Math. Neurosc., 11(3), 2021.

Michael D. Menz, Dongsoo Lee, and Stephen A. Baccus. Representations of the amacrine cell population underlying retinal motion anticipation. bioRxiv, 2020.

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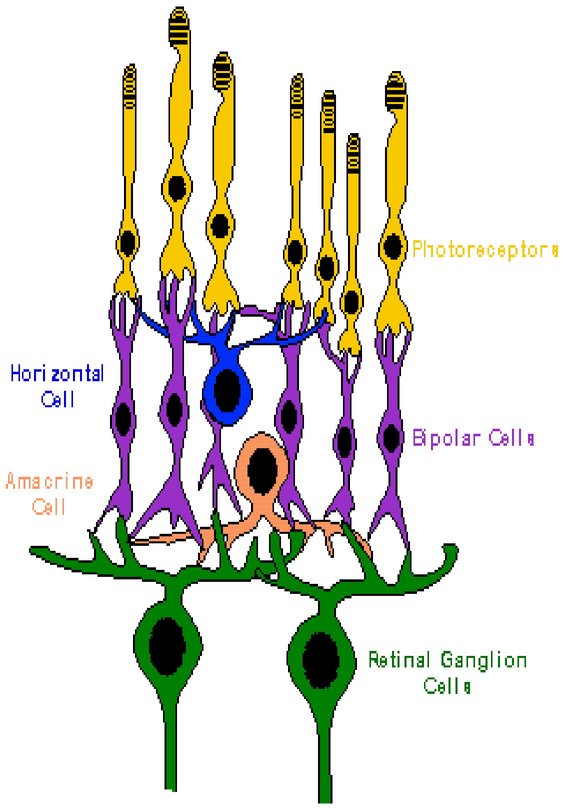

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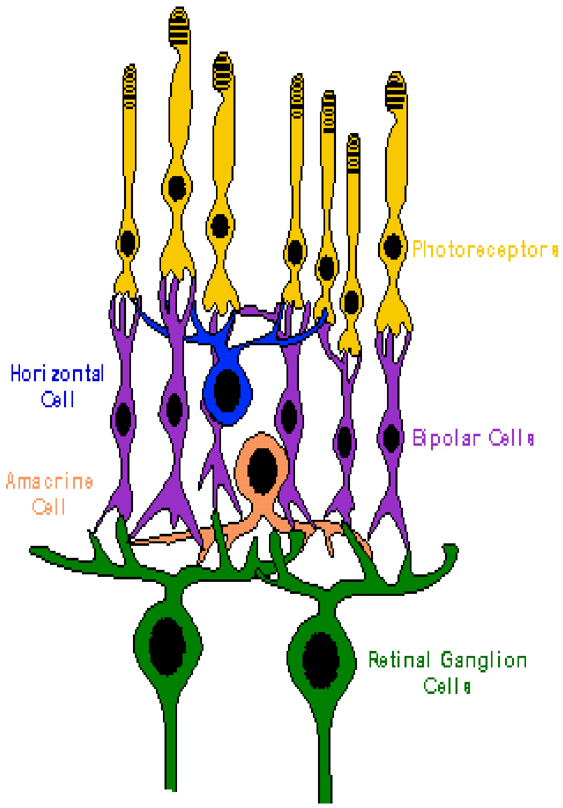

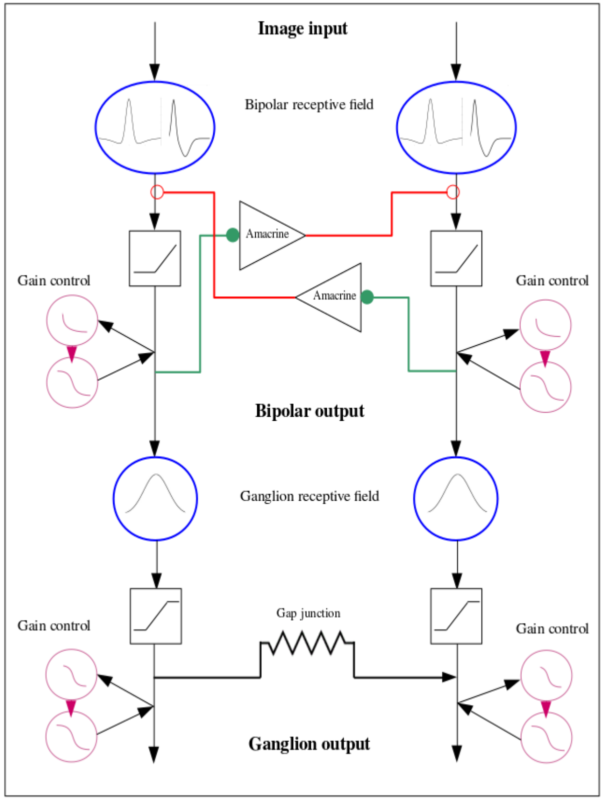

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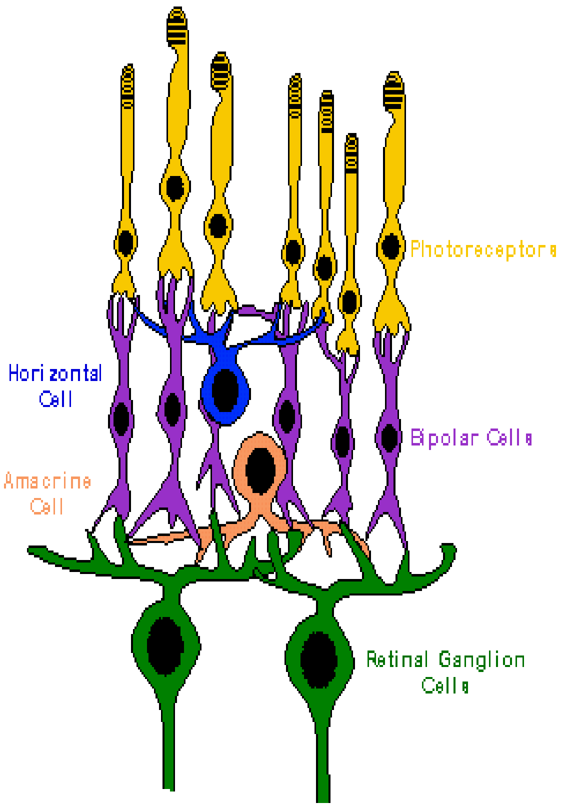

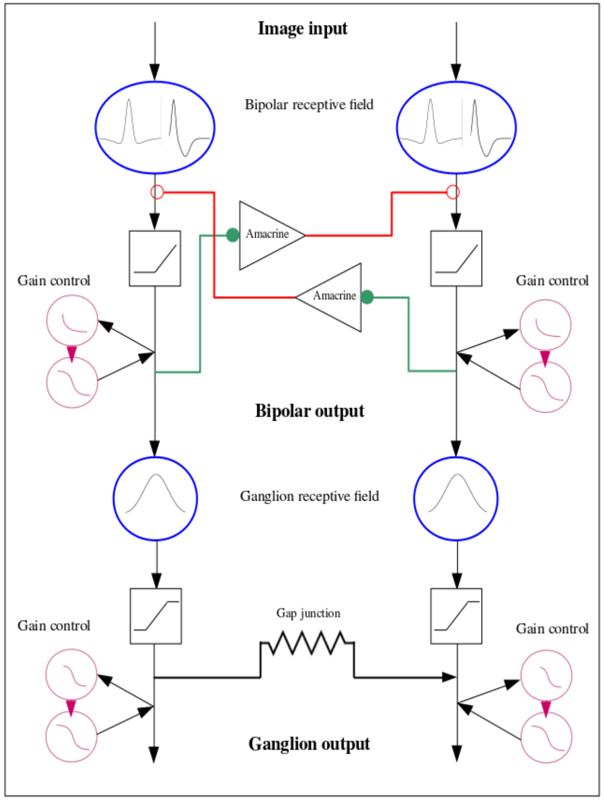

$$
\begin{cases}
\frac{dV_{B_i}}{dt} = -\frac{1}{\tau_B} V_{B_i} + \sum_{j=1}^{N_A} W_{B_i}^{A_j} V_{A_j} + F_{B_i}(t), \\
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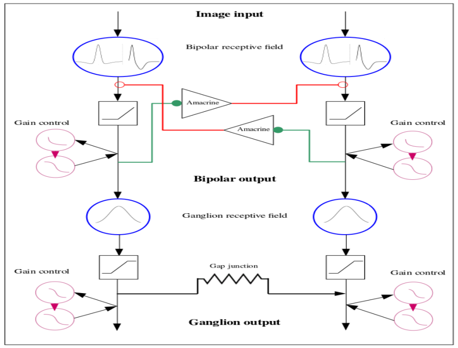
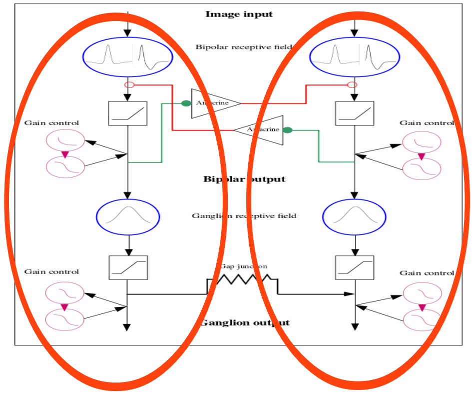


Local circuit

Motion Anticipation



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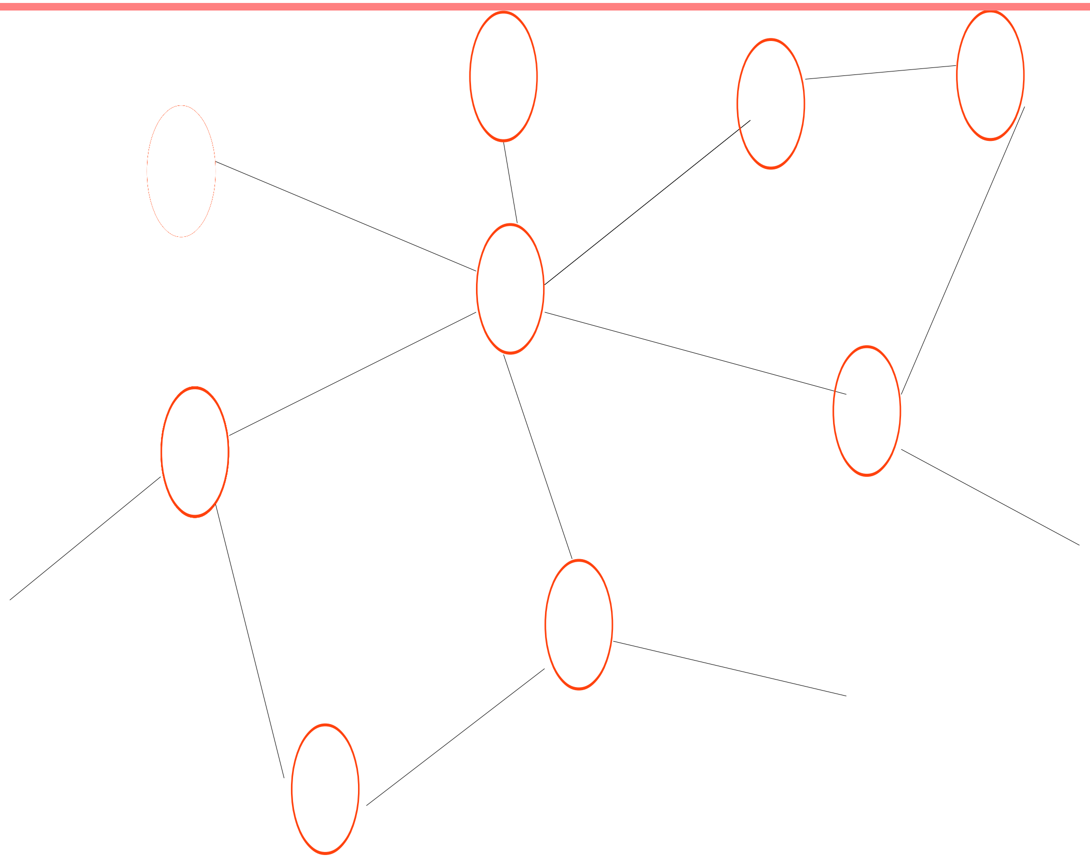

Network

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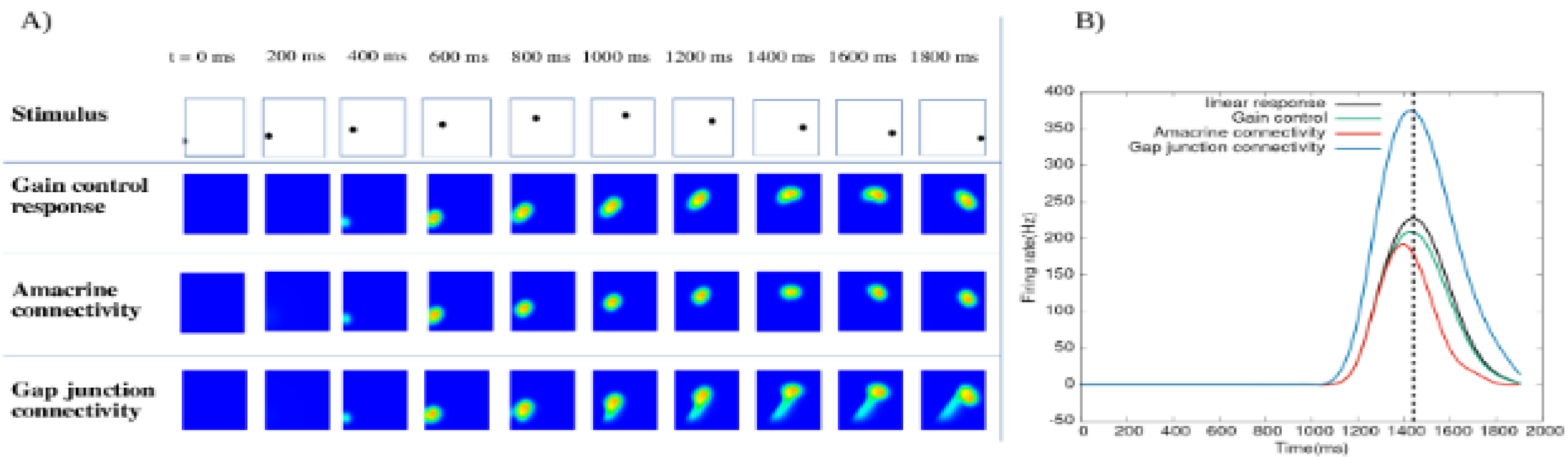

Figure 15: **Effect of anticipatory mechanisms on a parabolic trajectory.** A) Response to a dot moving along a parabolic trajectory. The first line shows the stimulus, the second line shows the GCells response with gain control, the third line presents the effect of lateral ACells connectivity with $w = 0.3\ ms^{-1}$, and the last line shows the effect of asymmetric gap junctions with $v_{gap} = 9$ mm/s . B) Time course response of a cell responding to the dot near the trajectory turning point. Linear response corresponds to the response to the stimulus without gain control.

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- A **moving object** induces a **retinal wave ahead** of the stimulus thanks to gain control and the amacrine cells network.

  1) Compensation of the **photo-transduction delay**.

  2) Simple implementation, **weak consumption**.

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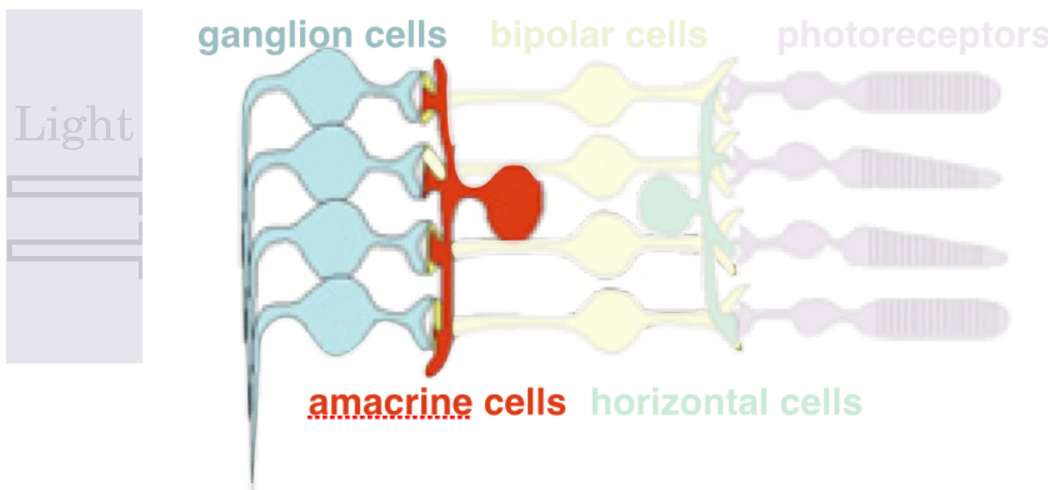
Motion is not a succession of images.

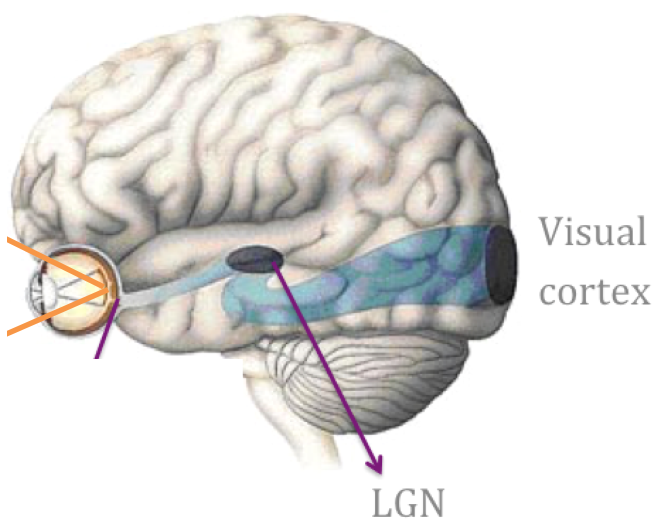
There is a spatio-temporal coherence-correlation, captured by waves.

How do our eyes learn to see ?

The structure of the retina during development

Retina's layered structure
is shaped during development



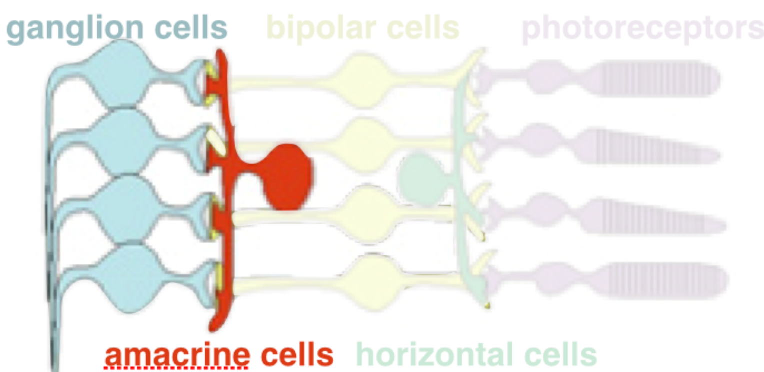


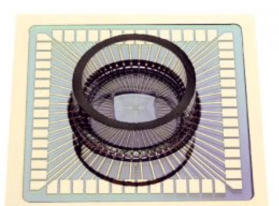
But How? ⇨ **Retinal waves!**

Retinal waves

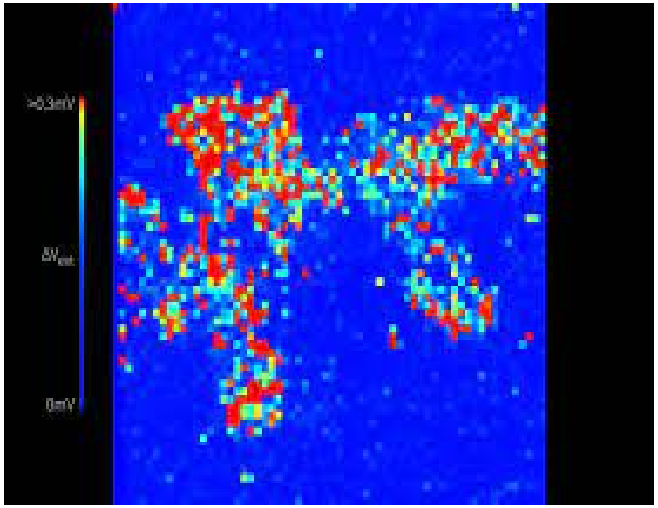
Spontaneous spatio-temporal waves during development
Disappear short after birth when vision is functional

Recordings from the retina





Multi-electrode array (MEA)



MEA recording of the voltage from a mouse retina https://www.youtube.com/watch?v=0kt5_mhTy4w.

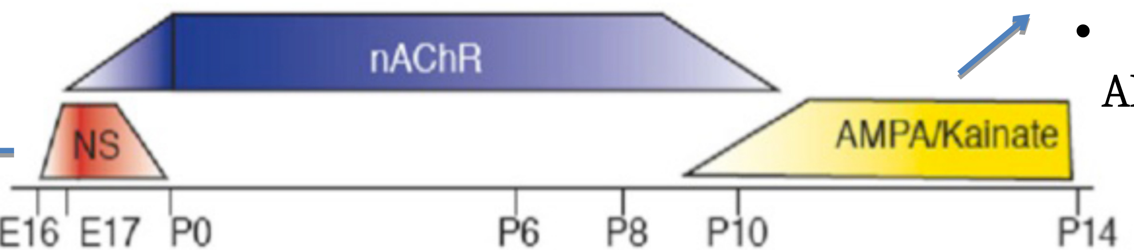
Stages of Retinal Waves During Development

Stage II

- Retinotopic mapping
- Nicotinic Acetylcholine Receptors (nAChR)

Stage III

- Disappear when vision is functional
- Glutamate – AMPA receptors



Stage I

- Formation of retina circuitry
- Chemical synapses <u>not</u> formed yet
- Gap juction-mediated

Retinotopy

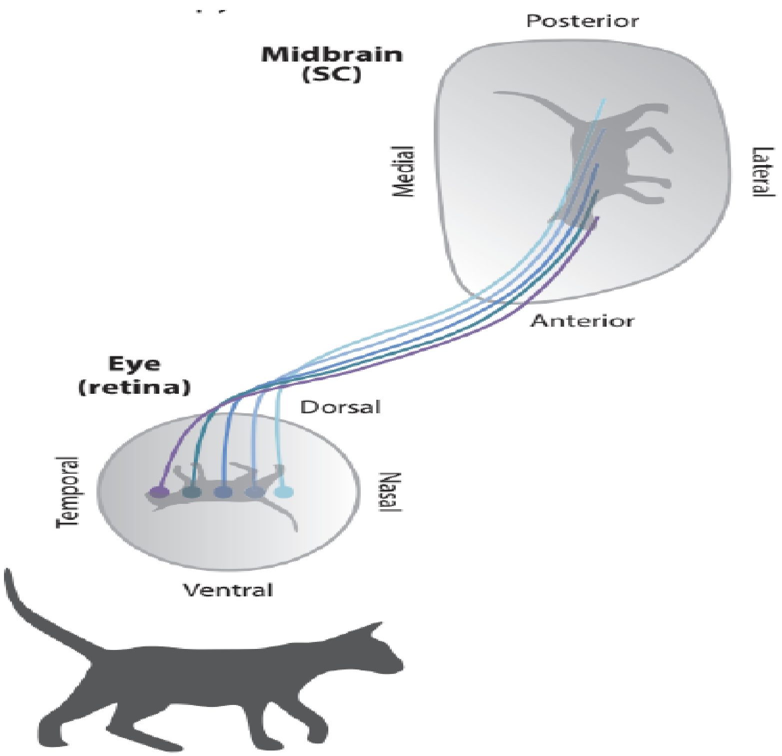


Figure 2.3: Cartoon showing the retinotopic projection and relationship with the visual field. Here a cat is presented as an image to a mouse's retina. This image is inverted by the lens of the eye and projected topographically into the SC where the neighbour relationships can be traced using the colour gradient. Figure adapted from Seabrook et. al. (2017) [190].

From Nicholas Gale thesis , «Theoretical Investigations into Principles of Topographic Map Formation and Applications », Cambridge 2022.

Retinotopy

Retinotopy results from :

1) **Competition** at the synaptic level (*fight for resources*)

2) **Chemotaxis** (retinal afferents affinity to colliculus location depends on the *concentration of ligands and receptors* at the location)

3) **Activity** (effects of *neuronal activity* on the organisation of topography)

4) **Plasticity**

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Variational formulation

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Retinal waves input

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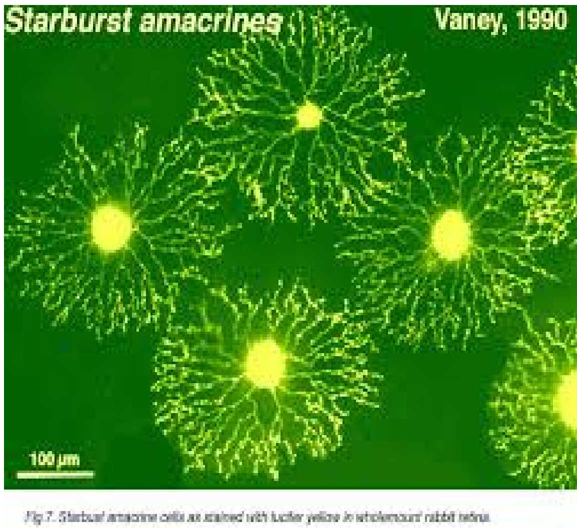
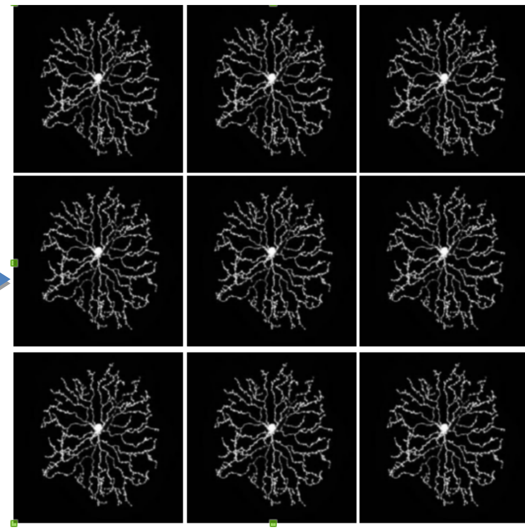
The Starburst Amacrine Cells Network

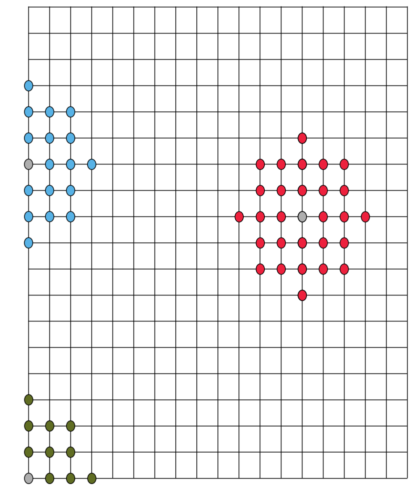
Model synaptic interactions



SACs realistic connections



SACs on a lattice



SACs become points on a lattice

A network model for stage II retinal waves

D. Matzakou-Karvouniari, L. Gil, E. Orendorff, O. Marre, S. Picaud, B. Cessac, « A biophysical model explains the spontaneous bursting behavior in the developing retina », Scientific Reports, Nature Publishing Group, 2019, 9 (1), pp.1-23. ⟨10.1038/s41598-018-38299-4⟩

$$\begin{cases} C_m \frac{dV_i}{dt} & = & -g_L(V_i - V_L) - g_C M_\infty(V_i)(V_i - V_C) - g_K N_i(V_i - V_K) \\ & & -G_{sAHP}(R_i)(V_i - V_K) - G_A(\{A_k\}_{k\in\mathcal{B}_i})(V_i - V_A) \\ \tau_N \frac{dN_i}{dt} & = & \Lambda(V_i)(N_\infty(V_i) - N_i) \\ \tau_C \frac{dC_i}{dt} & = & -\frac{\alpha_C}{H_X} C_i + C_0 - \delta_C g_C M_\infty(V_i)(V_i - V_C) \\ \tau_S \frac{dS_i}{dt} & = & \alpha_S(1 - S_i)C_i^4 - S_i \\ \tau_R \frac{dR_i}{dt} & = & \alpha_R S_i(1 - R_i) - R_i \\ \frac{dA_i}{dt} & = & -\mu A_i + \beta_A T_A(V_i), \end{cases}$$

The nonlinear dynamics of retinal waves

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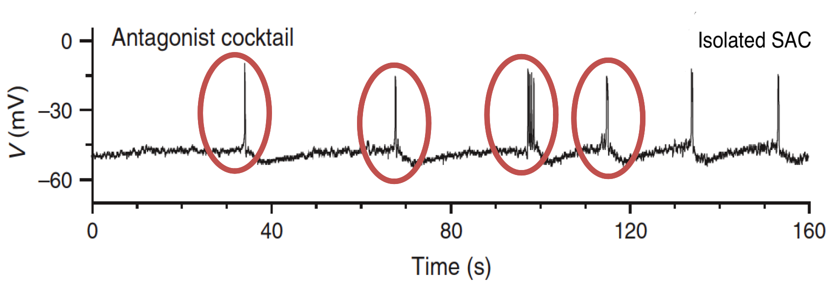

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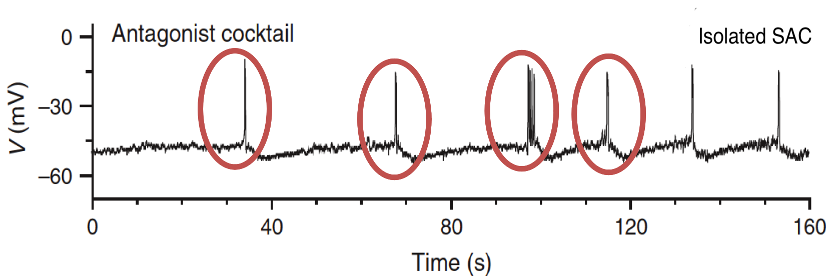

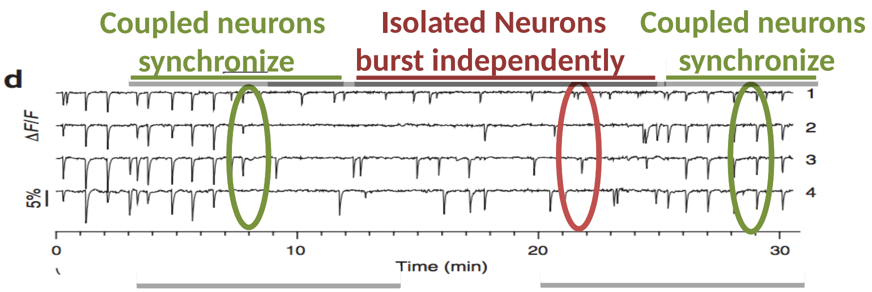

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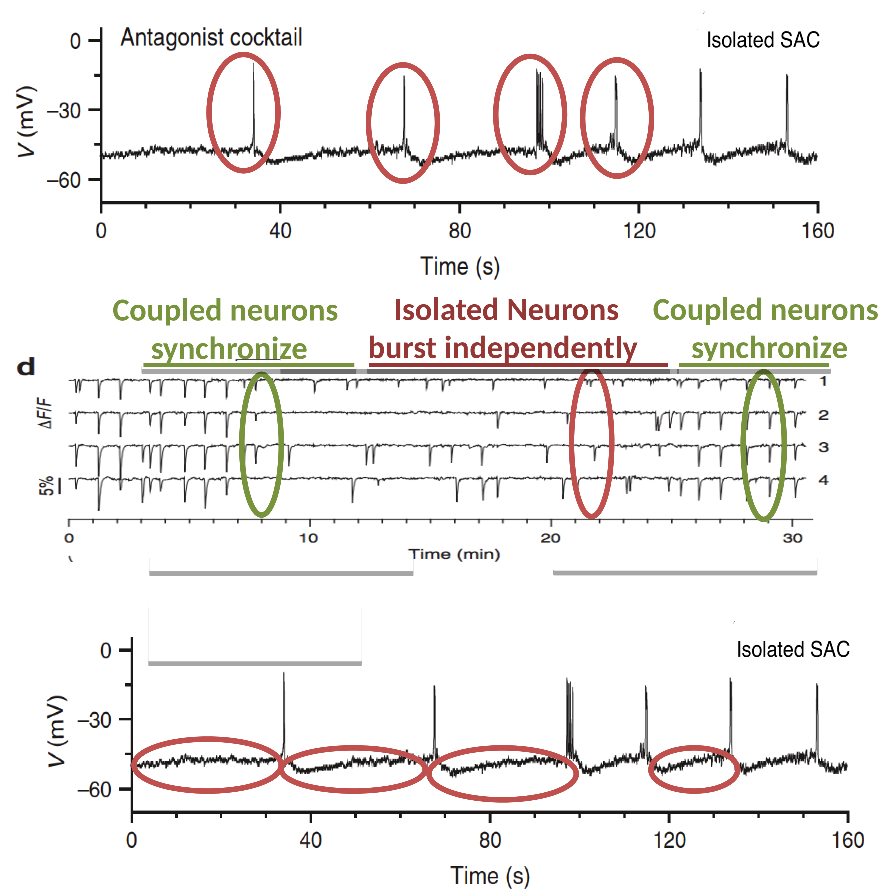

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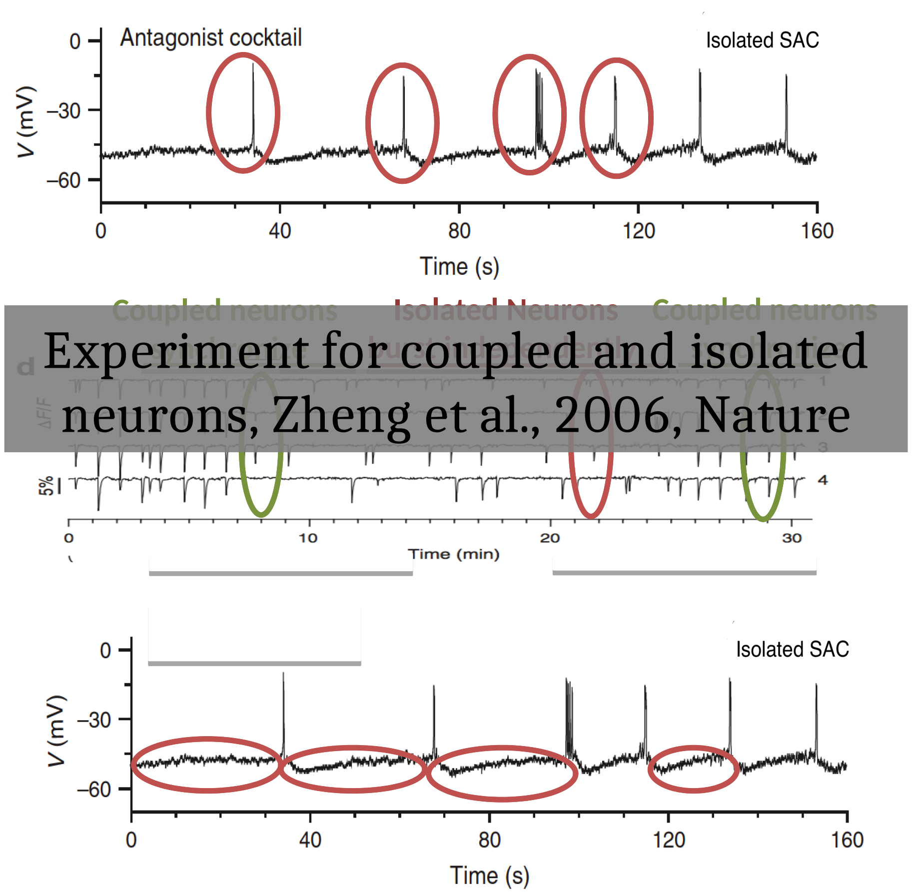

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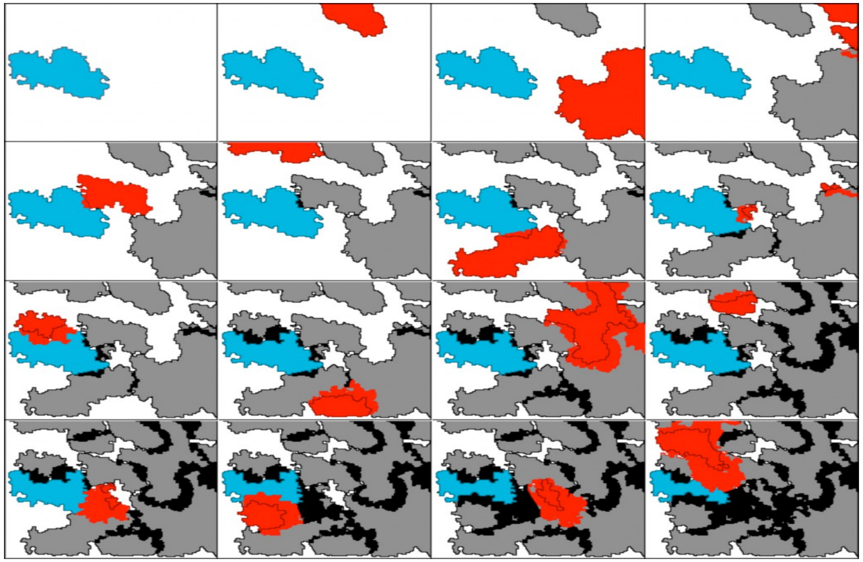

https://webvision.med.utah.edu/book/part-vi-development-of-cell-types-and-synaptic-connections-in-the-retina/formation-of-early-retinal-circuits-in-the-inner-plexiform-layer/

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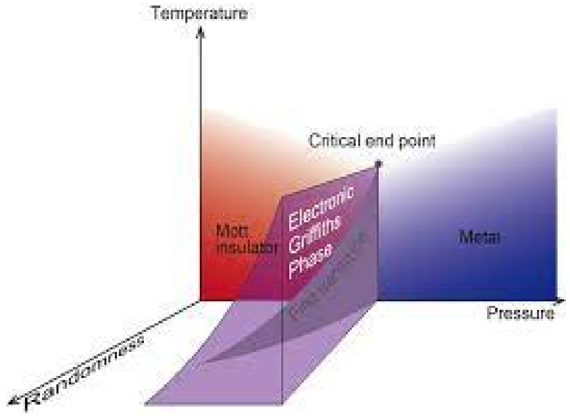

https://phys.org/news/2020-02-electronic-griffiths-phase-solid-state-physical.html

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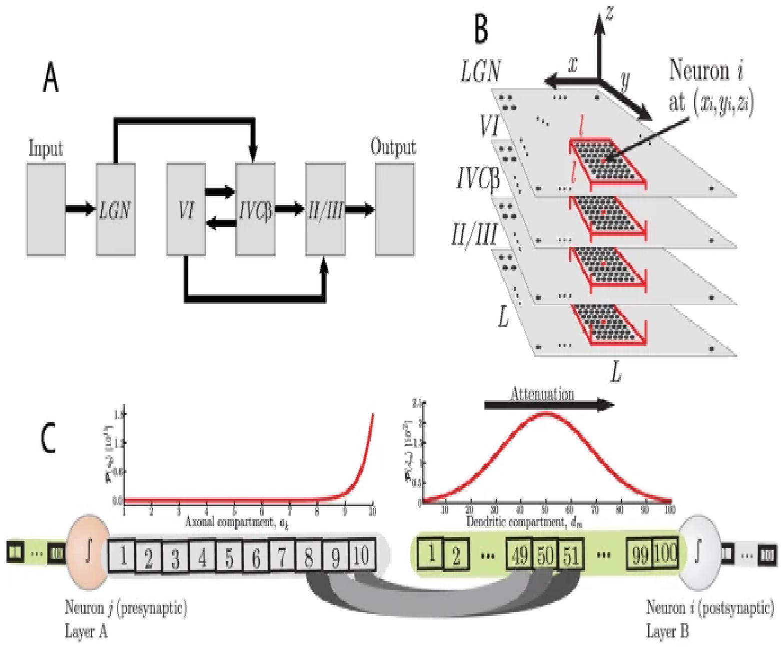

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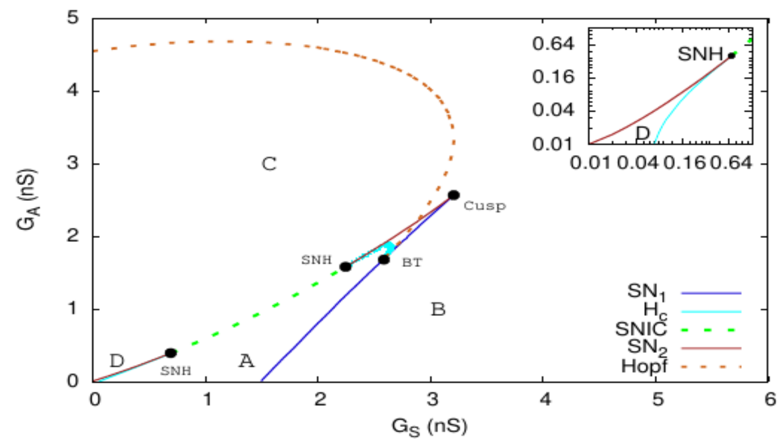
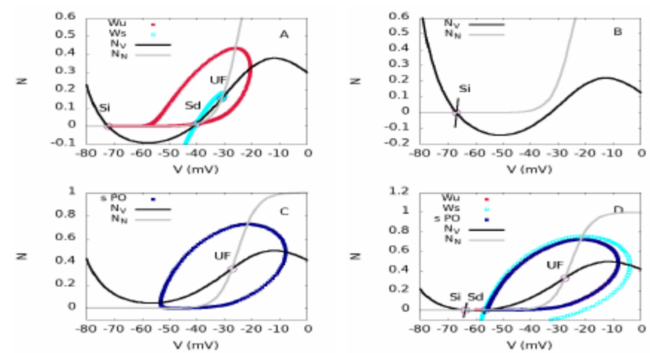
- This complex dynamics can be studied thanks to **bifurcation analysis** and **transport equations** (similar to KPZ).





How do our eyes learn to see ?

- Our eyes start to learn and see ***before birth***.
- This process (retinal waves) is ***spontaneous*** and does not require a huge data basis of « natural » images.
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- (Partly) due to this mechanism the visual system is able to handle **motion**.

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Using retinal waves to train ***AI networks*** ?

Waves ***distribution*** plays a major role
+
dynamical shaping of the retina and visual cortex.

Conclusions

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*Waves induce a **spatio-temporal ordering** which could be helpful to train **AI systems** featuring the visual processing.*

Thanks ⏪