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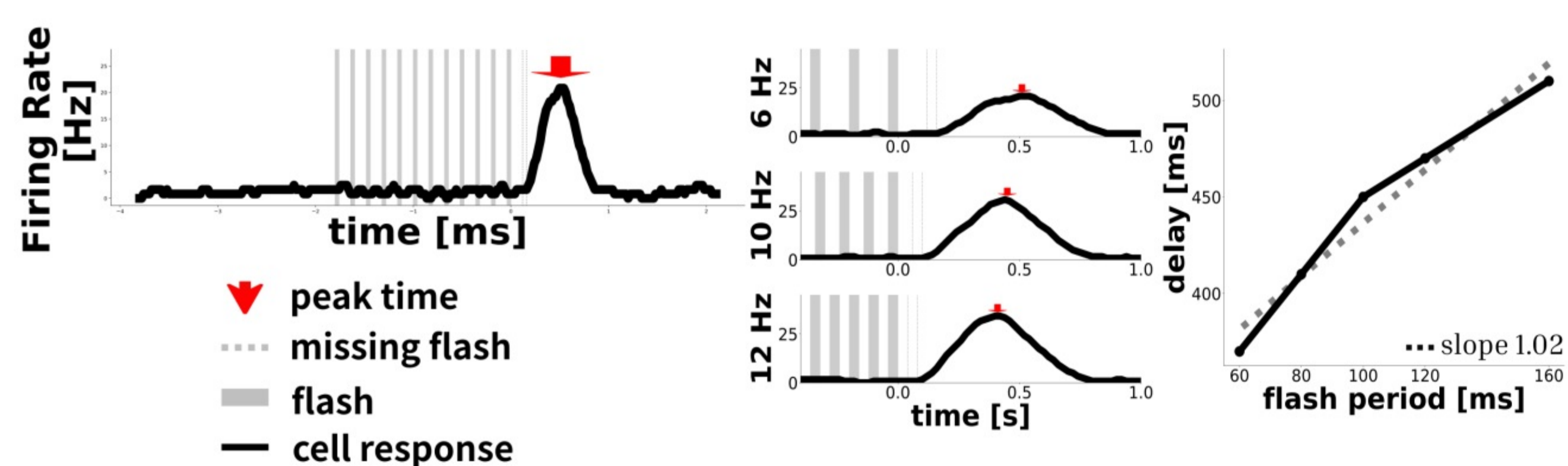
# The Role of Dynamical Synapses in Retinal Surprise Coding

## Abstract

The retina is the first stage of visual processing. The efficient coding theory postulates that it compresses relevant visual information before sending it to the brain. A long-standing hypothesis is that retinal ganglion cells, the retinal output, do not send signals about the visual scene per se, but signal only surprising events [1], such as mismatches between observation and expectation formed by previous inputs. A striking example of this is the Omitted Stimulus Response (Box 1) [2]. In this context, the main question of this study is :

**How can a local circuit detect 'surprise' and which cellular mechanisms enable these computations ?**

### Box 1 : The Omitted Stimulus Response



The retina emits an Omitted Stimulus Response when an **expected flash** in a periodic sequence is **missing**. The time-point of this response scales linearly with the period of stimulus, signaling the precise time when the next flash was expected.

## Experimental Approach

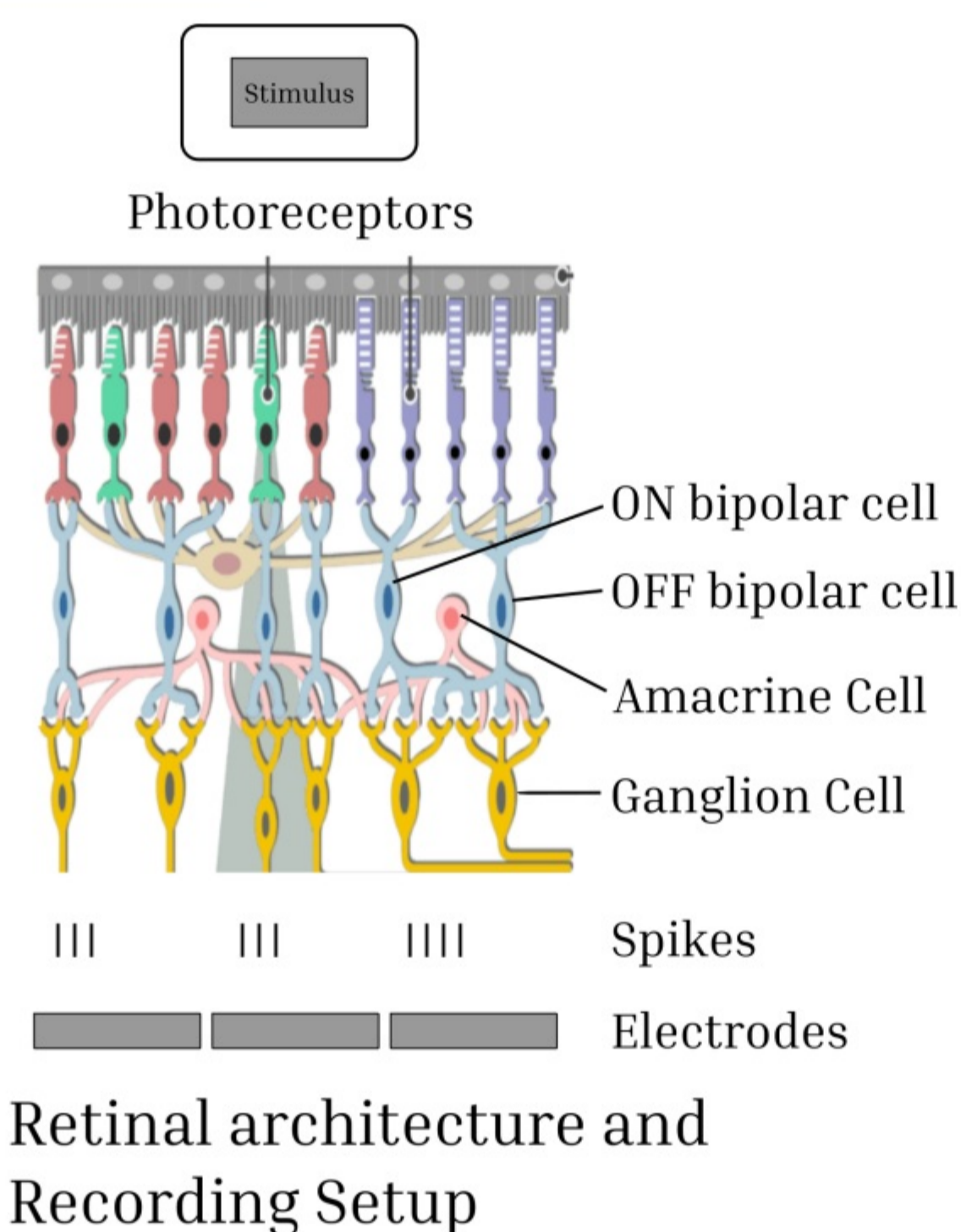
### Electrophysiology

The retina is stimulated with sequences of periodic dark flashes. Ganglion Cell spiking is recorded via multi-electrode arrays. Shown below are the firing rates of individual cells, averaged over multiple trials

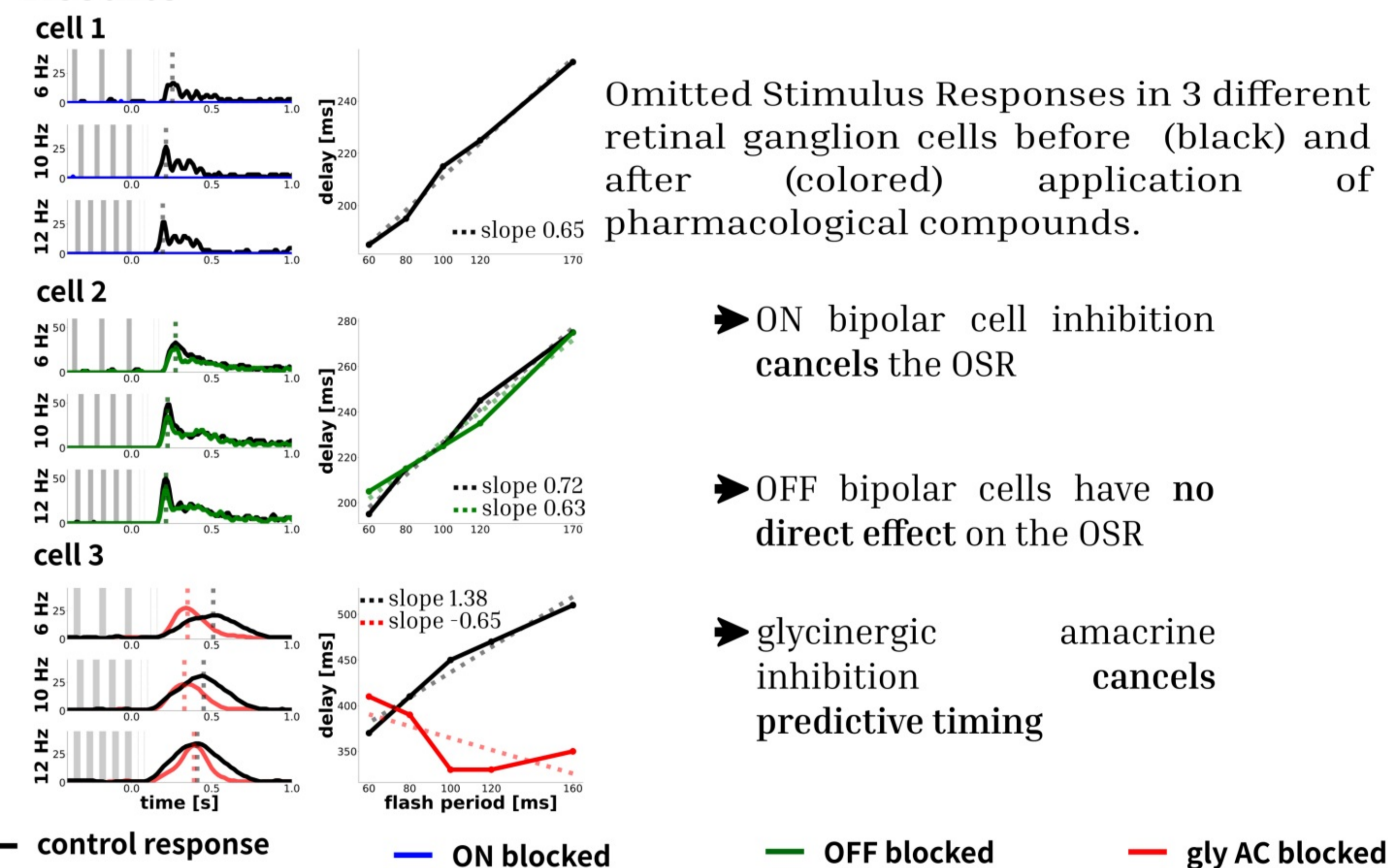
### Pharmacology

Pharmacological compounds selectively block synaptic transmission:

- onto ON bipolar cells
- onto OFF bipolar cells
- from glycinergic amacrine cells



### Results



Omitted Stimulus Responses in 3 different retinal ganglion cells before (black) and after (colored) application of pharmacological compounds.

➤ ON bipolar cell inhibition cancels the OSR

➤ OFF bipolar cells have no direct effect on the OSR

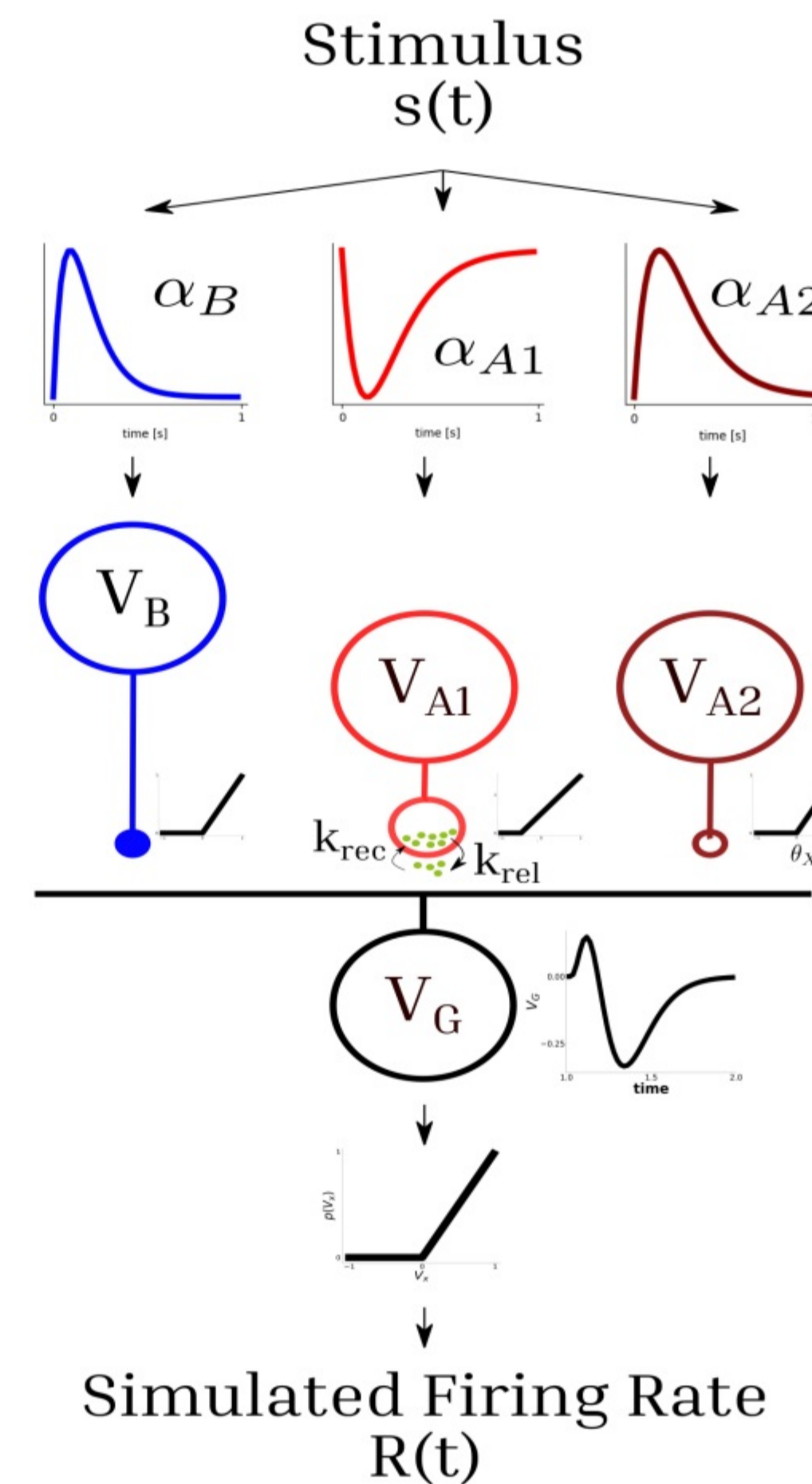
➤ glycinergic inhibition amacrine cancels predictive timing

## References

1. Hosoya, T., Baccus, S. A., and Meister, M. (2005). Nature, 436:71-77.
2. Schwartz, G., Harris, R., Shrom, D., and Berry, M. J. (2007a). Nature Neuroscience, 10:552-554.
3. Hennig, M. (2013) Frontiers in Computational Neuroscience, 10.3389/fncom.2013.00045.
3. Souhail, S., Cessac B. (2021). Journal of Mathematical Neuroscience, 10.1186/s13408-020-00101-z.

## Modeling Approach

### Network model with short-term plasticity



1. Convolution of stimulus and temporal kernel  
 $X = B, A1, A2$

$$F_X(t) = [\alpha_X * s](t)$$

2. Bipolar and amacrine cells integrate the signal into their membrane potential

$$\frac{dV_X}{dt} = -\frac{V_X}{\tau_X} + F_X(t)$$

3. Ganglion cells pool over the network.

$$\frac{dV_G}{dt} = -\frac{V_G}{\tau_G} + \sum_{X=1}^N w_X p_X(V_X(t), \theta_X)$$

Simulated Firing Rate R(t)

4. Ganglion cell voltage response is transformed into a firing rate

A Simple circuit with one excitatory (B), one delayed inhibitory (A2) and one adapting inhibitory unit (A1) to form predictive responses .

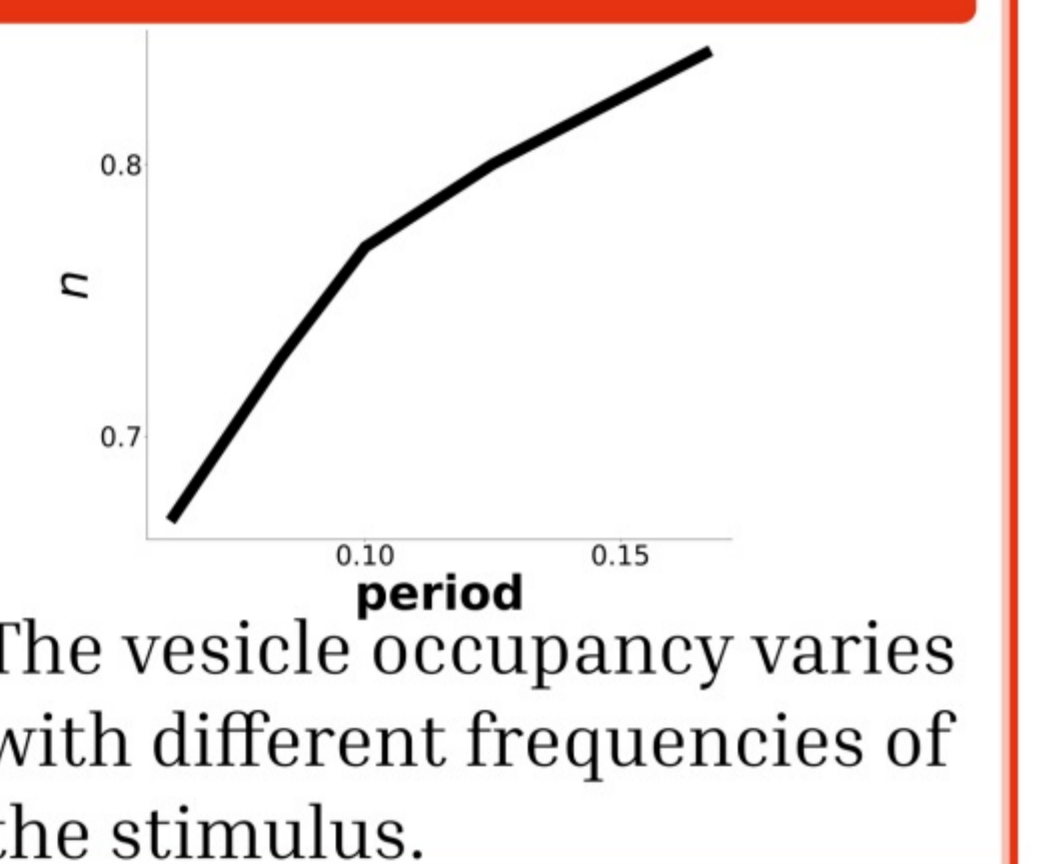
### Box 2 : Dynamic Synapse

The occupancy  $n$  of the vesicle pool follows the kinetic equation:

$$\frac{dn_{A1}}{dt} = \underbrace{(1-n)k_{rec}}_{\text{replenishment}} - \underbrace{\beta k_{rel} p_s n(V_{A1}(t), \theta_s n)}_{\text{release}} n_{A1}$$

The synaptic weight is scaled by  $n$

$$w_{A1}(t) = \bar{w}_{A1} n_{A1}(t)$$



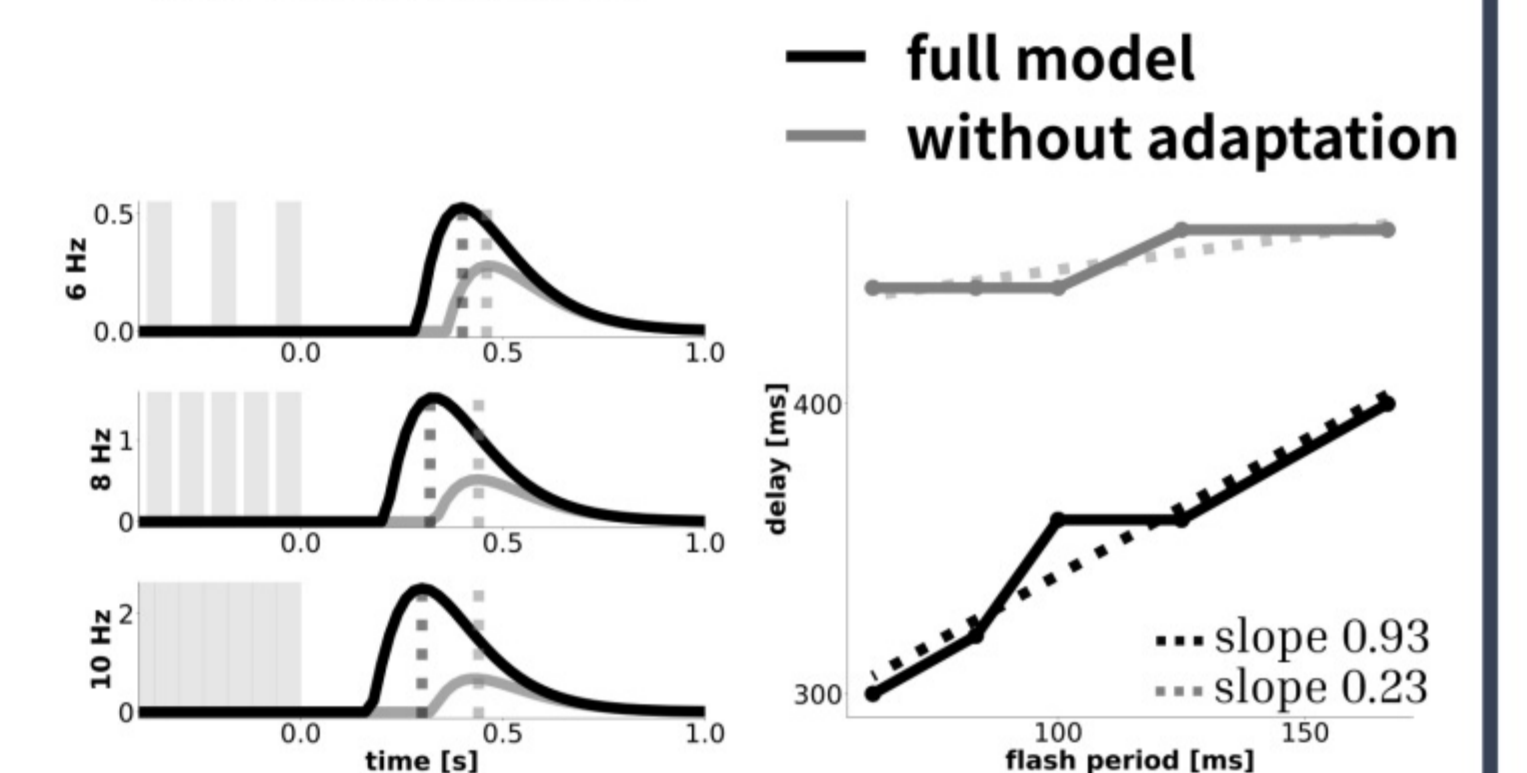
The vesicle occupancy varies with different frequencies of the stimulus.

### Mechanistic Explanation

1. Delayed inhibitory input via A2 causes rebound response after flash end.
2. Dynamically adapting synapse of A1 enables the circuit to have a fine temporal prediction by

- Adapting the weight of inhibitory inputs to the stimulus frequency
- Changing the amplitude and peak-time of the rebound response.

### Simulation



Simulated response of the mechanistic model can reproduce an Omitted Stimulus Response including its predictive timing. Simulations without the A1 unit predict a peak but do not capture the scaling with period.

## Conclusions & Perspectives

The retina encodes complex and rapidly moving visual scenes via its hierarchical, multilayered structure where most neurons respond by a graded variation of their membrane potential without spiking (except ganglion cells). Here, we show that inhibition via amacrine cells can enable the retina to encode surprise by

- (A) evoking a response to a change in the stimulus input via delayed inhibition and
- (B) adapting the timing of this response to the stimulus via short-term plasticity.

Besides temporal predictions on a spatially uniform stimulus, the retina has been shown to anticipate motion and to respond to changes in trajectories. Can we extrapolate the mechanism proposed here to a more general setting, where amacrine cells enable the anticipation of a moving object [4] while short-term plasticity allows to detect fast changes in its trajectory ?

## Acknowledgements

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