The Retina Predicts Information in Inertial Stochastic Dynamics

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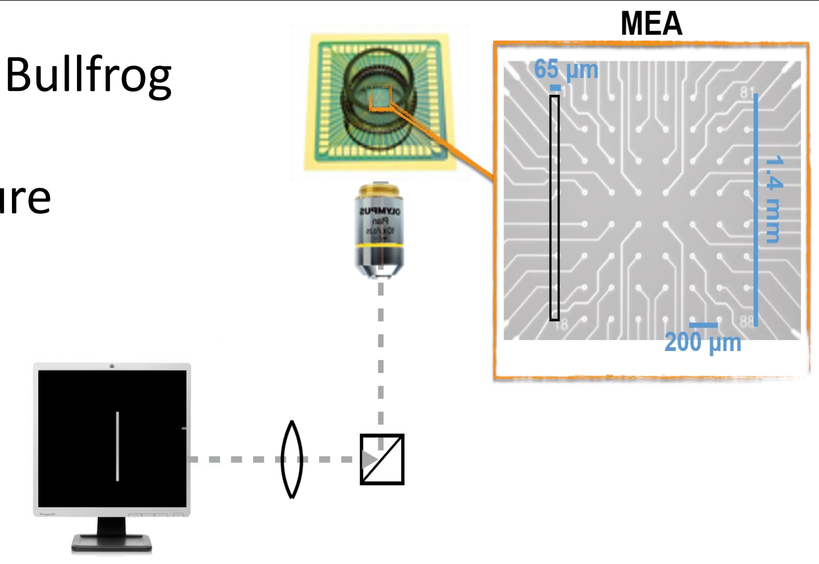
Introduction

- Visual stimuli are first received by the retina, but the processing of visual signals begins first at the retina, instead of the visual cortex [1].
- In experiments on the salamander retina, the mutual information between the visual signals and the responses of the retina with various time differences showed that responses of the retina actually have correlations with subsequent visual inputs [2].
- Not only can the retina transmit information, but it can also anticipate future signals based on what it has received.
- Experiments on the bullfrog retina showed that visual stimuli generated by Hidden Markov Model (HMM) and Ornstein-Uhlenbeck (OU) process resulted in different behaviors [3].
- To model these predictive behaviors, we propose a neural network model to simulate the dynamics of the amacrine cells and ganglion cells [4].

Experiment

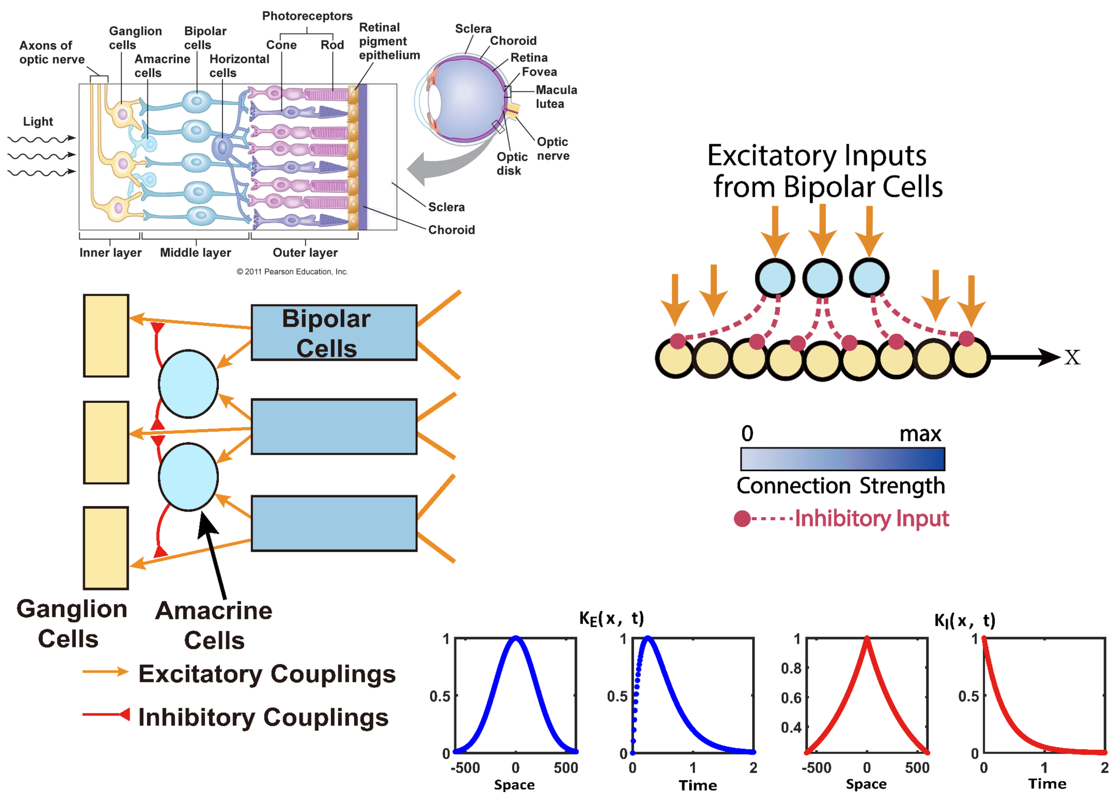
- Sample: Retina of Bullfrog
- Condition:
  - Room temperature
  - Ringer's solution



- MEA: electrode size 10 μm
- Stimulation:
- Moving Bar
  - Video refresh rate: 60 Hz
  - 1 pixel ~ 2.8 μm on retina
  - Bar luminance:
- 1.47~3.7 mW/m^2 with ~100% contrast

MEA provides recording of field potentials from a population of neurons.

Neural Network Model



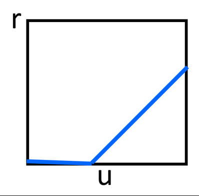
$$U(x,t) = g(x,t)\int_{-\infty}^{\infty} dx' \int_{-\infty}^{t} dt' K_E(x-x', t-t')\, E(x',t')$$

Synaptic inputs to ganglion cells; Responses of amacrine cells; Excitatory inputs from bipolar cells

$$g(x,t) = \exp[-\mathcal{A}\int_{-\infty}^{\infty} dx' \int_{-\infty}^{t} dt' K_I(x-x', t-t')\, I(x',t')]$$

Firing rates of ganglion cells

$$r(x,t) = \text{ReLu}\,[U(x,t)]$$



Simulations

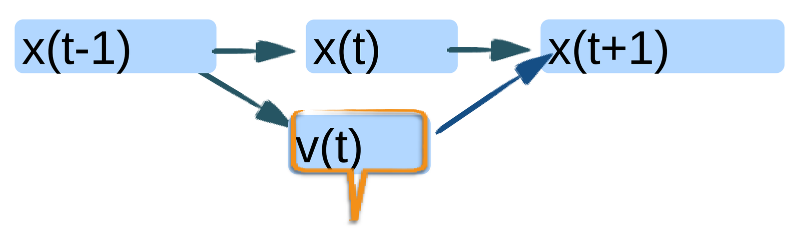
We calculated the mutual information between the inputs and the responses (firing rates) of the neural network at different time separations.

x_t: Input Positions

HMM (Hidden Markov model)

$$x_{t+\Delta\tau} = x_t + v_t\Delta\tau$$

$$v_{t+\Delta\tau} = [1-\Gamma\Delta\tau]v_t - \omega^2 x_t\Delta\tau + \xi_t\sqrt{D\Delta\tau}$$



OU (Ornstein-Uhlenbeck) Process

$$x_{t+\Delta\tau} = (1-\theta\Delta\tau)\, x_t + \xi_t\sqrt{D\Delta\tau}$$

Simulations and Experiments Results

The Mutual Information in HMM (Hidden Markov model)

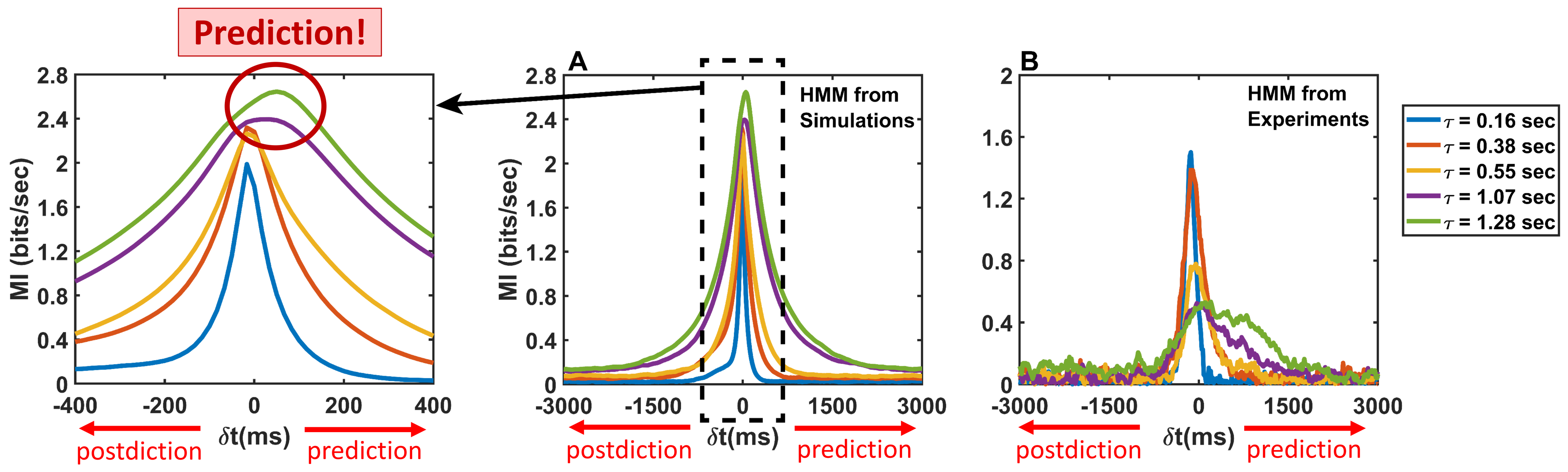


Figure 1. The mutual information (MI) curves for various correlation times τ of HMM. Positive δ_t denotes prediction. (A) The mutual information calculated from simulations. (B) The mutual information measured from experiments. Amplified part of 'predictive MI' in (A) is in the left figure.

The Mutual Information of Single Cells in HMM

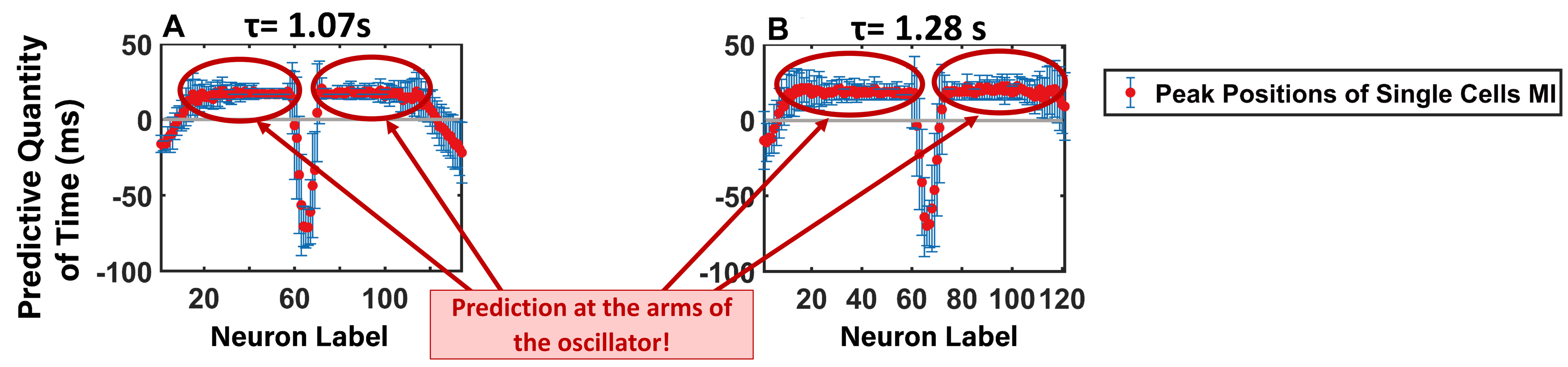


Figure 2. Peak positions of the mutual information curves of individual neurons for correlation times (A) τ = 1.07s and (B) τ = 1.28s averaged over 26 moving-bar movies.

The Mutual Information in OU (Ornstein-Uhlenbeck) Process

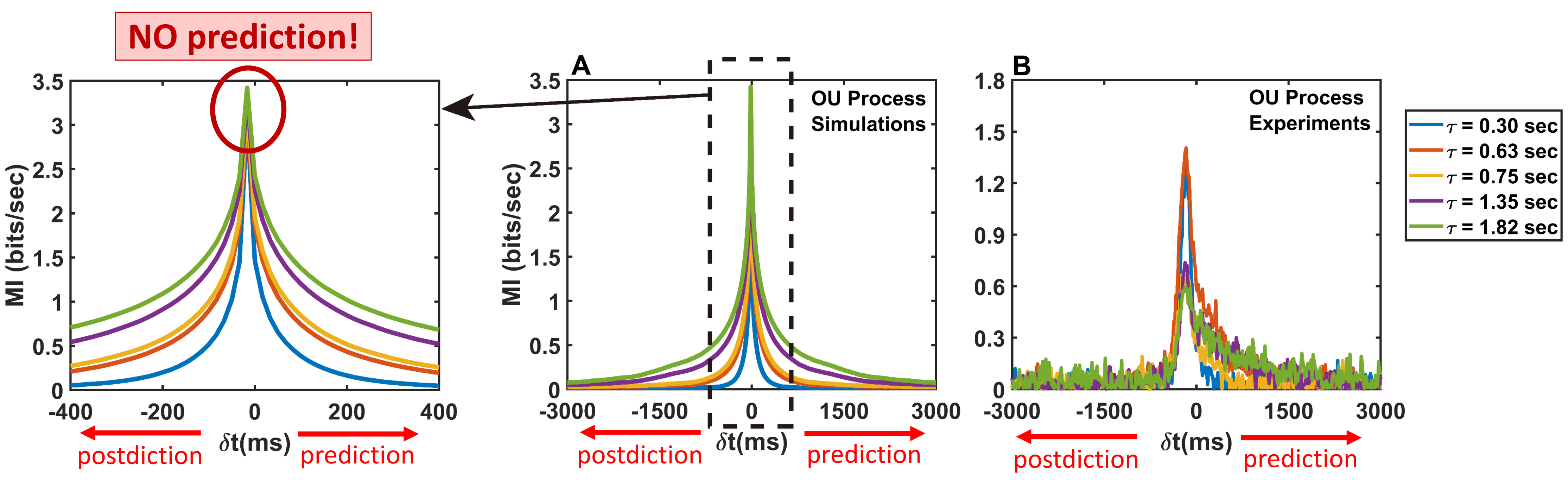


Figure 3. The mutual information (MI) curves for various correlation times τ of OU Process. Positive δ_t denotes prediction. (A) The mutual information calculated from simulations. (B) The mutual information measured from experiments. Amplified part of 'predictive MI' in (A) is in the left figure.

Conclusions

- Our model agrees with experiments well (Figs. 1 and 3).
- When the correlation time τ increases, the prediction effect becomes more and more prominent for HMM.
- In HMM, the predictive ability is strongest at the arms of the damped harmonic oscillator, where the dynamics can be predicted from its inertia (momentum) (Fig. 2).
- The inertial behavior in the retina is achieved by the local inhibition of the amacrine cells, as the response is weaker in the tail part of a continuously moving stimulus.
- There is no predictive behavior in OU process as it is not inertial.

References

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Acknowledgements

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