Adaptive Neural Information Processing

吴思
心理与认知科学学院
IDG/McGovern 脑科学研究所
北大-清华联合生命科学中心
北京大学

Adaptive Coding over Evolution

- Large monopolar cells (LMCs) in the blowfly compound eye encode contrast signals in the natural environment

- LMCs have limited response levels, and need to adapt their contrast sensitivity (gain function) to encode contrast signals efficiently.

- Here, efficiency means using the resource efficiently, i.e., the probability distribution of all our states should be constant, P(o)=constant

c : contrast level; o: output level

$o = g(c)$: the gain/contrast sensitivity

$$P(o)do = P(c)dc$$

$$\alpha g'(c) = P(c)$$

$$g(c) = \frac{1}{\alpha}\int_{-1}^{c} P(c)dc$$

Adaptive Coding over Evolution

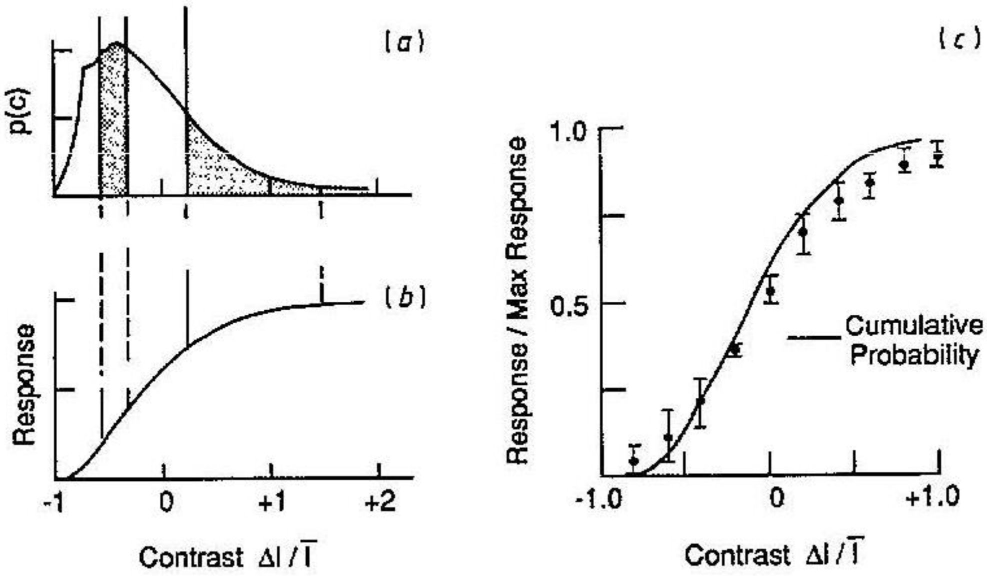
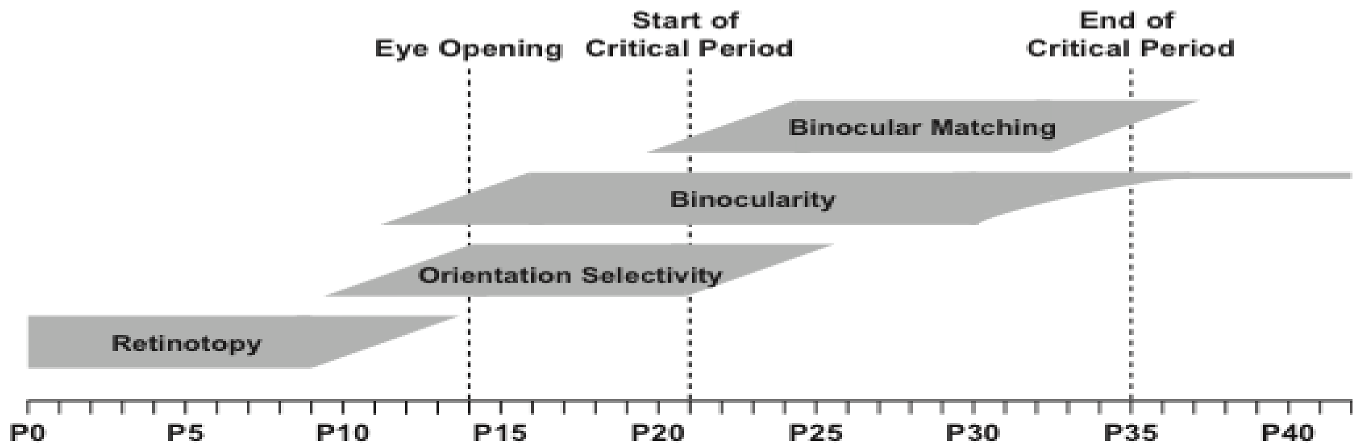


Figure 1. Probability distribution of contrasts, (*a*), in the fly environment from the measurements of Laughlin (1981). The contrast–response predicted by information theory is the cumulative probability map in (*b*). (*c*) is a comparison between the predicted response and that actually measured by Laughlin (1981) in the LMC.

J. Atick, Network, 3:213-251,1992

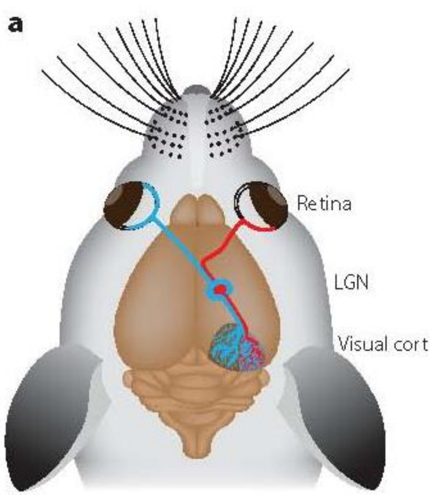
Adaptive Coding over Development

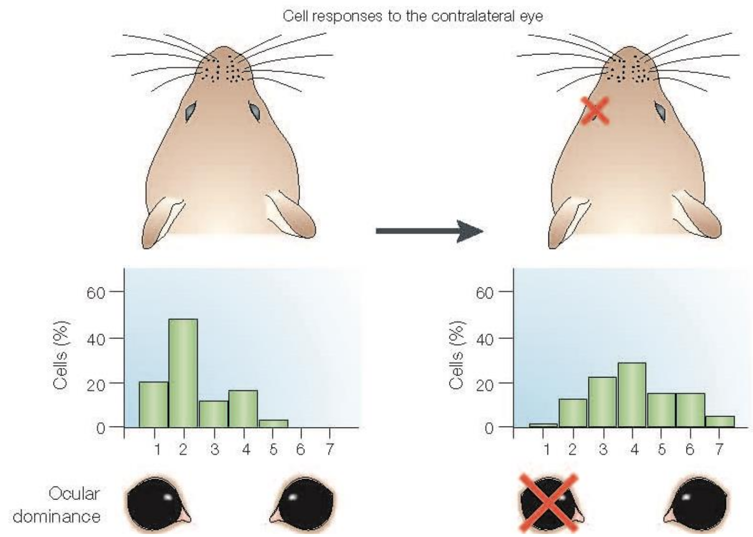
Critical Period in the development of
primary visual cortex of mouse



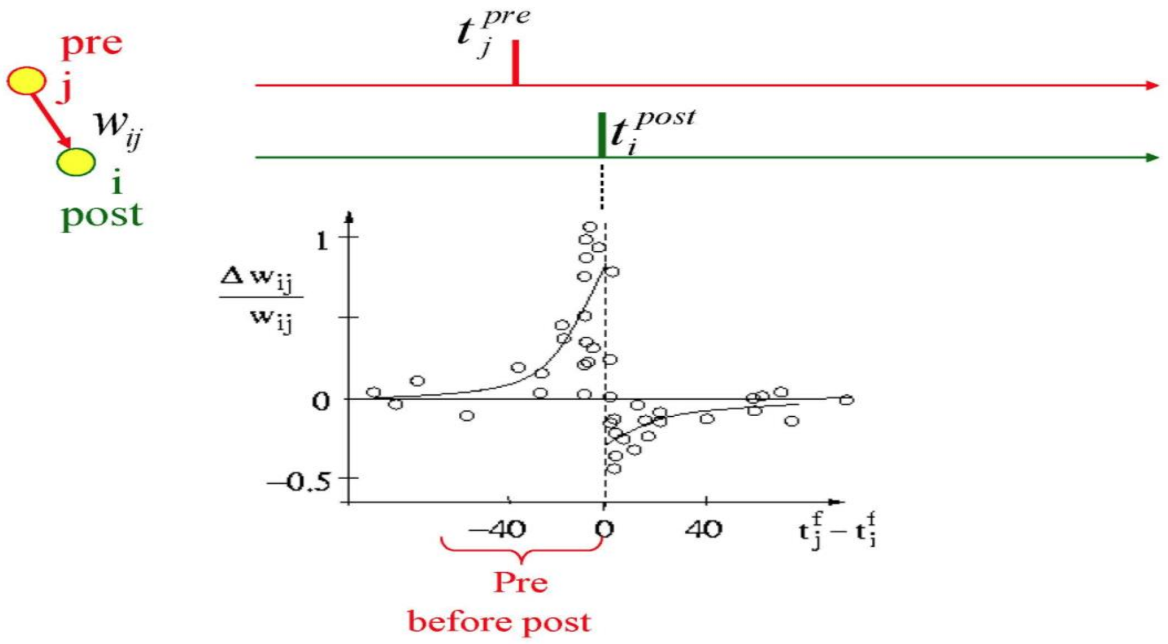
Espinosa & Stryker 2012

Monocular deprivation impairs binocular vision



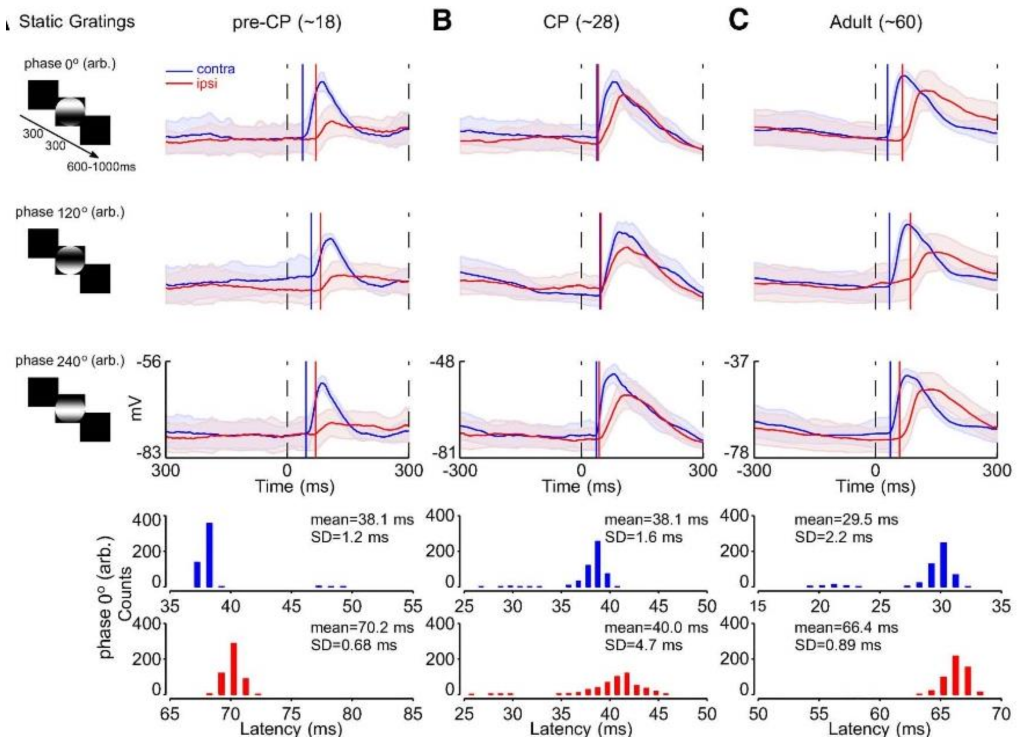


Spike-time-dependent-plasticity (STDP)



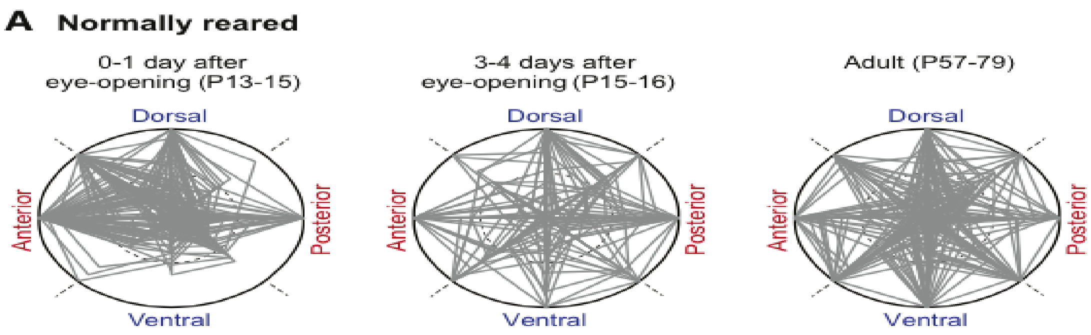
Bi & Poo, J. Neurosci. 1998

Increased synchronization of binocular inputs in the critical period

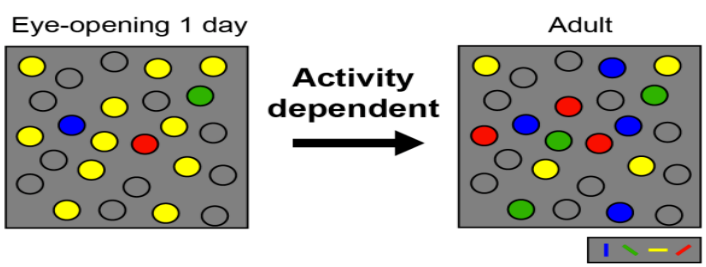


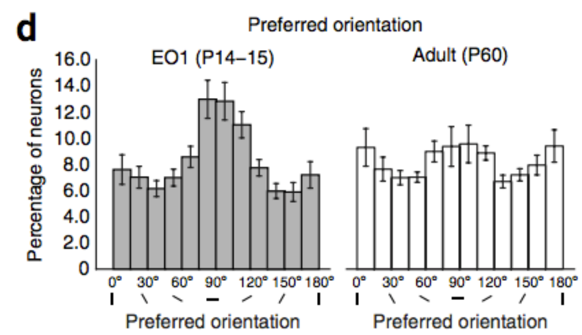
Chen et al., J. Neurosci. 2014

Balancing Direction/Orientation Tuning in Development



Rochefort et al 2011





Hagihara et al 2015

A Computational Model

The mechanism

- Different excitatory neuron groups encode different orientations
- All excitatory neuron groups are reciprocally connected to an inhibitory neuron pool, which mediates the competition between excitatory neurons
- Initially, horizontal orientation is encoded by neurons
- During development, new neurons are recruited to encode un-represented orientations

The prediction

- Development is accompanied with the maturity of inhibitory neurons
- Diversity of representation increases after exposing to the environment
- Tuning of inhibitory neurons becomes flat

On-line Adaptive Coding

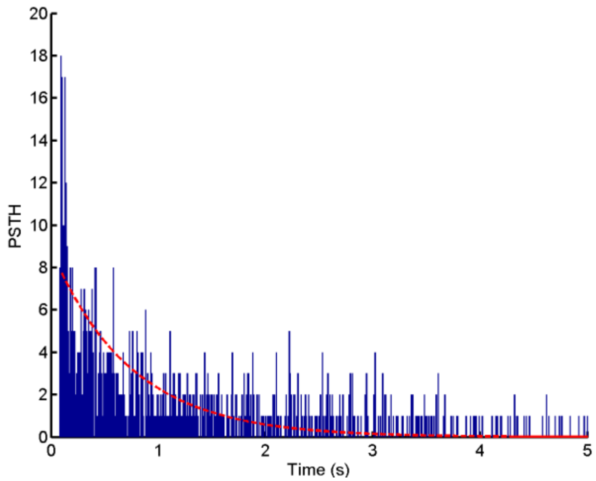
- Neural adaptation is a change over time in the responsiveness of the system to a constant stimulus.

  It is usually experienced as a change in the stimulus. For example, if one rests one's hand on a table, one immediately feels the table's surface on one's skin. Within a few seconds, however, one ceases to feel the table's surface. The sensory neurons stimulated by the table's surface *respond immediately, but then respond less and less until they may not respond at all*; this is neural adaptation.

  From Wikipedia

Neural systems adapt to invariant, not necessarily constant, stimuli

Neuronal Response in Adaptation



- Firing rate increases dramatically at the onset of a stimulation.
- For invariant stimulation, firing rate attenuates gradually to the background level

Is Adaptation Simply "Adaptation"?

- What does adaptation imply?
  - Constant stimulation conveys little "information".
  - Attenuating firing rates neglects input information?

- But the stimulus is still there?
  - Where is this information that "the stimulus is still there" encoded?
  - Is it possible that stimulus representation is shifted from firing rates to other neural response features?

Experiment Protocol

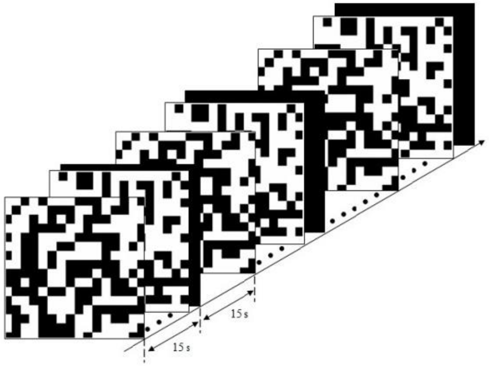
Material: Bullfrog retina;

Record: Multi-electrode Array (MEA);

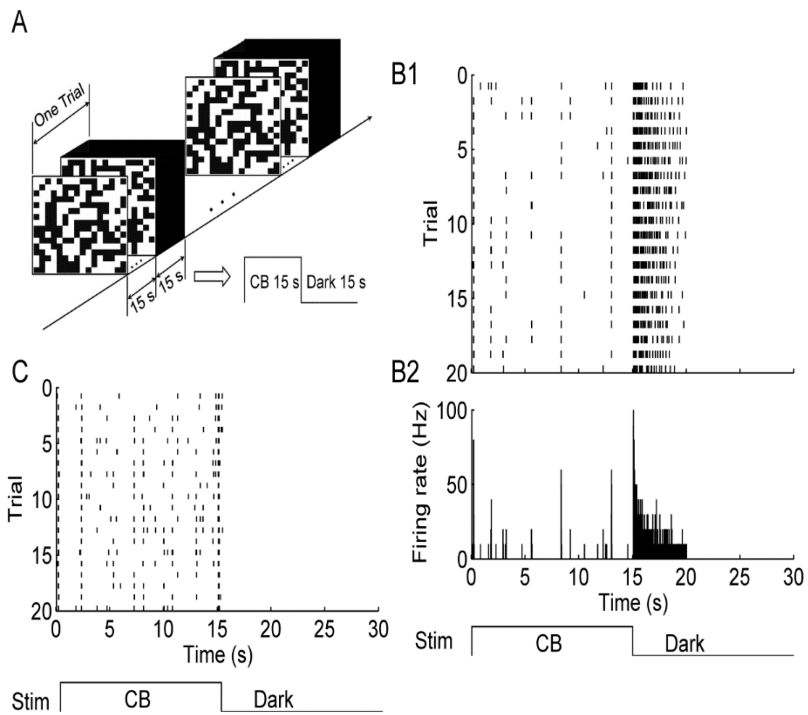
Stimuli.: 15s Checker-board followed by 10s Full-field <u>dark</u> or <u>gray</u> stimulation

Trails: 20-30 times

Task: Explore how luminance information is dynamically encoded in neural response features (firing rate vs. correlation)



Responses of Dim Detectors

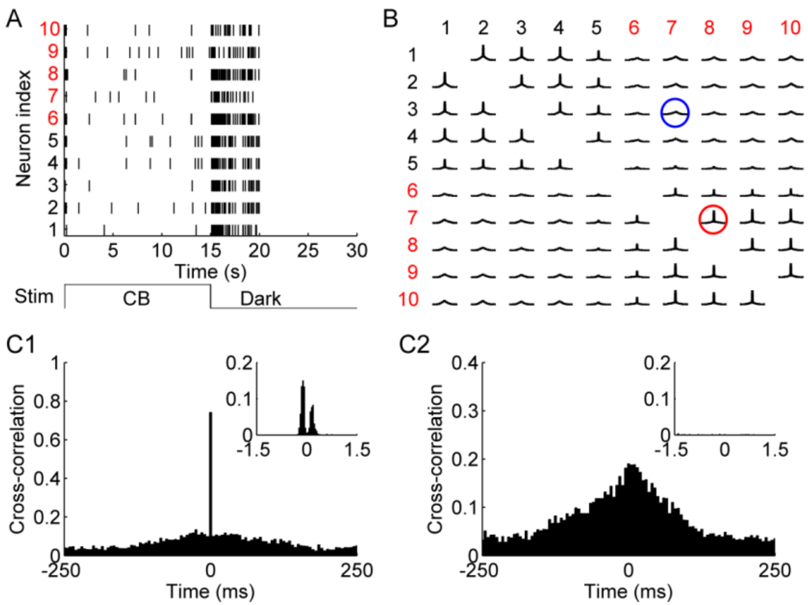


Non-dim detector

dim detector

- Sensitive to dimming condition
- Detecting the approaching of a predator from behind
- Display long-lasting adaptive response—lasting 5 s
- A good model to explore adaptation

Neuronal Correlation Patterns



		1	
6		3	2
10	8		4
	9	7	5

Two correlation types:

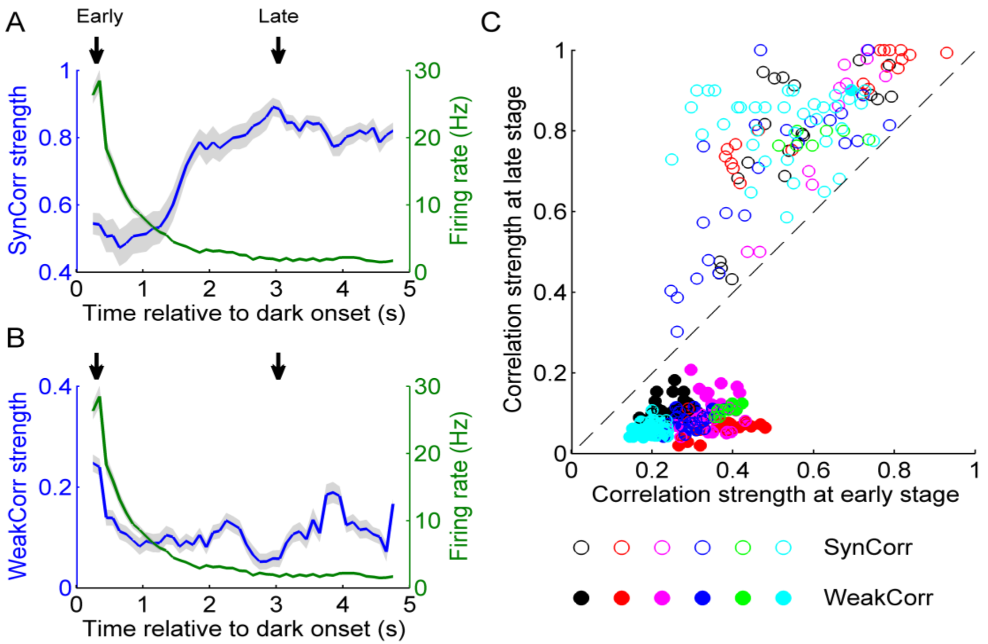
•Synchronization via gap-junction

• Weak correlation via common input

Cross-correlation:

$$C_{ij}(m) = \frac{M}{M-2|m|} \frac{\sum_{n=1+|m|}^{M-|m|} r_i(n) r_j(n+m)}{\sqrt{\sum_{n=1}^{M} r_i(n)^2 \sum_{n=1}^{M} r_j(n)^2}}$$

Correlation increases during adaptation



<u>A seemly paradoxical phenomenon</u>:

Neuronal firing rates attenuate, whereas, syn-corr increases!

A Discrimination Task

- Two stimuli: Dark vs. Gray
- Data: Neural population response over time
- Performance Indexes:
  - Information measure
  - Classification error

Information Measure

•Digitalizing neural responses (0101…)

- Mutual Information

$$I(S;r_1,r_2)=\sum_{S}\sum_{r_1,r_2}p(r_1,r_2\mid s)p(s)\log_2\left[\frac{p(r_1,r_2,\mid s)}{p(r_1,r_2)}\right]$$

- Synergy Information

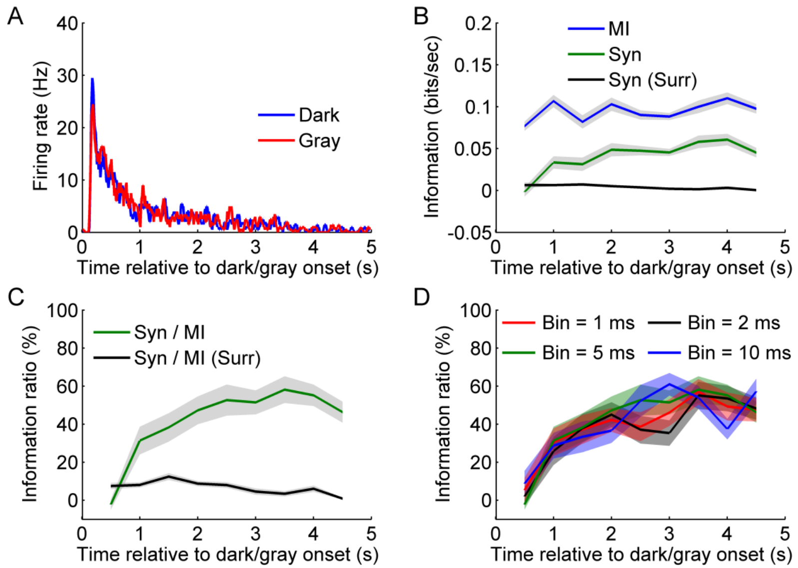
$$Syn(r_1,r_2)=I(S;r_1,r_2)-I(S;r_2)-I(S;r_1)$$

$Syn(r_1,r_2)=0:$ Independent

$Syn(r_1,r_2)>0:$ Information contained in neural correlated activities

$Syn(r_1,r_2)<0:$ Redundant

Shift of Neural Coding Strategy



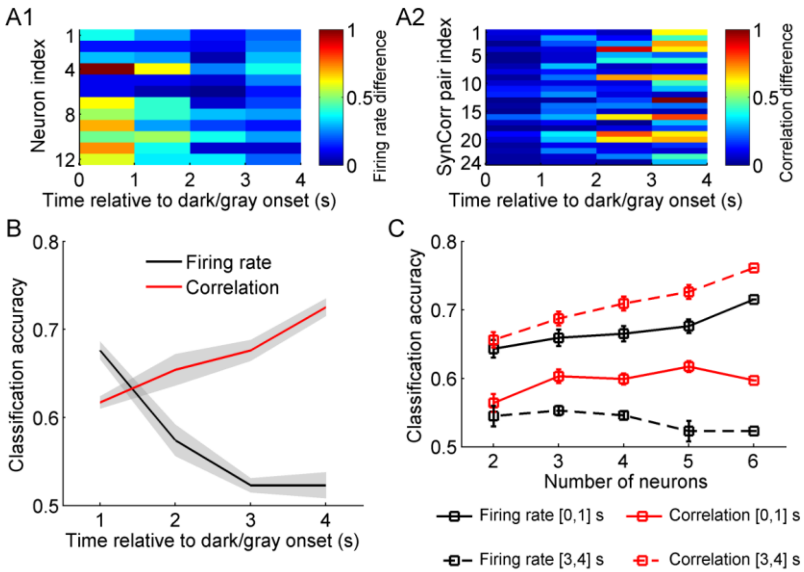
•Applied to a neuron pair

•Stimulus information conveyed by neural ensemble is rather stable

•Stimulus information conveyed by firing rates attenuate over time

•Stimulus information conveyed by neural correlation increase over time

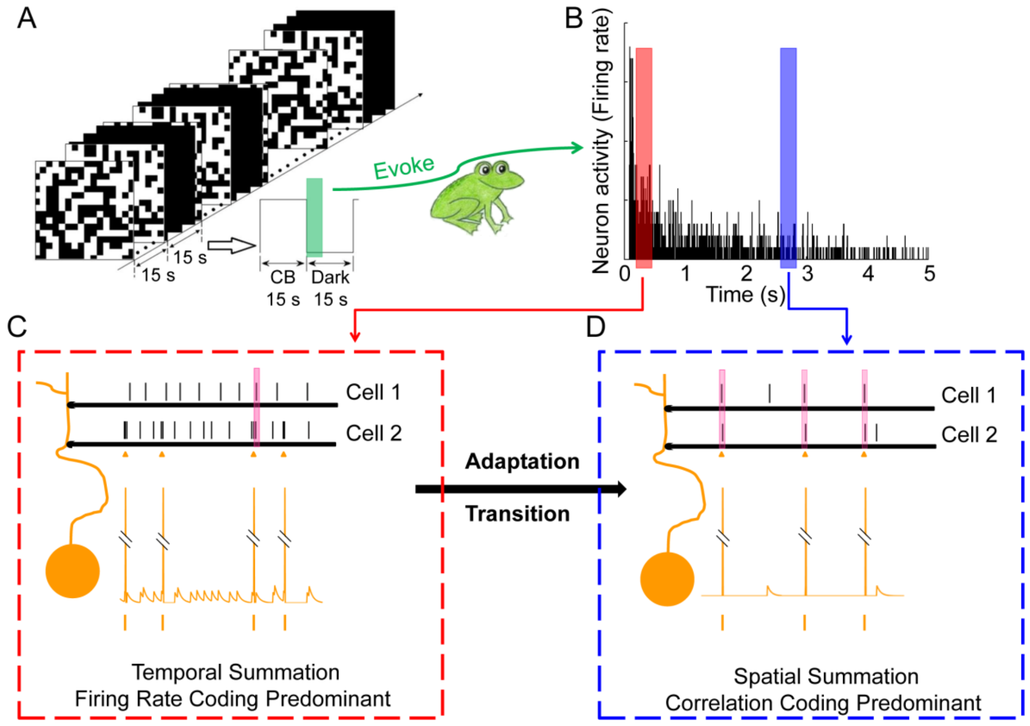
Classification Performances



- Applied to a neural population
- Linear classifier is used
- Classification accuracy based on firing rates attenuate over time
- Classification accuracy based on correlation increases over time

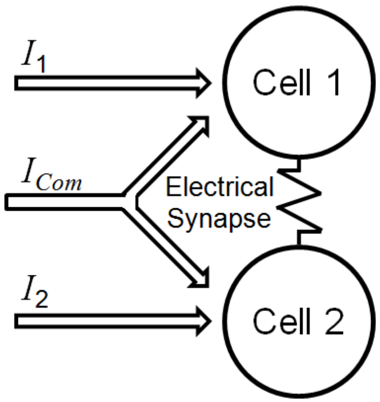
Input: firing rates of individual neurons or correlations between neuron pairs
Output: dark or grey

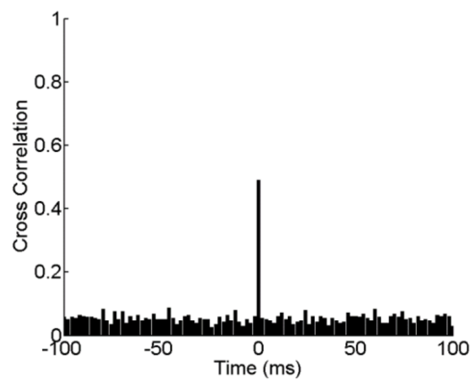
Why Adaptive Encoding?

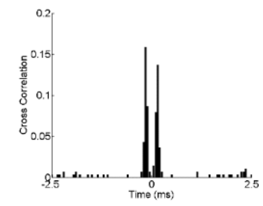


Xiao et al. Journal of Neurophysiology 2013.

A Computational Model for Retina Adaptation







$$C\frac{dV_i}{dt} = -g_L(V_i - V_{rest}) + I_i^{input} + g_{coupling}(V_j - V_i),\ \ i, j = 1, 2,$$

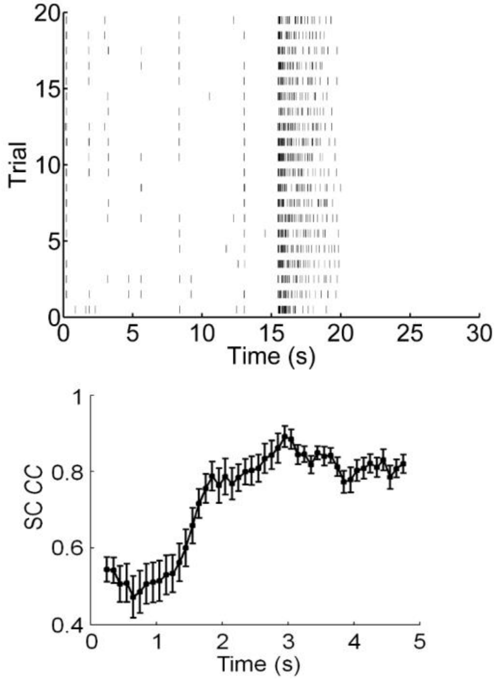
Facilitated Gap-junction

$$\tau_{coupling}\frac{d_{g_{coupling}}}{dt} = (-g_{coupling} + g_0) + \lambda(g_m - g_{coupling})e^{-|\Delta t|/\tau_g}$$

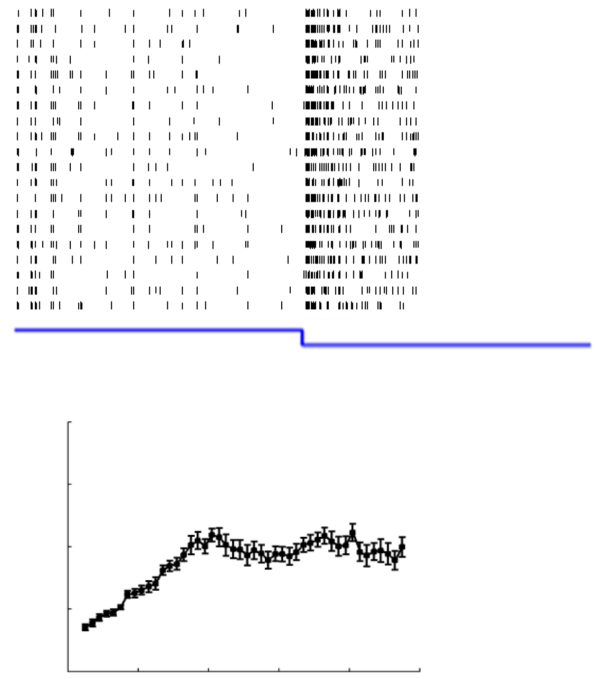
Xiao et al. Frontiers in Computational Neuroscience 2013.

Modelling Result

Experiment



Model



Summary

- Adaptation is not a simple process of neglecting the information of an invariant input.
- Neural coding is dynamical in nature:
  - Both rate and correlation codes hold, but work in different time scales.
  - Larger capacity, energy saving.
- The neural system has resources to implement dynamical coding.

References

1. Chapter 2 of Elements of Information Theory. Thomas Cover & Joy Thomas. John Wiley & Sons, Inc. 1991

2. Xiao-Jing Chen et al. (2014) Binocular input coincidence mediates critical period plasticity in the mouse primary visual cortex. J. Neurosci. 34: 2940-55.

3. L. Xiao, M. Zhang, D. Xing, P-J. Liang and S. Wu (2013). Shift of Encoding Strategy in Retinal Luminance Adaptation: from Firing Rate to Neural Correlation. Journal of Neurophysiology 110:1793-1803. doi:10.1152/jn.00221.2013.

4. Xiao Lei, Zhang Danke, Li Yuanqing, Liang Peiji and Wu Si (2013) Adaptive neural information processing with dynamical electrical synapses. Frontiers in Computational Neuroscience 7(36) doi: 10.3389\fncom.2013.00036

5. L. Li, Y. Mi, W. Zhang, D. Wang and S. Wu (2018). Dynamic information encoding with dynamical synapses in neural adaptation. Frontiers in Computational Neuroscience 12:16 doi: 10.3389/fncom.2018.00016.

6. Oizumi M et al. Mismatched decoding in the brain. J. Neurosci. 30: 4815-4826, 2010.

7. Nirenberg S et al. Retinal ganglion cells act largely as independent encoders. Nature 411: 698-701, 2001.