Chapter 51
Temporal and Spatial Characters of Retinal Ganglion Cells' Response to Natural Stimuli

Ying-Ying Zhang, Xin Jin, Hai-Qing Gong and Pei-Ji Liang

Abstract Results from physiological, theoretical, and computational studies suggest that the visual cortex processes natural sensory information with a strategy of sparse coding. To investigate whether this is also the case for retinal ganglion cells (RGCs), neuronal activities were recorded from a group of chicken RGCs in response to natural, time-varying images (movies) using extracellular multi-electrode recording system. The response of single RGC in exposure to natural stimulation showed sparse activity, while the ensemble responses did not. Such result may suggest that at the RGC level, the single unit activity is kept at a low level in response to natural stimuli for energy-saving, but the neuronal population are often activated in a correlated manner to achieve efficient information transmission.

Keywords Natural movie · retinal ganglion cell · life-time sparse activity · population activity

Introduction

The task of the visual system is primarily to process information in natural environment, it is therefore important to explore the visual information processing in response to natural stimuli [1]. It is suggested that the central visual system can use a strategy of sparse coding to optimize itself to match the natural scenes, which are inherently sparse in statistical structure [2, 3]. Sparse coding refers to the phenomenon that only a small portion of neurons are activated at a given time in response to a given stimulation [4], and at the mean time, the single neuronal activities are kept at a low level most of the time during stimulation. Sparse representation makes the structure in nature scenes explicit and simpler

Y.-Y. Zhang
Department of Biomedical Engineering, Shanghai Jiao Tong University, 800 Dong-Chuan Road, Shanghai 200240, China
e-mail: zcyyz@sjtu.edu.cn

R. Wang et al. (eds.), *Advances in Cognitive Neurodynamics*,

for the subsequent neurons to read out with high memory capacity and metabolic efficient [5].

Sparseness can be defined in two terms, lifetime sparseness and population sparseness. The fourth moment (i.e., the kurtosis) of the response distribution of a single neuron over time, and that of the firing rates distribution of the population neurons in response to a certain state of the natural stimuli can be applied to quantify the lifetime sparseness (K_L) and population sparseness (K_P) respectively.

In the present study, the activities of several dozens of RGCs in response to natural stimuli (movies) were recorded simultaneously from isolated chicken retina using a multi-electrode array (MEA). To represent the natural stimuli, each single neuron showed sparse representation while the ensemble neuronal activities are correlated. These results provide further experimental evidence from the earliest stage of the visual system to support the hypothesis that the nervous system can be well adapted to efficiently represent the natural input using a strategy of sparse coding combined with population correlation.

Methods

Electrophysiology Recordings and Visual Stimulation

Detailed extracellular-recording procedure can be found elsewhere [6, 7]. Spikes from ganglion cells were recorded by MEA electrodes (8×8) using a commercial multiplexed data acquisition system with a sampling rate of 20 kHz.

The stimulation protocols were: (1) Full-field white light flashes (1-s light-ON duration vs 9-s light-OFF intervals) to test the functional condition of the neurons being investigated; (2) Digitized segments of grayscale video recording (1920 frames, 128×128 pixels, refresh rate being 10 Hz) of natural outdoor scenes containing trees, rocks, streets, houses etc (download from the website of Hateren's lab, http://hlab.phys.rug.nl/vidlib/index.html; see also [8]). The images were projected onto the retinal piece via an optical lens system and covered the whole area of the multi-electrode array.

Data Analysis

Kurtosis is the fourth moment of a distribution for measuring the "peakedness" of the distribution [9]:

$$K = \left\{ \frac{1}{n} \sum_{i=1}^{n} \left[\frac{r_i - r^{-}}{\sigma_r} \right]^4 \right\} - 3 \tag{51.1}$$

This value is close to zero for a Gaussian distribution and a high positive value is related with a heavy-tailed peaky distribution, such as the case for sparse response of the neuronal activity.

Results

The firing probability distribution of an example neuron's response (firing rates counted in 1-s segments) in exposure to the natural movie is with a sharp peak as compared to the surrogate Gaussian distribution (Fig. 51.1a), with a K_L value being 1.8837 (the K_L value of the surrogate Gaussian data is -0.0390 ± 0.2761 (mean $\pm$SD, $n = 100$)). All the K_L values of the 21 ganglion cells recorded from the same piece of isolated retina are significantly larger than the K_L values of the surrogate Gaussian distribution data (Fig. 51.1b and c). These results demonstrate that the null hypothesis that the firing probability distribution follows a Gaussian distribution can be rejected for the single neurons' responses to natural movie, which gives evidence that the lifetime sparseness is a character of single neurons' responses to natural stimulation.

The response distribution of the neuronal population in exposure to an example segment of the natural movie (lasted for 1 s) is sharply peaked, but the data are more widely distributed (Fig. 51.2a), and the relevant K_P value is -0.21889 (with

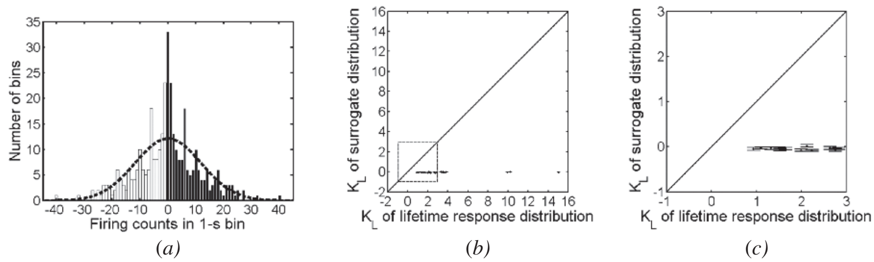

Fig. 51.1 (a) Response probability distribution (RPD) (filled bars, bin size = 1 s, with mirror values given in blank bars) for an example cell in exposure to the natural movie is compared to a Gaussian distribution (*dashed line*) which shares the same mean value and standard deviation with the reflected RPD to be analyzed. (b) Scatter plot of the K_L values of all the 21 neurons' surrogate Gaussian distribution against that of the RPDs. (c) Truncated from the dashed box in (b)

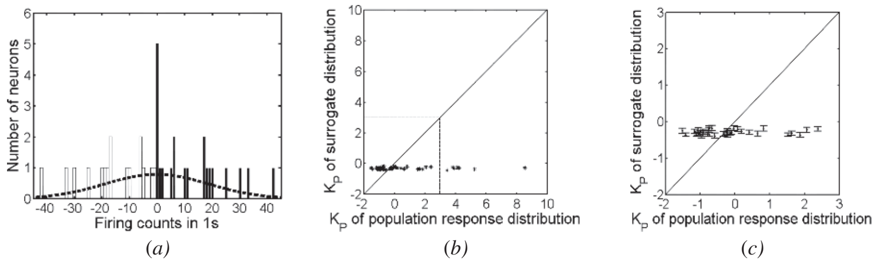

Fig. 51.2 (a) Response distribution (*filled bar, with mirror values given in blank bars*) for the population of 21 cells to 1-s segment of the natural movie is compared with a Gaussian distribution (*dashed line*) which shares the same mean value and standard deviation with the reflected response distributions to be analyzed. (b) Scatter plot of the K_P values of the surrogate Gaussian distribution against that of the response distribution of 40 segments of the movie (each lasted for 1 s). (c) Truncated from the dashed box in (b)

the K_P value of the surrogate Gaussian data being -0.19866 ± 0.68109 (mean $\pm$SD, $n = 100$)). Quite a portion of the neurons fired at a relatively low rate within the time window being investigated, but with a correlated manner. Figure 51.2b and c show that the K_P values of the response distribution in response to 40 segments of the movie (each lasted for 1 s) are widely distributed, while the K_P values of the surrogate Gaussian distributions are relatively constant. These results indicate that the population sparseness can not be detected and the activities of population RGCs in response to the natural stimuli in a correlated manner to provide an efficient information transmission.

Summary

Our results from temporal and spatial responses of the RGCs in exposure to natural movie provide further experimental evidence at the RGC level to support the hypothesis that the nervous system can be well adapted to efficiently represent the natural input using a strategy of sparse coding and suggest that the correlation among the population neurons is critical for efficiently encoding and transmitting the natural stimuli.

References

1. Reinagel, P.: How do visual neurons respond in the real world? Curr. Opin. Neurobiol. 11 (2001) 437–442.
2. Field, D.J.: Relations between the statistics of natural images and the response properties of cortical cells. J. Opt. Soc. Am. A 4 (1987) 2379–2394.
3. Simoncelli, E.P., Olshausen, B.A.: Natural image statistics and neural representation. Annu. Rev. Neurosci. 24 (2001) 1193–1216.
4. Olshausen, B.A., Field, D.J.: Natural image statistics and efficient coding. Network 7 (1996) 333–339.
5. Olshausen, B.A., Field, D.J.: Sparse coding of sensory inputs. Curr. Opin. Neurobiol. 14 (2004) 481–487.
6. Chen, A.H., Zhou, Y., Gong, H.Q., Liang, P.J.: Luminance adaptation increased the contrast sensitivity of retinal ganglion cells. Neuroreport 16 (2005) 371–375.
7. Jin, X., Chen, A.H., Gong, H.Q., Liang, P.J.: Information transmission rate changes of retinal ganglion cells during contrast adaptation. Brain Res. 1055 (2005) 156–164.
8. van Hateren, J.H., van der Schaaf, A.: Independent component filters of natural images compared with simple cells in primary visual cortex. Proc. R. Soc. Lond. B 265 (1998) 359–366.
9. Willmore, B., Watters, P.A., Tolhurst, D.J.: A comparison of natural-image-based models of simple-cell coding. Perception 29 (2000) 1017–1040.