

## **Firing coincidences between neighboring retinal ganglion cells: Inside information or redundant reformatting?**

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### **1. Background**

The simplest reading of the neural code presented by a spiking neuron is the rate at which it fires action potentials (impulses). Of course, extracting only the mean rate overlooks the temporal details of the firing pattern, an aspect that has recently been receiving attention (e.g.: Alonso *et al.*, 1996; Abbott, 2001). It also overlooks any relationships among the population of neurons involved in encoding even the simplest of stimuli (e.g.: Singer, 2000).

It has long been recognized that neighboring ganglion cells in vertebrate retinæ show correlations in the timing of their respective impulses (e.g.: Arnett & Spraker, 1981; Mastronarde, 1983; Ginsburg *et al.*, 1984). Neighboring ganglion cells of the same response type typically show an increased probability of both firing within some relatively narrow temporal window (coincidences), while those of opposite polarity (ON-center *versus* OFF-center) typically show a reduced probability of coincidences within a narrow window. For the most part, these cross-correlations have been studied as indicators of retinal processes (e.g.: Mastronarde, 1983; Johnsen & Levine, 1983, Brivanlou *et al.*, 1998; Levine, 1997, 1998).

Rather than being an epiphenomenon, however, coincidences may convey information. Meister *et al.* (1995; Meister, 1996) proposed that a simple coincidence detector could reconstitute a third impulse train from the firing arriving along two ganglion cell axons. They suggested that this “multiplexed” signal encodes finer-grained position information than is available from the separate neurons. This could easily treble the effective resolution of the optic nerve. In this series of experiments, we ask whether coincidences convey contributive information about the visual scene.

What information might be encoded by coincidences? The strongest hypothesis is that coincidences provide an independent stream of information not obtainable from the firing rates considered separately. This would be impossible if all the information available in each impulse train were extracted with the temporal resolution used to recognize coincidences; however, if only the mean firing rates of the separate impulse trains are considered, coincidences could restore information lost in the averaging operation. A weaker suggestion is that the information in the coincident impulse train is available in the separate impulse trains, but is more readily extracted by detecting coincidences than by performing a computation upon two firing rates. In that case, one would expect the actual coincidences to provide at least as good a signal as that obtainable by computation.

### **2. Methods**

Recordings were made from ganglion cells in the isolated retinæ of goldfish, *Carassius auratus*. An extracellular electrode recorded impulses from a pair of neighboring cells; logic circuitry parsed the two impulse trains into two channels (Ginsburg *et al.*, 1984).

In the experiments reported here, the stimulus light was modulated as a 1 Hz square wave, repeated for 32 cycles at each stimulus configuration. (In some earlier experiments, a

repeating Gaussian white noise stimulus was used; however, the ability of the cells to replicate the timing of the fast components obscured the coincidences). The stimulus imaged on the retina was an 0.3 mm diameter disk; wavelength was set by a  $\frac{1}{4}$  m monochromator, and neutral density filters provided attenuation over a 4 log unit range. For experiments examining coding for position, the disk could be situated anywhere within a 1 mm area in which the two receptive field centers lay. In the other experiments, the disk was centered upon the electrode, and successive presentations varied in wavelength, attenuation, or contrast (depth of modulation). Each consecutive series of presentations of 32 cycles in which the stimulus varied along a particular dimension was defined as a single experiment.

For each pair of cells, a window was selected within which the rate of firing of the one cell relative to each impulse in the other was distinctly different from that expected from the two mean firing rates. A coincidence was registered when both cells fired within that window. The average rates for each cell and of coincidences during stimulus ON and during stimulus OFF were taken separately; the ON and OFF half cycles were defined with a latency determined from the peristimulus time histograms of the responses.

### 3. Results

Data in which both cells were responsive were obtained from 27 experiments on 11 pairs of cells. To determine whether the coincidence rate was independent of the rates in the two separate cells, the coincidence rate in each experiment was predicted according to two models: linear regression and a model in which the coincidence rate is given by the product of the two cells' rates times an "effective binwidth". Since the null hypothesis is that coincidences are determined by the firing rates and are not influenced by the stimulus, ON and OFF responses were pooled for the fitting. Either model did extremely well, accounting for 84% and 82% of the variance of the coincidence rate, respectively.

While these predictions indicated that most of the variability in coincidences can be predicted from the individual firing rates, there remained the possibility that the residual variance conveys information that might "fine tune" the coincidence impulse train to make it a better carrier of some aspect of the information. To test for this, the predictions, and the residuals between the predictions and observed coincidence rate, were compared to the observed coincidence rate as indicators of the stimuli. For these comparisons, ON and OFF responses were treated separately, although the models from which the predictions were derived considered both responses.

Since many of the cells responded with increases of firing at both onset and offset of stimuli, we wondered whether the coincidence rate served to distinguish between ON and OFF responses. In 18 experiments, the coincidence rates at ON and OFF were significantly different (paired  $t$ -test,  $\alpha=0.05$ ); however, in every one of these experiments, at least one of the individual cells and both predictions also showed a significant difference. As a further test, we compared the unpaired  $t$ -values for the actual coincidence rates and the predicted coincidence rates for each experiment; the differences in  $t$  were not significant, but the tendency was for the predictions to be better at this distinction. Moreover, the better individual cell significantly outperformed the coincidence rate.

An experiment testing for wavelength coding was performed on each of six pairs; experiments testing for intensity (attenuation) or contrast (depth of modulation) coding was performed on each of three pairs; experiments testing for position coding (which is what had originally been suggested) were performed on all 11 pairs with repeat runs on four, yielding a total of 15 such experiments. Graphs of the separate ON and OFF responses, coincidence rates, predictions, and residuals *versus* the relevant independent variable were inspected and fit by linear regression (signs were adjusted such that the coincidence rate was positively correlated

with the relevant variable). For the position experiments, in which there are two independent variables, a projection axis was chosen that maximized the gradient of the coincidence rate. The regression fits to these plots provided measures of the coding by the actual coincidence rate and by the model predictions. Three measures were considered: the regression slope, which indicates the strength of the coding; the correlation between firing rate and the independent variable, which indicates the reliability of the encoding; and a signal-to-noise ratio (SNR) derived from the correlation, which indicates the robustness of the coding..

The regression slope of the actual coincidence rate tended to be steeper than that of either prediction, but this difference was significant only when all conditions were combined, and only in comparison to the linear model. Moreover, the differences between the Fisher  $z$ -transforms of the correlation coefficients of coincidence rate with any variable and the corresponding transforms of the correlations of the predicted rates were not significant (except for the effective binwidth model encoding contrast, which was significantly *better* than the actual coincidence rate). Similarly, there were no significant differences between the SNR of the actual coincidence rates and the predictions.

In all but one of the experiments, at least one of the individual cells showed a stronger relationship with the relevant variable than did the observed coincidences. The correlation and SNR of the coincidence rates were not significantly lower than those of the better cell in the pair, but the mean differences were in the direction of better performance by the one cell.

The superiority of the individual cells over the coincidence rate was confirmed statistically by an analysis of the information content of the impulse trains. Both the mean ON and OFF responses of *either* cell had greater information than the mean ON or OFF of the coincidence rate; these differences were significant overall, for position, and for wavelength. In every experiment, the information in the firing of at least one individual cell was greater than that in the coincidence rate.

## 2. Discussion

These data indicate that the coincidence rate is not a likely coding mechanism, at least for the variables tested here (ON *versus* OFF, wavelength, intensity, contrast, and position). Nearly 85% of the data potentially conveyed by coincidences is available from the individual firing rates. This conclusion agrees with Nirenberg *et al.* (2001), who determined the information available in impulse trains of mouse retinae shown a naturalistic movie (featuring mice) and found that most of the information was retained when the cross-correlations were neglected.

The encoding of stimulus information by coincidences is no better than obtaining it by computation (even assuming one of the two models tested is optimal for extracting it), and is less accurate than the firing of the better-suited single cell. Although it may be more difficult for a neural system to extract information by computation than by coincidence detection, the same data are readily available in the firing of the separate cells. We cannot rule out a process of encoding by coincidences, but it seems an unlikely candidate, at least in this system.

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