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Spatial asymmetries in cat retinal ganglion cell responses

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Abstract. Enroth-Cugell and Robson (1966) first proposed a classification of retinal ganglion cells into X cells, which exhibit approximate linear spatial summation and largely sustained responses, and Y cells, which exhibit nonlinearities and transient responses. Gaudiano (1992a, 1992b, 1994) has suggested that the dominant characteristics of both X and Y cells can be simulated with a single model simply by changing receptive field profiles to match those of the anatomical counterparts of X and Y cells. He also proposed that a significant component of the spatial nonlinearities observed in Y (and sometimes X) cells can result from photoreceptor nonlinearities coupled with push-pull bipolar connections. Specifically, an asymmetry was predicted in the ganglion cell response to rectangular gratings presented at different locations in the receptive field under two conditions: introduction/withdrawal (on-off) or contrast reversal. When measuring the response to these patterns as a function of spatial phase, the standard difference-of-Gaussians model predicts symmetrical responses about the receptive field center, while the push-pull model predicts slight but significant asymmetry in the on-off case only. To test this hypothesis, we have recorded ganglion cell responses from the optic tract fibers of anesthetized cat. The mean and standard deviations of responses to on-off and contrast-reversed patterns were compared. We found that all but one of the cells that yielded statistically significant data confirmed the hypothesis. These results largely support the theoretical prediction.

1. Introduction

This paper reports some experimental results that test a prediction generated by the push-pull model of X and Y ganglion cells (Gaudiano 1994). The details of the push-pull model, which were originally published in this journal (Gaudiano 1992a, 1992b), have been the subject of some debate (e.g., Freed and Nelson 1994). The goal of this paper is to show that the model was able to generate a testable prediction that is supported by the data.

After an overview of X and Y ganglion cells, and a summary of the push-pull model and its prediction, we show results obtained from the optic tract of the cat. The results are followed by an analytical explanation of the model's prediction. The paper concludes with some observations about the push-pull model and its implications for the existence of strong nonlinearities in the earliest stages of visual processing.

1.1 X and Y ganglion cells

In 1966, Enroth-Cugell and Robson proposed a functional classification of retinal ganglion cells into two broad classes, which they termed X and Y cells. According to their proposal, X cells respond in a sustained fashion to inputs, and exhibit linear spatial summation, whereas Y cells respond in a more transient fashion, and do not exhibit linear spatial summation.

Linear spatial summation was tested by Enroth-Cugell and Robson (1966) by measuring the response of ganglion cells to a sinusoidal grating that is turned on and off[1] at various relative spatial phases, that is, as the grating is located at varying positions relative to the receptive field center. At a spatial phase of 0° or 180°, when the zero-crossing (point of average luminance) of the grating is located directly over the receptive field center, X cell responses show no modulation as the grating is turned on and off. This is known as a *null response*, and it has been taken to imply that X cells perform *linear spatial summation*, meaning that the increased input to one half of the X ganglion cell's receptive field is exactly canceled by the simultaneous decreased input to the other half of the receptive field. In contrast, when presented with the same stimulus, Y cells

[1] When the grating is off, it is replaced by a homogeneous gray field with luminance equal to the average luminance of the sinusoidal grating

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exhibit *frequency doubling*, an increased response to both onset and offset of the grating.

These results, which were verified and extended in several subsequent studies (e.g., Hochstein and Shapley 1976a, 1976b), has been found to hold for various levels of contrast, adaptation level, and temporal modulation functions. It is because of the robustness of this result that Enroth-Cugell and Robson (1966) and others concluded that all retinal processing prior to the X ganglion cells must be linear: any deviations from linearity would distort the spatial luminance pattern, in which case the null response points would either disappear, or they would shift in location as a function of contrast, luminance, or other stimulus parameters.

The difference in response characteristics of X and Y ganglion cells has led to the hypothesis that the underlying retinal circuitry differs between these two cell classes. In particular, Hochstein and Shapley (1976b) proposed two distinct models for the X and Y cell receptive fields. The X cell receptive field consists of an excitatory, linear center region and an inhibitory, linear surround region, with each region modeled as a Gaussian (Rodieck 1965). In addition to this same basic structure, Hochstein and Shapley hypothesized that the Y cell's receptive field includes several small subunits whose response characteristics are strongly nonlinear, for instance as given by half-wave rectification. The primary reason for assuming the existence of small nonlinear subunits came from the observation that a grating whose spatial frequency is too high to be resolved by the Y cell's receptive field center is still able to elicit a frequency-doubled response, regardless of the grating's relative spatial phase (Hochstein and Shapley 1976b).

A few years ago, one of us (Gaudiano 1992a, 1992b) proposed a push-pull model of X and Y ganglion cells, which was later used to provide detailed fits of the original results of Enroth-Cugell and Robson (Gaudiano 1994). According to the push-pull model, incoming light is first transformed into neural signals by photoreceptors through a dynamic gain control mechanism. The (nonlinear) photoreceptor output is then conveyed to ON and OFF bipolar cells, which converge in a push-pull fashion onto both ON and OFF ganglion cells (Fig. 1). The push-pull inputs summate through a nonlinear interaction, and the net effect is to adjust the ganglion cell's response around the average response of the photoreceptor. When the receptive field of the simulated ganglion cells is adjusted to mimic the shape of the β cell (the anatomical counterpart to X cell) receptive field, the model exhibits linear spatial summation in response to modulated sinusoidal gratings. When, on the other hand, the receptive field of the simulated ganglion cells is adjusted to mimic the shape of the α cell (anatomical counterpart to Y cells) receptive field, the model exhibits frequency doubling, which is independent of spatial phase for sufficiently high grating spatial frequencies (Gaudiano 1994).

1.2 Nonlinearities in the retina

One important aspect of the push-pull model is that it relaxes the assumption that all neural stages leading up to the X ganglion cells must be linear, an assumption that is refuted by several observations. First, because our visual system can encode several orders of magnitude of luminous intensity, all cells up to the X cells would require a dynamic range capable of carrying the full range of luminous intensities. In reality, the dynamic range of individual neurons is probably limited to one or at most two log units (e.g., Dowling 1987). Second, it is well known that many cell types in the outer plexiform layer of the retina, including photoreceptors and bipolar cells, exhibit strong nonlinearities (e.g., Naka and Rushton 1966). In particular, a significant amount of adaptation is already found as early as the photoreceptor outer segment, where the main phototransduction stages take place (Pugh and Lamb 1990; Schnapf et al. 1990). By definition, adaptation is a form of nonlinearity, since the same system gives different responses to the same input depending on its state. Third, no definitive anatomical evidence has been found to support the original hypothesis that X and Y cell receptive fields are constructed from fundamentally different neural circuits.

It has been argued that perhaps the nonlinearities of the outer plexiform layer are slight, and do not appear at low contrast level. However, there are no quantitative models to support this hypothesis, and in fact X cells exhibit null responses to sinusoidal gratings even at relatively high contrast levels: for instance, the original study of Enroth-Cugell and Robson (1966) used contrast levels of over 30%.

The push-pull model offers a simple way to explain X cell linear spatial summation. The photoreceptors need to be nonlinear in order to compress dynamically a broad range of input into the narrow range of neural signals. The information is then split into ON and OFF

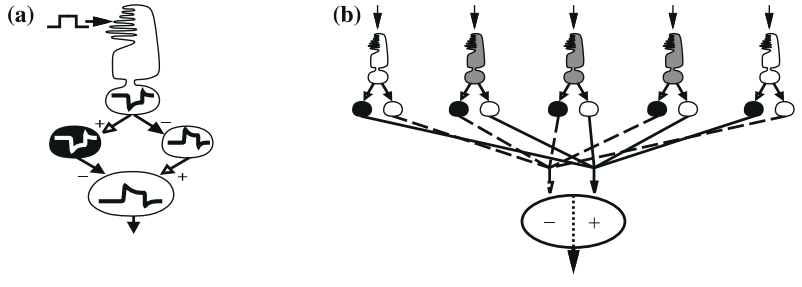

Fig. 1a,b. Diagram of the push-pull shunting network. **a** Light impinging on each photoreceptor generates equal and opposite ON and OFF signals, which converge in a push-pull fashion on each ganglion cell. **b** Schematic of the push-pull connectivity extending to the center and surround of each ganglion cell's receptive field. Adapted from Gaudiano (1994) by permission of Pergamon Press

channels and rejoined at the ganglion cells in such a way that effectively the ganglion cells respond to *contrast* by adjusting their response relative to the mean photoreceptor output level. The push-pull inputs further act to reduce the effects of spatial asymmetries arising from the photoreceptor nonlinearities.

An additional important aspect of the push-pull model is the prediction that much of the nonlinearity observed at the Y ganglion cells may arise from the photoreceptors. In the push-pull model there are no thresholds or rectification operations. The frequency-doubling response of Y cells is the result of an asymmetry in the photoreceptor responses to input increments and decrements. Specifically, the incremental response to a change from a lower input level I_0 to a higher input level I_1 is larger in magnitude than the decremental response to a change from the higher input level I_1 down to the lower input level I_0 (details are given in Sect. 3.1). Intuitively, this is because the photoreceptors have a lower gain when they are adapted to I_1 than to I_0, so equal size input changes lead to smaller size responses.

Consider now the response of a Y ganglion cell to a contrast-reversed sinusoidal grating, as schematized one-dimensionally in Fig. 2. When the retina has adapted to the luminance pattern represented by the dashed line (bright left, dim right), the photoreceptors feeding into the right half of the receptive field have a higher gain than those on the left, so that at the time of the contrast reversal the net increment in input coming from the right side of the receptive field is larger than the decrement in input coming from the left side of the receptive field. The result is a net increase in ganglion cell output (an 'on-response'). After the contrast reversal, once the system has reached equilibrium the situation is exactly reversed, with the photoreceptors on the left side now having a higher gain than those on the right side (as shown by the solid line in Fig. 2); at the next contrast reversal, once again the increment in input (this time coming from the left half of the receptive field) is larger than the decrement in input (this time from the right), and the Y cell's response once again shows a net increase. Hence the Y cell exhibits frequency doubling. In an earlier manuscript, Gaudiano (1991) was able to show analytically that the photoreceptor nonlinearity is necessary and sufficient to generate the frequency-doubling response of Y cells as explained here.

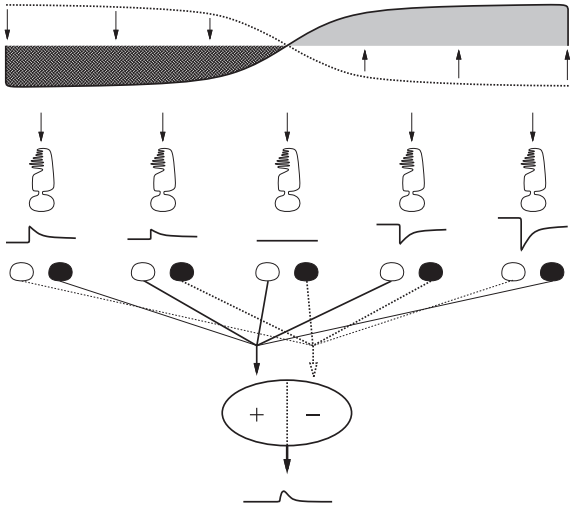

Fig. 2. Generation of the Y-cell frequency-doubling response in the push-pull model. When a sinusoidal grating (*dashed line*) is contrast reversed (*solid line*), the photoreceptors on one side of the receptive field have a higher gain than those on the other side, leading to a net, transient response increment. At subsequent reversals the situation will be the same, because again the photoreceptors starting under the dark side of the grating will have a higher gain

1.3 X cell nonlinearities

Given that Y cell nonlinear responses in the push-pull model are due primarily to the photoreceptor nonlinearities, why do these nonlinearities not appear in the X cell responses? The difference is largely due to the overall shape and size of the receptive field center and surround. In a few words, the asymmetry between photoreceptor incremental and decremental responses will be more pronounced as the spatial summation area increases. In reality it is not simply the receptive field size, but mainly the balance between center and surround that affects the sensitivity to photoreceptor response asymmetries. When the input is a sinusoidal grating, the X cell's relatively small receptive field center, coupled with its relatively broad surround, contributes to minimize the asymmetry in photoreceptor responses at each contrast reversal (Gaudiano 1991).

The above explanation of the difference between X and Y cells led Gaudiano (1994) to the following observation: if the nonlinearity of Y cell responses is due to the cumulative effect of asymmetric photoreceptor responses, then the same kind of nonlinearity might be seen in X cells if the input is such that the asymmetry about the receptive field center is enhanced. In fact, when the input consists of a sharp light-dark edge (step pattern) that is suddenly replaced with a uniform gray field, small but clear frequency-doubling responses are also visible in X cells (Enroth-Cugell and Robson 1966; their Fig. 12). This result was simulated by Gaudiano (1994).

1.4 Asymmetry in responses to light-dark patterns

An additional, related finding led to the formulation of an experimental prediction that is the main subject of this article. Enroth-Cugell and Robson measured the sensitivity of X cells to introduction and withdrawal of a light-dark step pattern as a function of spatial phase, i.e., as a function of the location of the edge relative to the receptive field center. Gaudiano (1994, see p. 1777) pointed out that a small but noticeable asymmetry relative to the X cell's receptive field center was evident in Enroth-Cugell and Robson's sensitivity data, which are reproduced here in Fig. 3a, and also in the computer simulations shown in Fig. 3b. He proposed that if the

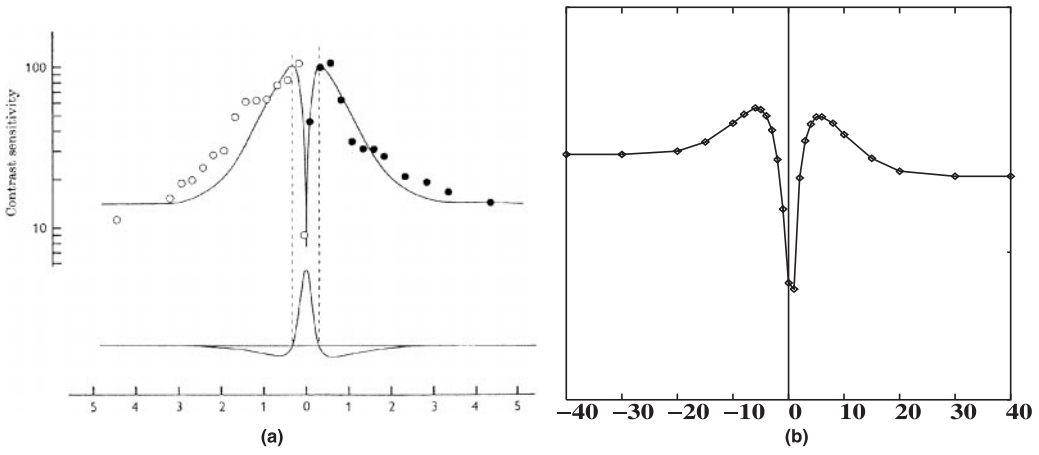

Fig. 3a,b. X cell contrast sensitivity in response to on-off modulation of a light-dark edge. **a** Experimental data reproduced from Fig. 13 of Enroth-Cugell and Robson (1966) by permission of the Physiological Society. **b** Simulation of the empirical data using the push-pull model, reprinted from Gaudiano (1994) by permission of Pergamon Press. Note the small but noticeable asymmetry between the sensitivity profiles on the left and right sides of the receptive field center

experiment was repeated, but doing a full contrast reversal of the step pattern rather than just turning it on and off, the asymmetry should disappear. The reason for this prediction is that the observed ganglion cell asymmetry once again depends on the photoreceptor asymmetry to equal magnitude increments and decrements, as explained in detail in Sect. 3.1. We now turn to a description of the experiments that we designed to test this hypothesis.

2 Methods

We have recorded the response of X and Y ganglion cells from the cat optic tract. The stimulus consisted of a square-wave pattern presented at different locations (spatial phase) in the receptive field. At each spatial phase, the square-wave grating was contrast reversed for some of the trials, and it was turned on and off in other trials. To test for the presence of spatial asymmetries, we averaged the amplitude of the responses for all trials at a given spatial phase and looked at asymmetries in the overall response amplitude functions. As long as the response characteristics of ganglion cells are monotonically increasing functions of input contrast, the asymmetry should be similar to that obtained with a sensitivity measure of the type depicted in Fig. 3. In fact, we expect the asymmetry to be more pronounced as the photoreceptors are pushed further along their nonlinear operating range.

2.1 Preparation and recordings

Experimental procedures were similar to those described previously (Lankheet et al. 1990, 1993), and are only summarized here. All cells were recorded from two adult cats (4.0 and 3.8 kg in weight). Throughout the experiments the animals were kept under fairly deep Na-pentobarbital (Nembutal) anesthesia, and were paralyzed by gallamine triethiodide (Flaxedil). Atropine and phenylephrine hydrochloride were applied locally to dilate the pupils and to retract the nictitating membranes. Lidocaine 2% was infiltrated at all surgical sites and pressure points. Heart rate, blood pressure, rectal temperature, and end tidal CO_2 were continuously monitored and were regulated within physiological ranges. The contact lenses covering the eyes had an artificial, elliptical pupil of 1.5×6 mm. Action potentials of single optic tract fibers were recorded extracellularly with tungsten microelectrodes. The action potentials and trigger pulses of the light stimulus were stored on a digital tape recorder (Bio Logic, DTR1800). The pass band of the recording equipment was from d.c. to 12 kHz. Data analysis was performed off line using the IDL graphics package (Research Systems, Boulder, Colo.).

2.2 Stimulation parameters

The visual stimuli were produced on a cathode-ray-tube (CRT) monitor (Nec Multisync-plus) by means of a specially programmed, commercially available graphic system (HD 63484 advanced CRT controller, Megavision, Sang Computer systems). An Atari Mega ST was used to program and control the image generation. The display pattern, composed of 600×400 pixels, was presented at a frame rate of 100 Hz. In the present experiments we used only 'white light' stimuli which consisted of equal contributions of the red-, green-, and blue-color channels (each 6 bits). The display was viewed via a mirror and placed at a distance of 100 cm from the cat's eye, where it subtended 10×14 deg. of visual angle. The mean luminance level of the display was fixed at 125 cd/m^2. The monitor was linear around this mean luminance up to contrasts of 0.5. Only those stimulus parameters were chosen that caused the luminances to fall within the linear range of the monitor.

Two types of square-wave grating stimuli were used in the present study: contrast reversal grating and on-off grating (see Fig. 4). The spatial frequency ranged from 0.08 to 0.5 cycles/deg. and the temporal frequency was 1 Hz. The contrast of a grating is defined as $(L_{max} - L_{min})/(L_{max} + L_{min})$, where L_{max} is the peak luminance of the grating and L_{min} is the luminance at the trough of the grating. The contrast was either 0.5 or 0.25. In the absence of a test stimulus we presented a gray field with a mean luminance of 125 cd/m^2 (the same as the average of the grating).

3 Results and data analysis

We measured the responses of X and Y retinal ganglion cells by recording extracellularly from the optic tract during successive stimulation periods. A stimulation period consisted of 5 cycles of contrast reversals or on-off cycles.

Our initial goal was to measure sensitivity, as was originally done by Enroth-Cugell and Robson (1966). For this reason, we measured responses for various contrast levels. In addition, in order to avoid biases in the location of the receptive field center, we utilized square-wave gratings of varying spatial frequencies, and assumed that the spatial phase yielding the smallest response corresponded to the receptive field center. Each

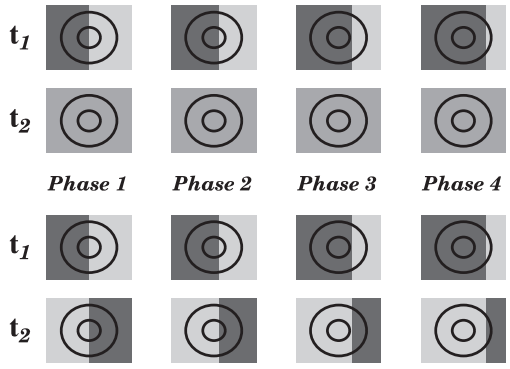

Fig. 4. Schematic illustration of the experimental paradigm, which uses a square-wave grating that is either turned on and off (*top*), or contrast-reversed (*bottom*). The grating is cycled five times for each condition, and at each of 20 equally distributed positions

cell was tested with at least two values of spatial frequency to ensure that a full range of spatial phases was incorporated in the data. However, in order to test all these variations in the limited amount of time available, we only repeated each stimulus condition five times. This led to a fairly low signal-to-noise ratio, which was not sufficient to extrapolate exact sensitivity values, so instead we measured the peak response amplitude for the largest contrast value. As discussed in the methods section above, this choice does not affect the basic conclusions drawn from the results.

In order to obtain a measure of response amplitude, cell responses in each stimulation period were divided into 4–20 bins (50–250 ms bin duration). The difference between the maximum and the minimum response to each stimulation period was calculated, and the mean and standard deviation of this difference were analyzed. The same procedure was repeated 20 times for each cell, by changing the spatial phase of the grating in 18-deg. phase shifts (relative to the grating). This produced a plot of the amplitude of response as a function of the spatial phase of the stimulus. Examples of typical recordings with the results of this analysis are shown in Fig. 5.

In order to determine the predicted presence or absence of spatial asymmetries in the response amplitudes, the maxima of the response amplitude functions for the left (0–180 deg.) and right (180–360 deg.) parts of the spatial phase shift were calculated. The difference, if any, between left and right maxima were tested under both types of stimulation (i.e., on-off and contrast-reversal). The statistical significance of these differences was calculated using a standard T-test. The result of the T-test on the difference between left and right peak under each condition is printed in the figures along with the data.

In evaluating the results, two things need to be considered: first, whether the difference in response amplitude between the left and right maxima for a given type of stimulation is statistically significant. If in fact there is a statistically significant difference, this would indicate the presence of an asymmetry. Second, whether the difference (i.e., the asymmetry) is more pronounced in the on-off case than in the contrast-reversal case, as predicted by our model.

We obtained stable recordings of sufficient duration from 16 cells, of which eight were classified as X-cells and eight as Y-cells, according to the criteria of Enroth-Cugell and Robson (1966). Results from representative cases are shown in Fig. 5. From these 16 cells, we found that:

1. **Eleven cells** showed a statistically significant ($p < 0.05$) spatial asymmetry for on-off stimulus. In seven of these no asymmetry was found in response to the contrast-reversed stimulus. In one of the 11 cells, for one spatial frequency (0.1) and one contrast (50%), the contrast-reversed stimulus shows asymmetry, where we recorded almost symmetrical response of on-off stimulus. For this cell, stimulation with two other, higher spatial frequencies (0.3, 0.5) with contrast of 25% and 50% always gave spatial asymmetry for on-off stimulus and a symmetrical response for contrast-reversed stimulation. In another cell of the 11, a change of grating contrast from 50% to 25% caused the contrast-reversed spatial asymmetry to change into on-off asymmetry. In the remaining two cells (one shown in Fig. 5, cell 941716) we observed the same contrast and spatial frequency asymmetry for both on-off and contrast-reversal gratings.

2. **Two cells** showed an asymmetry for the on-off stimulus without asymmetry for contrast-reversed gratings. However, the p values were 0.066 in one case and 0.078 in another case and thus were not statistically significant at the 5% confidence level.

3. **In three cells** (two X, one Y) we could not find any asymmetry in either of the conditions of this experiment.

Since only 3 out of 16 cells showed no signs of asymmetry, the results largely support the prediction advanced by Gaudiano (1994). The total number of cells is of course modest, but suffices as an existence proof of the predicted phenomenon. A more extensive study of a larger sample of cells for a wider range of parameters might thus be rewarding.

It is important to understand what aspects of the proposed model are responsible for the observed asymmetry. In fact, one of the key properties is an asymmetry resulting from a stage of adaptive gain control, which in the proposed model takes place within the photoreceptors, as we now describe.

3.1 Analysis of asymmetries from gain control

The fundamental reason for the predicted response asymmetry depends on the asymmetry in the response of individual photoreceptors to equal size input increments and decrements. To see this, we consider the simplest form of the photoreceptor equation utilized in the push-pull model (Gaudiano 1992b, 1994). It is assumed that the response of the photoreceptor is proportional to the input, multiplied by a gain term that fluctuates in response to input variations. Specifically, let $I(t)$ represent the fluctuating input. Then the photoreceptor response $r(t)$ is given by:

$$r(t) = I(t)g(t) \tag{1}$$

where the gain term $g(t)$ is given by an equation of the form:

$$\frac{\mathrm{d}g}{\mathrm{d}t} = \alpha(1 - g) - \gamma g I \tag{2}$$

The constants α and γ determine the rate at which the gain changes in response to input increments and decrements. Unlike a simple leaky-integrator equation, this equation assures that the gain term is always bounded between 0 and 1.

When a steady input I_0 is presented long enough for Eq. (2) to reach equilibrium, the net response will be

$$r = I_0 \frac{\alpha}{\alpha + \gamma I_0} \tag{3}$$

This equation, which is in the form of the classical Naka-Rushton equation (Naka and Rushton 1966), shows that the steady-state response of the photoreceptor is a saturating function of the input.

Consider now a situation in which the input is suddenly switched from a lower value I_0 to a higher value I_1. At the instant just after the input is switched ($t = 0^+$), the gain remains virtually unchanged, so that the instantaneous response is given by

$$r(t = 0^+) = I_1 \frac{\alpha}{\alpha + \gamma I_0} \tag{4}$$

After the gain Eq. (2) has equilibrated to the new input I_1, the steady-state response will be

$$r = I_1 \frac{\alpha}{\alpha + \gamma I_1} \tag{5}$$

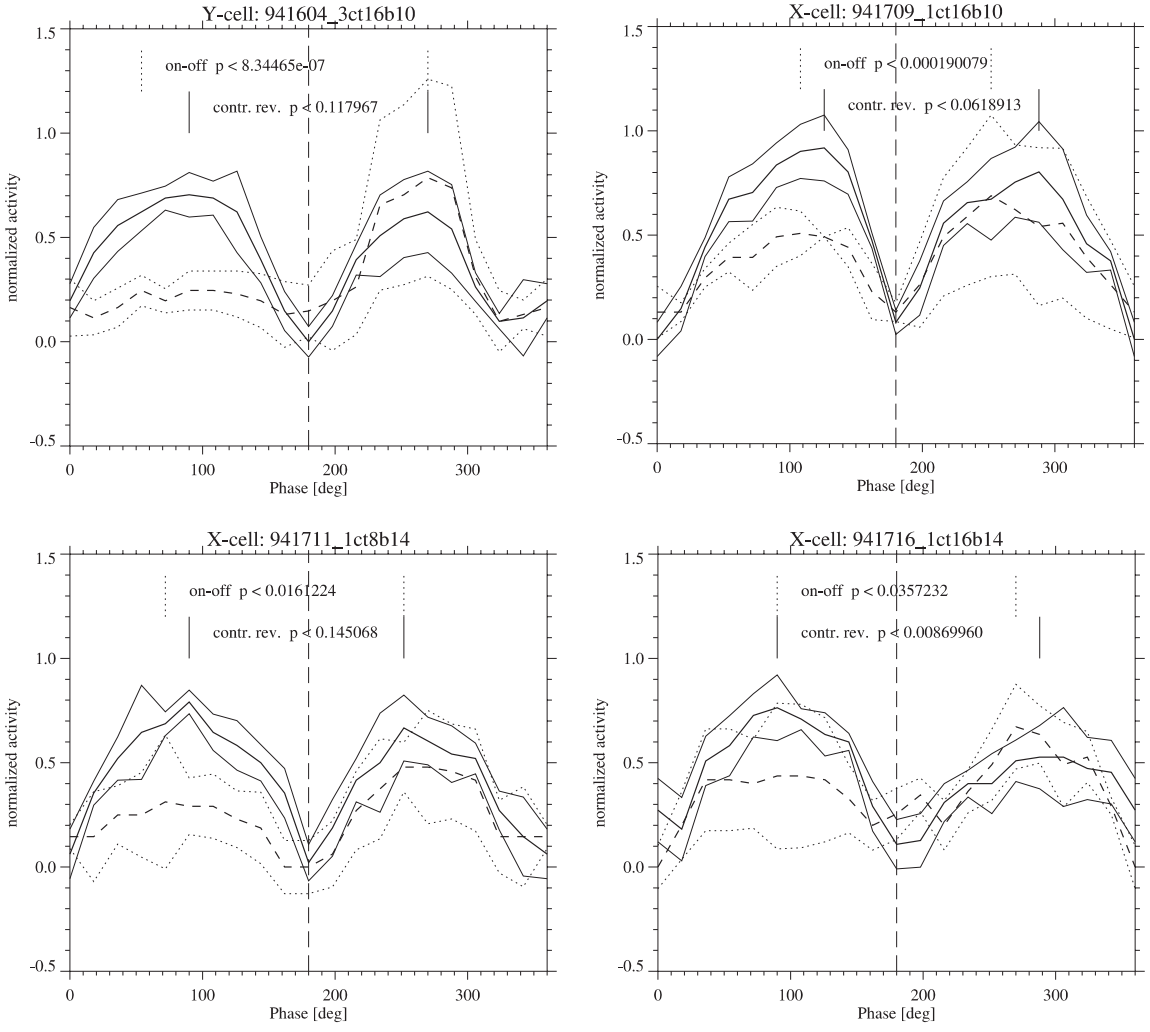

Fig. 5. Sample responses of recorded ganglion cells. The data were collected and organized as described in the text. *Solid lines* correspond to contrast-reversed stimulation; *dashed lines* correspond to on-off stimulation. Each plot includes the significance of the difference between the left and right peak under each condition. The hypothesis is that the difference between left and right peaks in the on-off condition should be statistically significant, while in the contrast-reversed condition it should not. Three cells (one Y and two X-cells) that satisfy this criterion (941604, 941709, and 941711) and one X-cell that does not (941716) are shown

By comparing Eqs. (4) and (5), one sees immediately that, as a result of the adapting gain control term appearing in the denominator, the photoreceptor's steady-state response is lower than the initial transient response. More formally, the time response of the photoreceptor to an input step from I_0 to I_1 can be found analytically to be:

$$r(t) = I_1 \frac{\alpha}{\alpha + \gamma I_0} e^{-t(\alpha+\gamma I_1)} + I_1 \frac{\alpha}{\alpha + \gamma I_1} \left[1 - e^{-t(\alpha+\gamma I_1)}\right] \quad (6)$$

Figure 6 shows the response of Eq. (6) to a step increment followed by a step decrement. Note that the change in response at the step increment is larger in magnitude than the change in response at the step decrement.

To formalize this observation, we can calculate the *incremental response* to any step input change by subtracting Eq. (3) from Eq. (4):

$$\Delta r = \alpha \frac{I_1 - I_0}{\alpha + \gamma I_0} \quad (7)$$

Regardless of whether the step change is from a higher input level to a lower one ($I_1 \rightarrow I_0$) or vice versa ($I_0 \rightarrow I_1$), the magnitude of the incremental response is proportional to the change in input *divided by a quantity proportional to the input level before the change took place*.

Consider now the experiment of Enroth-Cugell and Robson (1966) whose results are reproduced in Fig. 3a. Here the light-dark pattern is alternated with a uniform field. Because the intensity of the uniform field is equal to the average of the light and dark sides, the magnitude of the input increment from dark to intermediate is equal to the magnitude of the input decrement from bright to intermediate. However, the magnitude of the response of a photoreceptor going from dark to intermediate is *larger* than the magnitude of the response of a photoreceptor going from bright to intermediate because the photoreceptor that was in the dark has a higher gain than the photoreceptor that was in the light. This gain difference introduces an asymmetry about the receptive field center: having 2/3 of the photoreceptors going back-and-forth between light and intermediate (Fig. 7a) has a different effect than having 2/3 of the photoreceptors going back-and-forth between dark and intermediate (Fig. 7b).

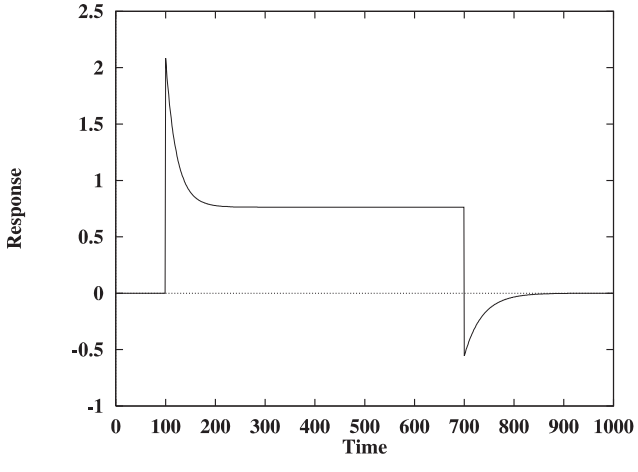

Fig. 6. Sample response of the simulated photoreceptor, as given by Eq. (6). Note that the transient response increment at light onset is larger than the transient response decrement at light offset. Both axes are in arbitrary units

Note that the asymmetry relative to the receptive field center disappears if the light-dark edge is reversed, rather than being replaced by the average-intensity field. This is because now, regardless of which side of the receptive field one considers, 2/3 of the photoreceptors are going from bright to dark during one reversal, and from dark to bright during the next reversal (this is the condition shown in Fig. 2). Hence even though the asymmetry in individual photoreceptor responses remains (as evidenced by the small on-off responses seen in X cells), the configuration is symmetrical about the receptive field center, so the sensitivity profile should likewise be symmetrical.

A similar argument will hold whether one is measuring the sensitivity or simply the response amplitude to these light-dark patterns. To measure sensitivity, Enroth-Cugell and Robson (1966) manipulated the contrast until no modulation could be heard in the cell's firing as the pattern was turned on and off. We have instead measured the amplitude of the responses at various contrast levels. In fact, our recordings show more pronounced asymmetries, undoubtedly because the photoreceptor responses become increasingly nonlinear as contrast is increased.

4 Discussion

The idea of push-pull connectivity has been around for over two decades, since Levine and Abramov (1975) proposed such a model and found evidence for it in goldfish. Later work suggested the possibility that push-pull connectivity may also be found in the cat retina (McGuire et al. 1982, 1984). However, the validity of the push-pull hypothesis has been questioned because of the small amount of data on which it was based (Nelson and Kolb 1983), and because of accumulating anatomical evidence for the clear segregation of dendritic arbors of ON and OFF ganglion cells into separate sublaminae of the inner plexiform layer (Famiglietti and Kolb 1976; Nelson et al. 1978). The push-pull model proposed by Gaudiano (1992a, 1992b) differed from previous models in two main ways: (1) it suggested the need for a (nonlinear) dynamic gain control mechanism within the photoreceptors, and (2) it proposed that the convergent ON and OFF inputs activate different ionic channels in the ganglion cells. The latter hypothesis was recently tested by Freed and Nelson (1994). Their results support the hypothesis that ganglion cell inputs modulate at least two conductances, selective to two ionic species having positive and negative reversal potentials, respectively. However, the mathematical formulation of Gaudiano's push-pull model specifies identical strength of the ON

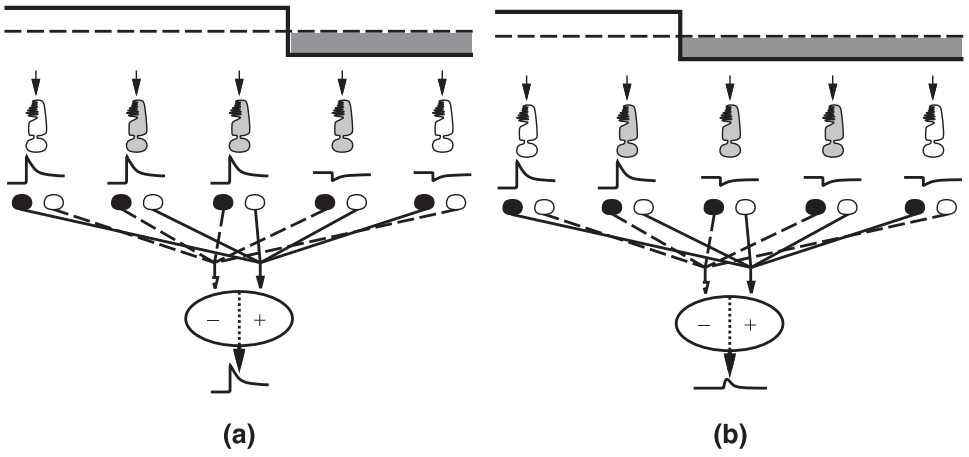

Fig. 7. Diagram of the experimental design when a light-dark edge is switched on and off, with either 2/3 of the receptive field falling under the light side of the pattern **(a)**, or 2/3 of the receptive field falling under the dark side of the pattern **(b)**

and OFF inputs, which means that the net conductance change to any input should be zero. This was not found to be true by Freed and Nelson (1994).

As discussed at length in a previous publication (Gaudiano 1994), the mathematical formulation of the push-pull model was necessarily simplified in order to make the model analytically tractable. This includes not only the perfect balance between ON and OFF inputs, but also the (erroneous) assumption that each bipolar cell only receives input from a single photoreceptor. The model should still make correct predictions, and in fact should even improve some of its fits to the empirical data, if these simplifying assumptions were relaxed. For instance, the bipolar cells should include center-surround receptive fields (presumably generated by horizontal cells), they should have different dynamics, and the strength of their influence upon ganglion cells should not be perfectly symmetrical. Furthermore, given the strong evidence for segregation of ON and OFF ganglion cell dendritic arbors (Famiglietti and Kolb 1976; Nelson et al. 1978), it may be necessary to identify alternative means of effecting a push-pull mechanism, perhaps through amacrine cells (Gaudiano 1994).

It is obvious that the push-pull model as formulated by Gaudiano (1994) needs several refinements, as we have in fact begun to do (Przybyszewski et al. 1995). Nonetheless, certain fundamental aspects of the push-pull model, namely, the necessity for strong photoreceptor nonlinearities and the need for antagonistic, push-pull inputs, seem valid from a functional standpoint, regardless of specific implementation details. For instance, there is no other model of which we are aware that can reconcile the apparent linear spatial summation of X cells with the well-known nonlinearities of photoreceptors and other retinal cell classes. Furthermore, there is no model that can explain why a change in spatial, rather than temporal, frequency of a stimulus can suddenly enhance the X cell's nonlinearity of spatial summation. To classify these and other phenomena as 'higher-order effects' and to whisk them away by invoking small-range linearity is a fallacy that can hinder further understanding of basic aspects of visual processing.

5 Conclusions

The results presented above provide some support for the experimental prediction. Only one cell under one stimulus configuration seemed to go against the hypothesis. These results help to strengthen the claim that a significant amount of nonlinearity takes place in early retinal processing, beginning with the photoreceptors. From a functional point of view, this seems to be an unavoidable conclusion, because the compression of 8–10 log units down to 2 log units must take place at the very first processing stage, namely, the photoreceptors. However, the approximate linear spatial summation of X cells has justified resistance to this idea for the past three decades. The push-pull model suggests a way in which the visual system can take advantage of the power of nonlinear mechanisms, such as adaptation, and yet maintain some of the desirable properties of linear systems.

We would like to suggest that a similar scheme may be at work in later parts of the visual system. For instance, null responses have been observed in cortical simple cells, even though the output of both X and Y ganglion cells is known to exhibit intensive nonlinearities (Victor 1987, 1988). One way to explain this finding is to postulate a push-pull convergence of ON and OFF ganglion cells (through the lateral geniculate nucleus) onto cortical simple cells. In fact, push-pull mechanisms have been previously suggested to explain certain aspects of the response of cortical cells (Emerson et al. 1989, 1992).

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