

THE DYNAMICS OF PRIMATE RETINAL GANGLION CELLS

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Abstract

A knowledge of the dynamics (temporal properties) of neuronal populations is essential for an understanding of their function, and is also crucial when one attempts to develop computational or mathematical models of the neurons. Here we review the temporal properties of the receptive fields (RFs) of the two best-studied types of ganglion cells in the primate retina, those that project to the parvocellular (P) and magnocellular (M) layers of the dorsal lateral geniculate nucleus.

The center and surround mechanisms of the P RFs are approximately linear, and their impulse responses are very similar, although the surround lags the center by a few milliseconds. The center and surround are chromatically opponent. With the appropriate stimulus one can find significant nonlinearities in their responses, and also in the interaction between the center and surround. The phase lag between the responses of the center and surround depends on the temporal frequency, so that at high temporal frequency the antagonism between them is reduced or abolished. The temporal responses of M cells are nonlinear, and with increasing contrast they show the effects of a contrast gain control.


The different dynamical properties of the two populations suggest that M cells participate in motion analysis, while P cells are used for the analysis of form, texture, and perhaps color.

Introduction

In this section we shall review briefly the properties and anatomical organization of the neuronal populations that we shall consider, and provide the motivation for a discussion of the dynamical aspects of their function.

Parallel pathways from retina to cortex

The vertebrate retina is a complex structure, with well over 100 million neural elements, which include approximately 80 different cell types (Dacey, 2000), arranged in



5 major layers. The retina converts the visual image that impinges on its photoreceptors into a spatio-temporal pattern of neural signals, and after significant processing, which lasts for an astonishing 15-35 msec. (see, for example, Maunsell *et al.*, 1999), the results are delivered to the rest of the brain via axons of the retinal ganglion cells (RGCs), which together make up the optic nerve. In the primate, each optic nerve contains approximately one million axons, 90% of which project to the lateral geniculate nucleus (LGN).

It is now well established that – at least in the primate retina – the ganglion cells include several classes, with distinct anatomical and physiological properties (for a review, see Rodieck, 1988; Kaplan *et al.*, 1990). The two best-studied classes of RGCs are the M and P cell classes, which project, respectively, to the magnocellular and parvocellular layers of the LGN. They correspond to the anatomically identified parasol and midget retinal ganglion cells, described by Polyak (1941). These two cell types are sometimes referred to as P_{α} and P_{β} (Perry and Cowey, 1981): the P is for Primate, and the α and β subscripts are a reference to the α and β ganglion cell types of the cat retina (Boycott and Wässle, 1974). In the LGN, a third type, usually referred to as K (koniocellular), has been added more recently. It represents the intercalated cells, which account for approximately 9% of the cells in the LGN (Hendry and Yoshioka, 1994; Casagrande, 1994). The identity of the retinal cells that project to it is still under active investigation, and they will not be discussed here.

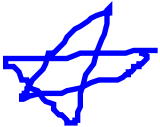
The first report of a functional difference between the M and the P neuronal types focused on their *dynamical (and chromatic)* properties: Gouras (1968) reported that some primate ganglion cells were *phasic* (and chromatically broad-band), while others were *tonic* (and chromatically antagonistic) in their responses to steps of light increments. These have later become known as M (transient) and P (sustained) cells. These two types were later shown to differ in their size and projection patterns: the tonic cells project to the upper 4 layers of the monkey LGN, which contain small cells (parvocellular), while the phasic cells project to the lower two layers, those that contain large cells (magnocellular) (Perry *et al.*, 1984).

The three neural streams (M, P and K) project from the LGN to distinct layers and compartments of the primary visual cortex. The magnocellular axons terminate in layers $4C_{\alpha}$ and $4B$, while the parvocellular axons project to $4C_{\beta}$. The axons of the K group project to layers 2-3 and terminate in the cytochrome oxidase blobs (Carroll and Wong-Riley, 1984; Livingstone and Hubel, 1984; Hendry and Yoshioka, 1994; Casagrande, 1994). There is some evidence that the segregation persists beyond V1 as well (Wong-Riley and Carroll, 1984), although functionally there is evidence for mixing of the signals that are conveyed by the M and P streams (Merigan and Maunsell, 1993). Our knowledge of the third group is much more limited at the present.

In addition to the difference in their temporal response patterns, the M and P streams have been shown to differ in several other important ways (for a review, see Kaplan *et al.*, 1990). The M cells (and their magnocellular LGN targets) have larger receptive fields and cell bodies, have higher sensitivity to luminance contrast (Kaplan and Shapley, 1986), and, as noted earlier, show little or no chromatic antagonism (but see Derrington *et al.*, 1984 and Smith *et al.*, 1992). The P cells (and their parvocellular LGN targets) have smaller receptive fields and somas, their luminance contrast sensitivity is lower, and

most of them show clear chromatic opponency (Wiesel and Hubel, 1966; De Monasterio and Gouras, 1975; Derrington *et al.*, 1984). It is this constellation of different properties, together with the distinct projection patterns of the two streams, that has led to the notion that the two are engaged in parallel processing of different aspects of the visual scene (Livingstone and Hubel, 1988; Zeki and Shipp, 1988).

Why neuronal dynamics is worth studying



We use the term *dynamics* to describe processes that evolve in time. Much of what is interesting about the *function* of various systems in the body, including the nervous system, is dynamical. The dynamical properties of a neuron (such as the time course of its response, the latency, the temporal spectrum of its sensitivity or of its response) serve at least two important functions: 1) they suggest a possible function for the neuron or neuronal stream, and 2) they inform us about the possible cellular (or network) mechanisms that are involved in shaping the dynamical properties. For example, the short latency and transient response of the Y ganglion cells in the cat retina suggest that they might be involved in temporal analysis or in an alerting response, while the more sustained response of X cells makes them more suitable for the (spatial) analysis of form. In addition, dynamical analysis of the responses of Y ganglion cells from the cat retina has suggested the existence of rectifying “non linear subunits” that are responsible for some of the features of the responses from these cells (Enroth-Cugell and Robson, 1966; Hochstein and Shapley, 1976a,b). Such insights are useful in directing further exploration of the anatomical circuitry and biophysical properties of neurons.

The rich anatomical diversity of retinal ganglion cells is bewildering (see, for example, Watanabe and Rodieck, 1989; Rodieck and Watanabe 1993; Dacey, 1999a, 2000). One possible reason for it is that each of the various cell types carves out a temporal niche for itself, and together they cover the entire dynamical spectrum that the animal requires. For example, cells that report diurnal changes in light level do not need a high temporal resolution, but cells that track possible predators do. In addition, it is possible that some of the morphological diversity has to do with chromatic selectivity, or some other kind of selectivity. After all, the number of aspects of the visual environment that the visual system must analyze is unknown, but it is probably not small.

Knowledge of the dynamical properties of the neuronal streams that we consider is useful in another context. Quantitative modeling of (any part of) the visual system requires a reasonably detailed understanding of their temporal capabilities. In addition, such knowledge can be used in the interpretation of experimental data. For instance, when one examines recordings that reflect the responses of many cells, such as the electroretinogram (ERG), electroencephalogram (EEG), or data obtained with various imaging methods (magnetoencephalogram, MEG, or functional magnetic resonance imaging, fMRI), one might be able to discern in the records the typical dynamical signature of one cell type or another (for example, Valberg and Rudvin, 1997; Baseler and Sutter, 1997; Klistorner *et al.*, 1997; Rudvin *et al.*, 2000).

Finally, certain aspects of the dynamics have some theoretical importance. For example, some hypotheses about the function of some of the types of primate ganglion cells hold only if they are linear (for example, Ingling and Martinez-Uriegas, 1983). It is

important, therefore, to study the neuronal dynamics with the appropriate experimental and analytical tools in order to establish the limits of linearity.

In the following sections we shall review the dynamics of the major classes of retinal ganglion cells in the primate retina. In each sub-section we shall consider first linear responses, followed by a discussion of the non-linear behavior.

Dynamics of the magnocellular pathway

Linear responses

The M class of primate RGCs projects to the two most ventral layers of the LGN (Perry and Cowey, 1981). A number of investigators have recognized the unique properties of this type of RGC. In particular, four aspects were emphasized: the transient response to flashes, the larger size of the receptive field, the lack of clear chromatic opponency and the relatively high sensitivity to luminance contrast (Gouras, 1968; Kaplan and Shapley, 1986; Kaplan *et al.*, 1990; Croner and Kaplan, 1995).

Early experiments indicated that the temporal frequency responses of both ON and OFF M cells depended on stimulus contrast (Benardete *et al.*, 1992; Lee *et al.*, 1994). For a typical M cell, as contrast increased from 1% to 12%, the peak of the temporal frequency response shifted from 8 to 16 Hz. To see the effect more clearly, we calculate the contrast gain, which is the response divided by the stimulus contrast, a quantity that has units of impulses/sec-% contrast. As contrast increases, the contrast gain at low temporal frequencies decreases (Figure 2). In addition, the phase of the sinusoidal response advances (Figure 1). If the frequency response of an M cell is transformed into the time domain, it is evident that with increased contrast the response of an M cell to a pulse of unit contrast becomes smaller and less delayed (Figure 3).

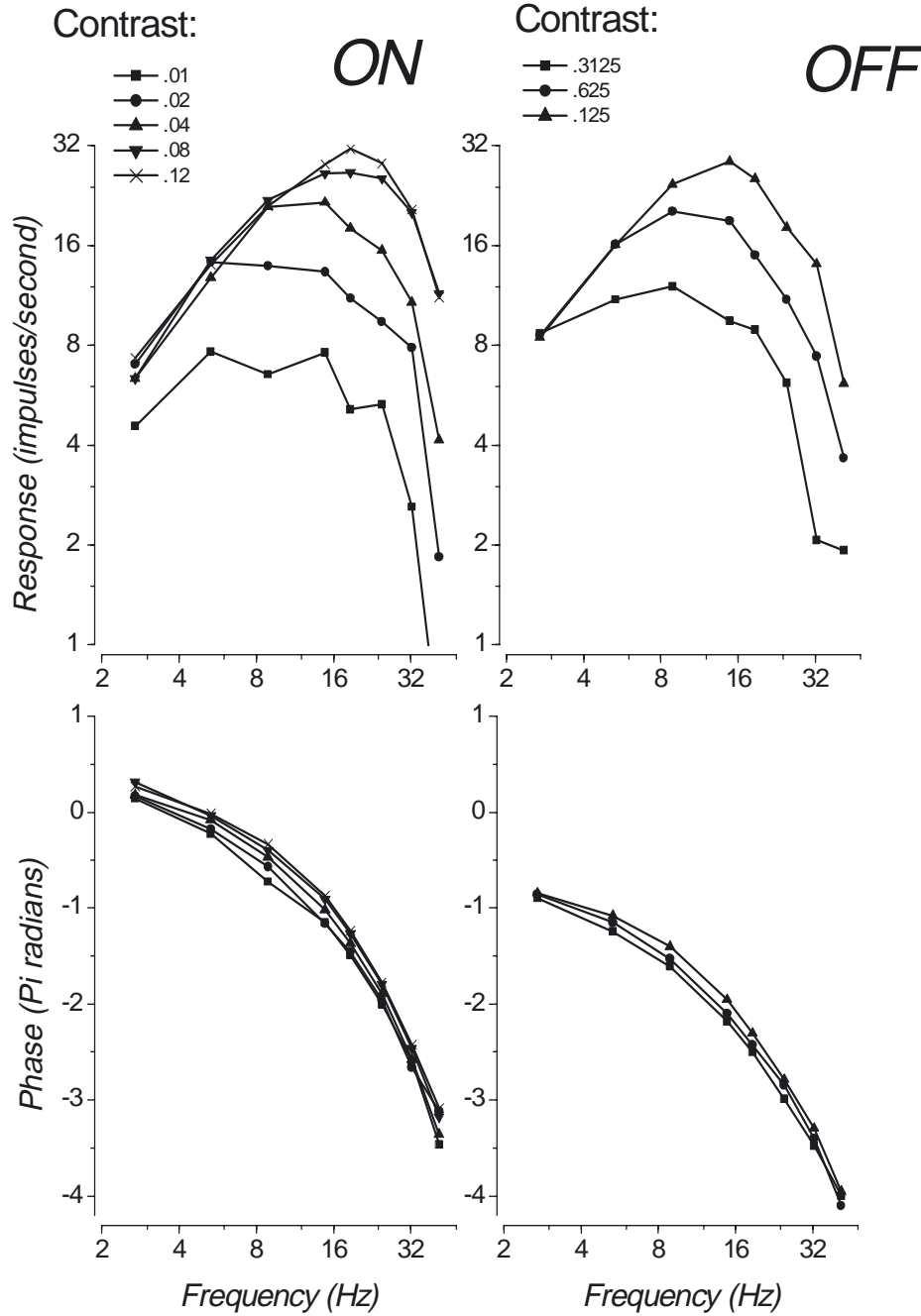
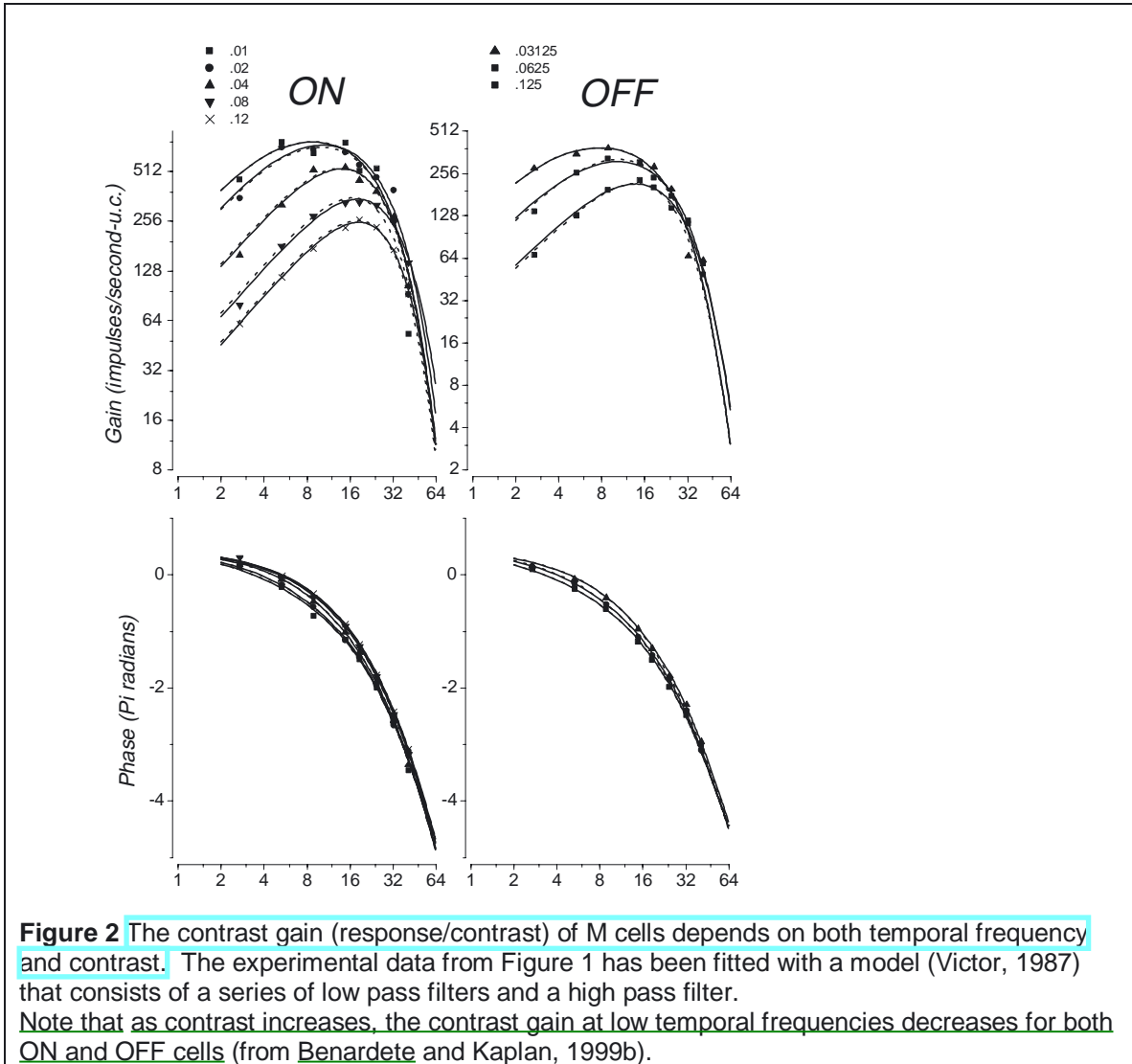


Figure 1 The temporal frequency response of two representative M cells: an ON cell (left) and an OFF cell (right) at several contrasts. The upper row shows the amplitude of the response and the bottom row shows the phase. The contrasts used in each case are listed in the upper left of each column. The stimulus was an achromatic grating modulated by a sum-of-sinusoids. Note that amplitude of the response increases more at high temporal frequency as contrast increases; the phase of the response also advances (From Benardete and Kaplan, 1999b).

Benardete and Kaplan (1999b) wished to characterize in more detail the temporal

properties of M cells, and used a temporally broadband stimulus, composed of a sum of several frequencies. They found that at low luminance contrast (< 2%), M cells have a temporal frequency response that peaks at approximately 10 Hz, similar to what was found for P cells (Benardete and Kaplan, 1997a; Figure 1). However, even at low contrast, the response of M cells shows less phase lag than that of P cells, indicating that it peaks earlier than the response of P cells.



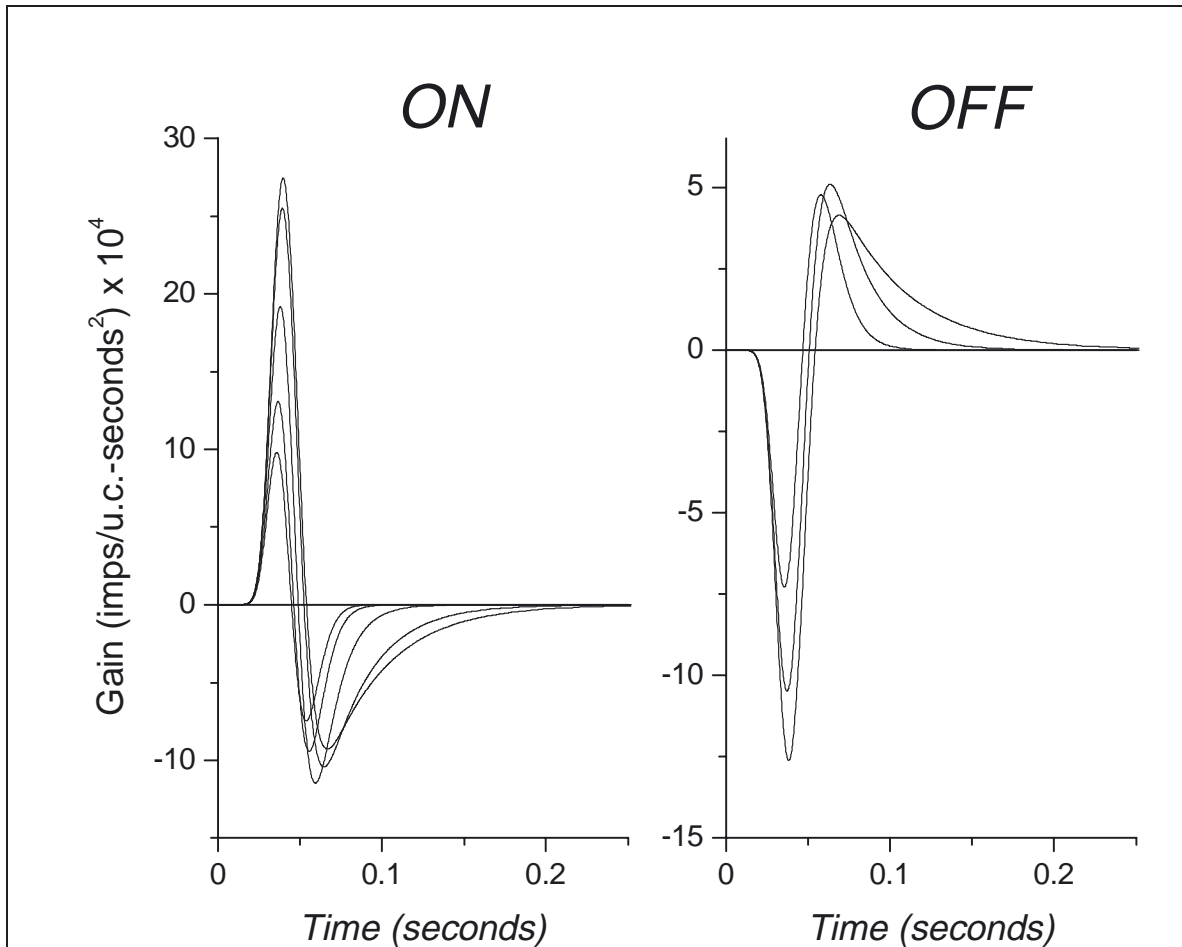


Figure 3 The impulse response of M cells changes with increasing contrast. Data from two typical cells are illustrated: ON cell (*left*) and OFF cell (*right*). The impulse responses were calculated as the inverse Fourier transforms of the data shown in Figure 2. Note that as contrast increases, the size of the impulse response decreases and the peak of the impulse response becomes less delayed (from Benardete and Kaplan, 1999b).

In the cat retina, it was observed previously that both X and Y RGCs show a selective attenuation of contrast gain at low temporal frequency and phase advance with increasing contrast. Shapley and Victor (1978, 1979) termed the nonlinear mechanism that regulates this change in gain “the contrast gain control.” While the same phenomenon is observed in M cells, it is not observed in P cells, suggesting a possible homology between the M cell population and some of the RGCs of lower mammals (Benardete *et al.*, 1992).

Teleologically, the contrast gain control mechanism allows the M cell to function as a selective filter. As contrast in the visual scene (and with it, the signal-to-noise ratio) increases, the low temporal frequencies that dominate the visual environment can be relatively attenuated, to allow the finer temporal detail (the higher frequencies) to stand out. A similar theory has been used to explain the spatial selectivity of RGCs (Atick and

Redlich, 1992). Experimentally, this has been demonstrated by observing that the response of M cells to steps of contrast becomes more transient as contrast in the step increases (Benardete and Kaplan, 1999b).

Nonlinear responses

Because of the contrast gain control mechanism, the temporal frequency responses of M cells are nonlinear, except at very low contrast ($< 1\%$). In other words, the response does not scale linearly with contrast. As in the cat (Shapley and Victor, 1979), most of the contrast signal that controls the contrast gain originates in the surround of the M cell receptive field, and is spatial-phase insensitive (Benardete and Kaplan, 1999b).

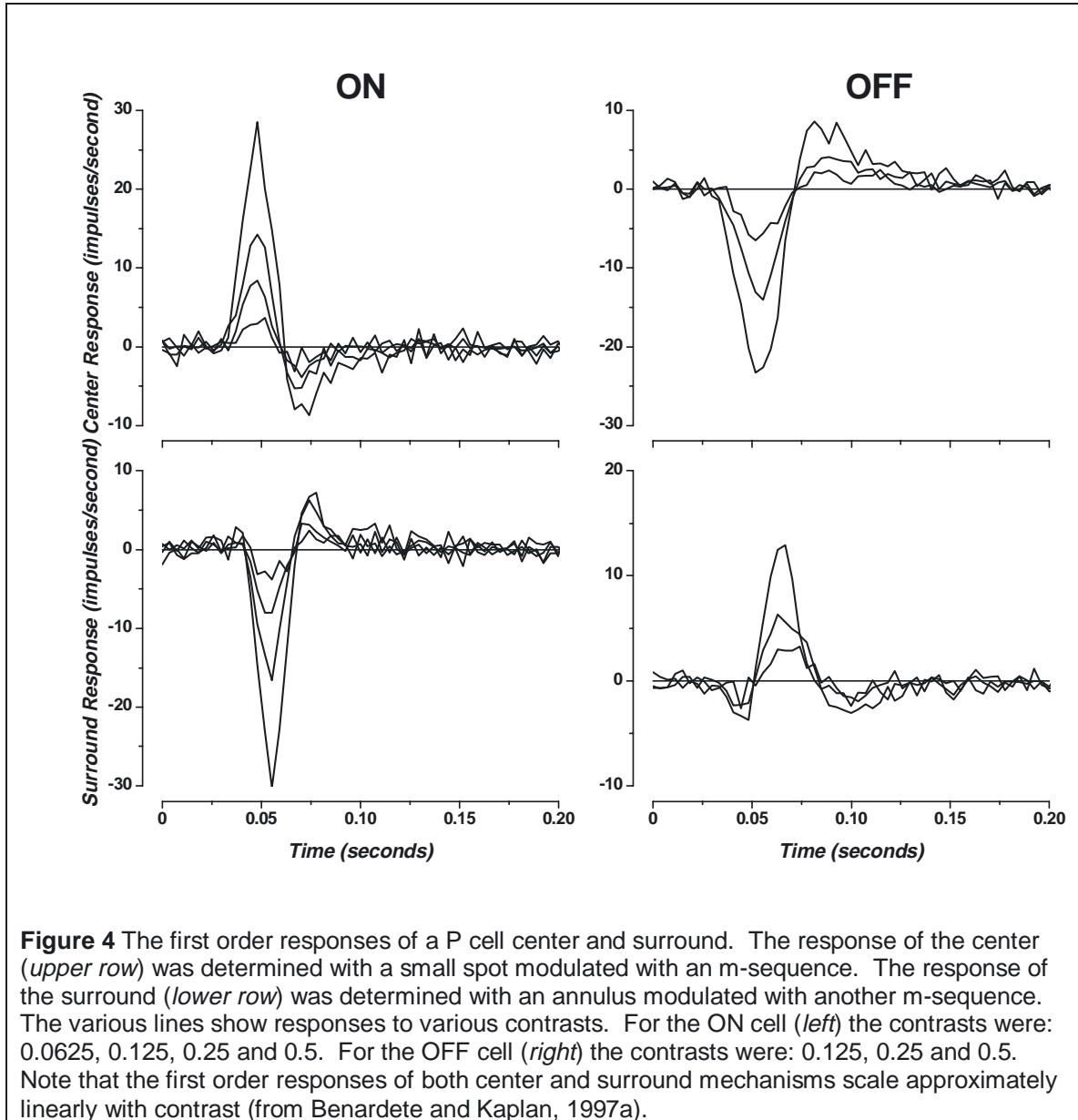
Another manifestation of the nonlinearity of M cells is the X/Y classification adapted from the experiments of Enroth-Cugell and Robson (1966) and of Hochstein and Shapley (1976b) on the cat retina. Kaplan and Shapley (1982) have reported that a minority of M cells in the primate retina are Y-type when classified according to the linearity of spatial summation within their receptive fields, as Enroth-Cugell and Robson did originally for cat RGCs. These cells have spatial-phase insensitive responses that are mostly at *twice* the frequency of the stimulus. This nonlinearity was thoroughly investigated in cat Y RGCs by Shapley and Victor (1979), and there it was found to depend on input from a collection of small, nonlinear receptive field subunits. However, the Y-type M RGCs seem to be much less numerous than the X-type (Kaplan and Shapley, 1982; Derrington *et al.*, 1984; Benardete and Kaplan, 1999b). Although both types of M cells demonstrate the contrast gain control mechanism, only M cells of the Y-type show strong frequency doubled responses. Lee *et al.* (1989b) have shown that, as was found in the cat, the M cells' frequency doubled response reflects the activity of a spatially extended mechanism, since small spots centered on the middle of the receptive field failed to elicit such responses.

Dynamics of the parvocellular pathway

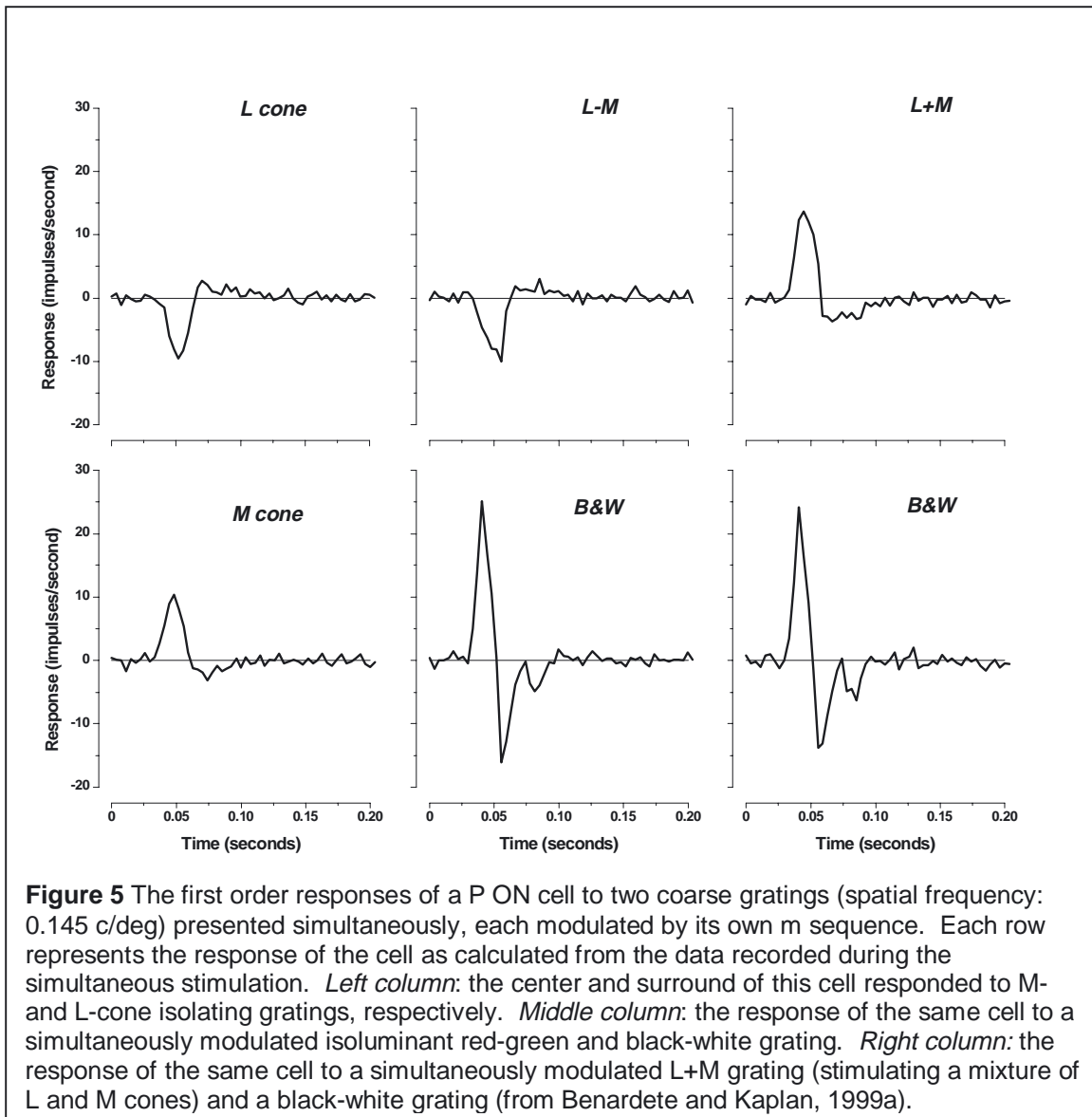
Linear responses

P cells make up the majority of the RGCs in the primate retina. The temporal responses of these cells have been usually characterized as being predominately linear (for example, Smith *et al.*, 1992). In general, however, these studies employed stimuli of low contrast. In order to verify and expand upon these results, Benardete and Kaplan used sinusoidal gratings as well as spots and annuli modulated by a pseudorandom sequence ("m-sequences", Sutter, 1987) of contrast pulses to determine the temporal response of P cells to chromatic and achromatic modulations over a wide range of contrasts (Benardete and Kaplan, 1997a, 1997b). The center and surround of the receptive field of P cells were stimulated with spots and annuli respectively. The responses of both center and surround regions were found to scale linearly with contrast (Figure 4). The center response peaks around 40-50 msec. when measured in the LGN as a synaptic (S) potential, a measurement that includes the conduction time from the retina to the LGN and the synaptic delay within the LGN (see Kaplan and Shapley, 1984). The surround response, measured with a large annulus, is delayed, on average, an additional

5-10 msec. This value is similar to the 3-8 msec. delay reported by Smith *et al.*, (1992). The response of the P cell to a large spot is predicted reasonably well by the linear addition of the center and surround responses. The linear prediction failed only at high luminance contrast and with low spatial frequency stimulation.



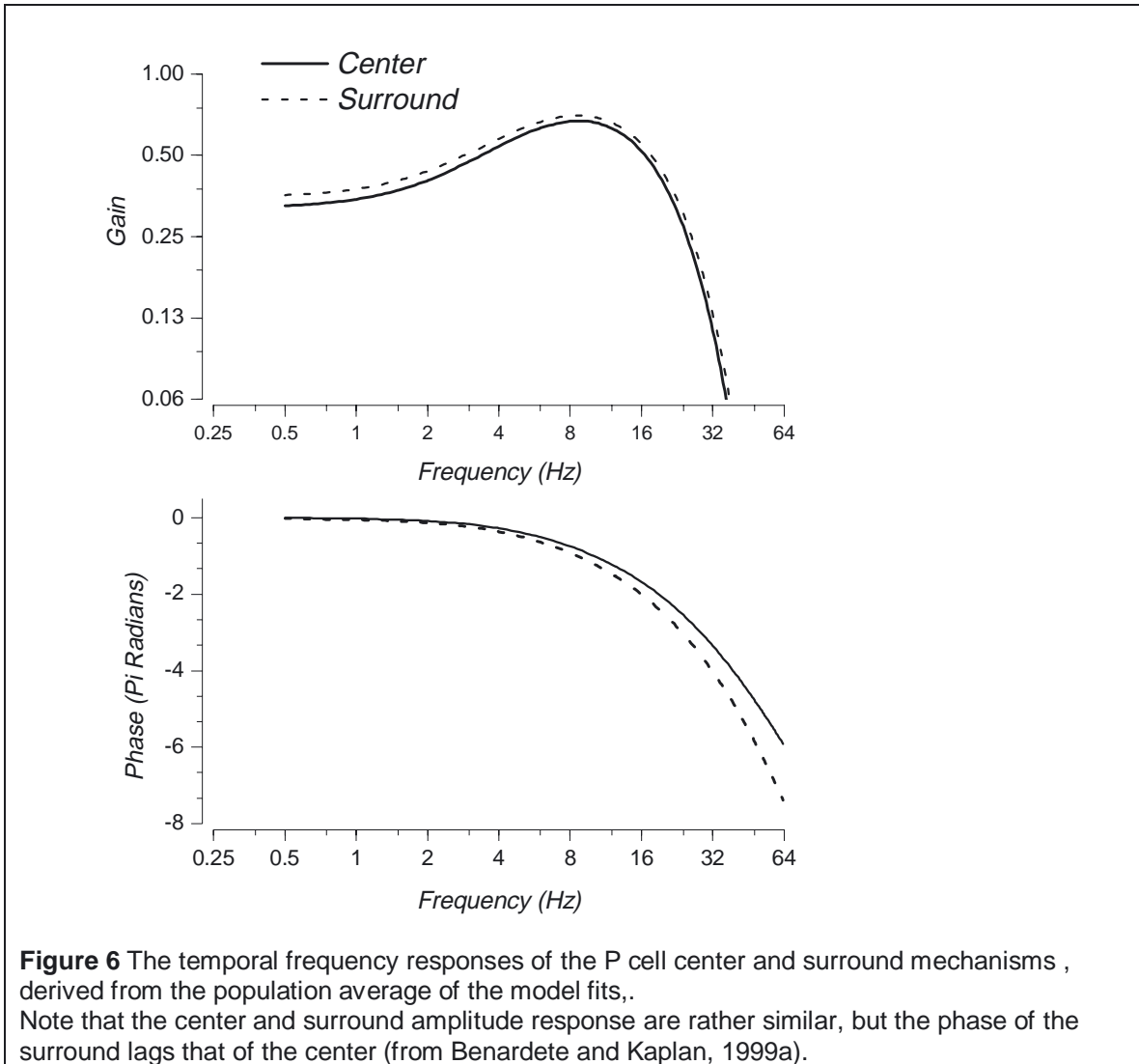
To investigate further the dynamics of the cone input to the center and surround mechanisms of the receptive field, Benardete and Kaplan employed an extension of the m sequence technique (Benardete and Victor, 1994). They modulated *simultaneously* but *independently* two chromatic sinusoidal gratings in the receptive field of an individual P cell. The chromaticity of each grating was adjusted to stimulate only a *single* cone class



(so-called “cone-isolating gratings”, see Estevez and Spekreijse, 1982). The results confirmed what has been observed in the previous experiments that used spots and annuli: the center and surround of the P cell receptive field are chromatically opponent, with each mechanism dominated by a single cone class, e.g. M (middle wavelength) or L (long wavelength) cones in the center and L (or M) cones in the surround (Figure 5). This similarity of the temporal behavior of the center and the surround of P cells is consistent with earlier results obtained by Gielen *et al.*, (1982), who used white noise stimulation to measure the temporal properties of monkey LGN cells, and with the results of Smith *et al.*, 1992.

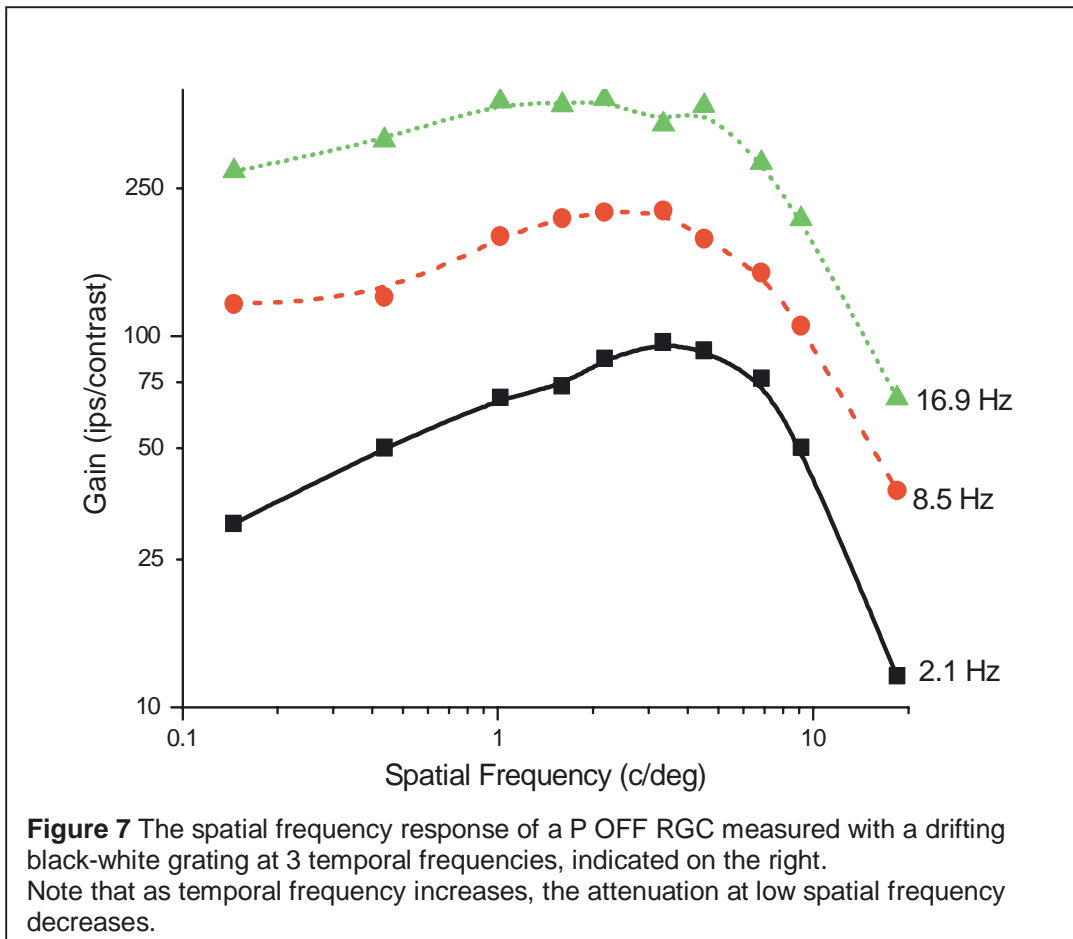
The chromatic opponency of P cells and their parvocellular LGN targets is well known (Wiesel and Hubel, 1966; De Monasterio and Gouras, 1975; Derrington *et al.*, 1984). Furthermore, the center and surround again behaved linearly with increasing cone contrast, and their responses summed in a linear way. The peak of the center response

occurs at approximately 40-50 msec., similar to the results obtained with small spots. The surround response is delayed by an additional 3-5 msec. under conditions of chromatic isolation (Figure 5). The optimal temporal frequency for both the center and surround responses is approximately 8 Hz. The phase of the surround response typically lags that of the center response (Figure 6). Once again, the overall linearity of the P cell response seems to be violated only at high luminance contrasts and low spatial frequencies.



Spatio-temporal coupling and center-surround phase lag

When the response of a system (in our case, a receptive field of a RGC) can be described as the product of two functions, one dependent on space and the other dependent on time, the system is said to be *spatio-temporally separable*. In that case, the spatial properties of the receptive field do not depend on the temporal frequency at which they are measured, and the temporal properties are independent of the spatial parameters of the stimulus used to measure them. RGCs in the primate retina, however, are not spatio-temporally separable, as is shown in a typical example from a P OFF cell in Figure



7. Similar results for the cat RGCs were reported by Dawis *et al.*, (1984) and by Frishman *et al.*, (1987). As Figure 7 shows, at high temporal frequency the receptive field becomes less selective for size: the attenuation at low spatial frequencies is reduced, compared to what is seen at low temporal frequencies. This reduction in spatial antagonism could, in principle, be due to the surround being slower than the center, or to a change in the phase relationships between the center and surround as temporal frequency increases. Figure 6 shows that the high frequency cutoff of the surround mechanism is similar to that of the center, and that the phase difference between the responses of these two mechanisms *increases* as temporal frequency increases. This results in the loss of spatial antagonism that is depicted in Figure 7

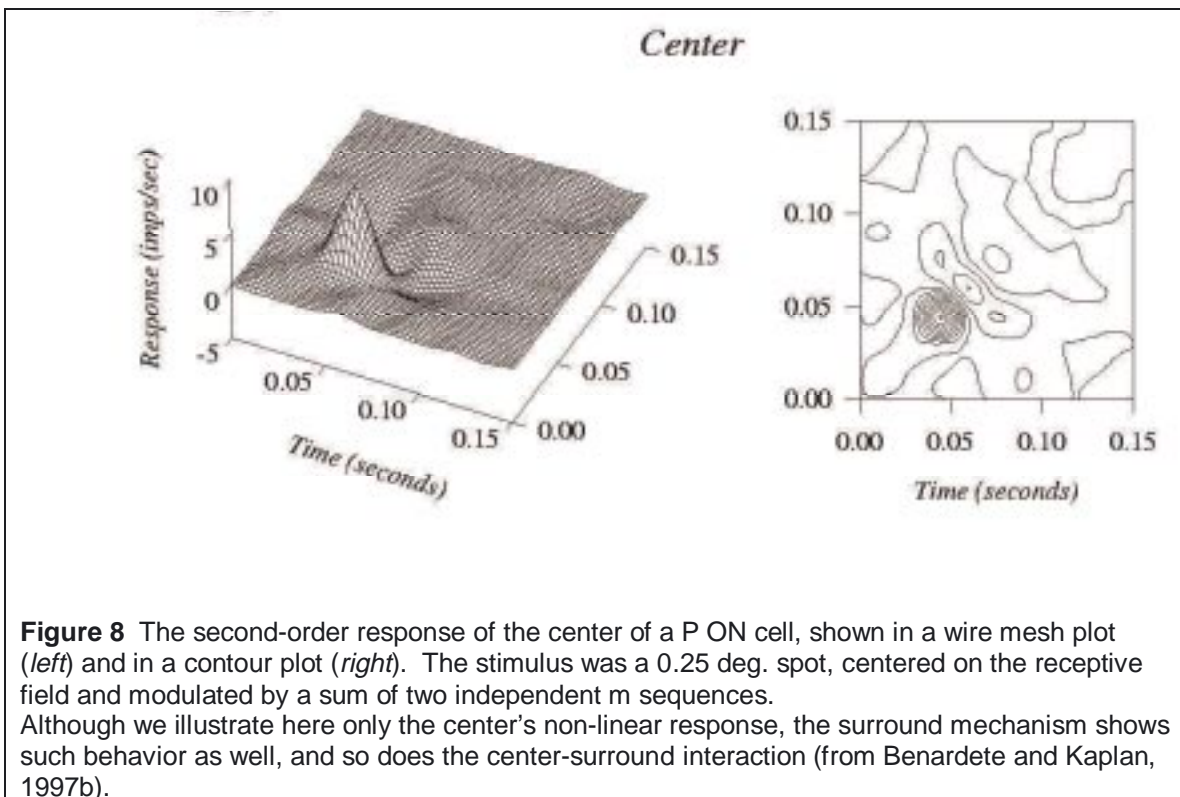
The dependence of the center-surround phase lag on temporal frequency also abolishes the chromatic antagonism that is observed in parvocellular neurons (Wiesel and Hubel, 1966; De Monasterio and Gouras, 1975; Gouras and Zrenner, 1979; Benardete *et al.*, 1992; Smith *et al.*, 1992). A similar loss of spatial antagonism at higher temporal frequencies had been reported for the celebrated lateral eye of the horseshoe crab, *Limulus* (Ratliff *et al.*, 1969, 1970) and in the receptive fields of cells in the cat LGN (Kaplan *et al.*, 1979).

The results just cited tell us that the classical view of the center and surround receptive fields as mutually *antagonistic* mechanisms (Kuffler, 1953) holds *only* at those (low) temporal frequencies where the phases of the responses elicited from them are

approximately opposite. At other frequencies, the center and surrounds responses add constructively, and their summed response is *larger* than the response of either the center or the surround mechanism alone.

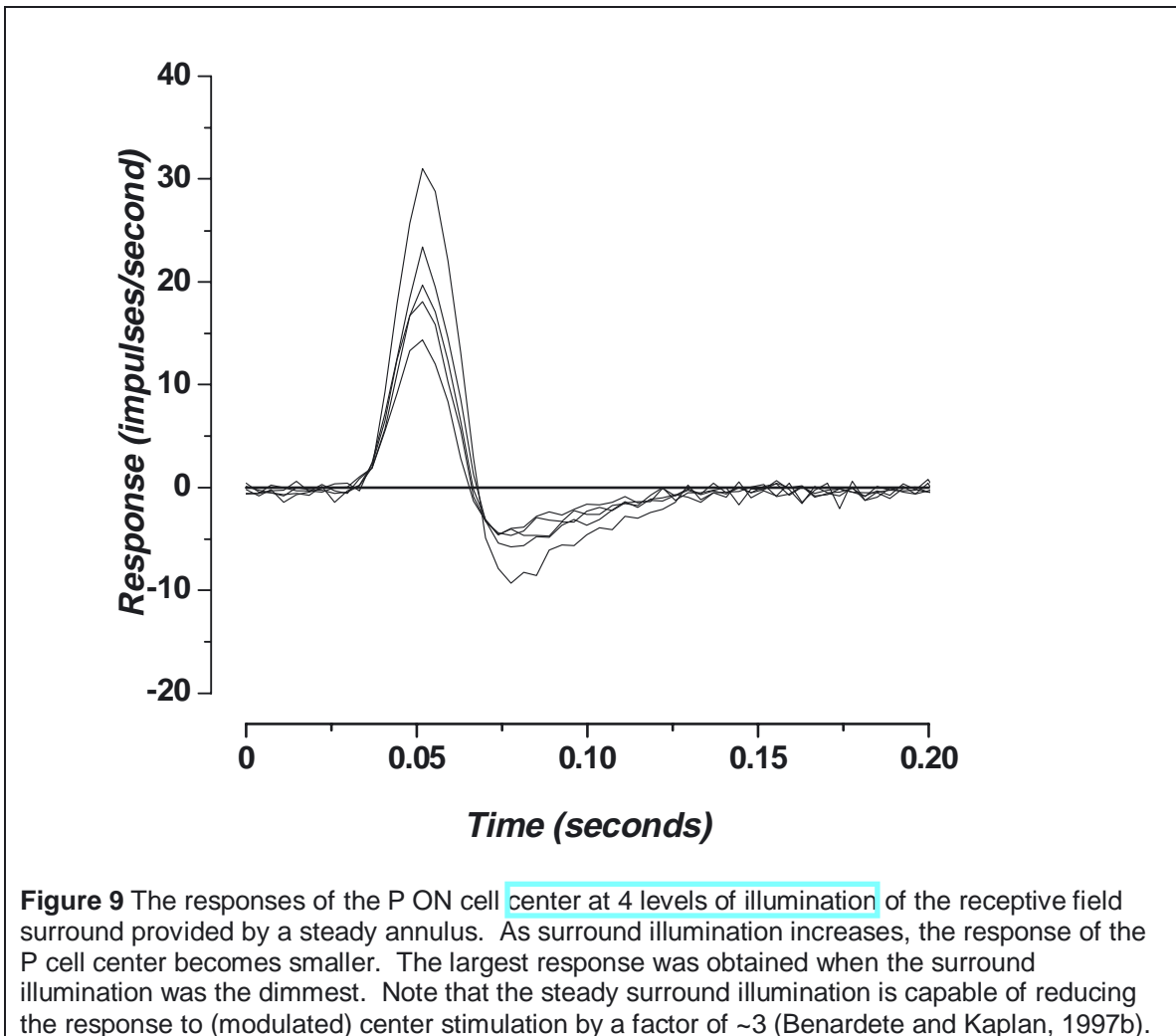
Nonlinear responses

When one is investigating the linearity of a system, it is best to use specialized methods that are appropriate for the task. For that reason, and to further investigate the nonlinearity of P cells at high luminance contrast, Benardete and Kaplan (1997b) used the extended m sequence method again to modulate simultaneously a spot and an annulus in the receptive field of a P cell. Significant second-order responses were detected in both ON and OFF P cells, and these responses originated from the center, from the surround, and also from the interaction of the two. The nonlinear response of the center mechanism is illustrated in Figure 8. These second-order responses were consistent with a nonlinear mechanism acting in the P cell pathway. This mechanism can be mathematically modeled by a Linear-Nonlinear-Linear (*LNL*) filter “sandwich”, suggesting that this second-order response does not represent a trivial nonlinearity like saturation or spike truncation.



A clue to the possible function of this nonlinearity was found by Kaplan and Shapley (1989), who found that steady illumination of the surround of P cells’ receptive fields modulates the gain of the center. This phenomenon represents a true nonlinear

interaction between the center and surround mechanisms, since summation of the two responses no longer explains the responses. As the luminance of the P ON cell surround increases, the response of the center becomes less delayed and has a *lower* amplitude (Figure 9). For P OFF cells, as surround illumination increases, the center response becomes less delayed but *increases* in amplitude. Thus, the nonlinear interaction between center and surround of the P cell receptive field represents a fast adaptation mechanism that adjusts the gain of the P cell center according to the ambient illumination over a large region of the retina. Perhaps P cells take advantage of the higher signal-to-noise ratio that is available at high illumination by increasing the speed of their response.



Discussion

Comparison with other species

Cat:

Linear and nonlinear subunits: The cat retina has been studied intensively in the past, and therefore we have a rather detailed description of the dynamics of the RGCs of this nocturnal mammal. The discovery of the X and Y types of RGC (Enroth-Cugell and Robson, 1966), which differ in the linearity of spatial summation within their receptive fields, focused attention on further distinctions between these two types. It was evident early on that Y cells are more transient than X cells, and several groups (for example, Cleland *et al.*, 1971) based the dichotomous classification of cat RGCs on the time course of their responses to steps of light, or on their responses to moving targets. Hochstein and Shapley (1976a,b) applied Fourier analysis to the averaged responses of cat RGCs, and showed that the receptive fields of Y cells had non-linear subunits, which rectified the time-varying input to produce a “frequency doubling” response. They also showed that these subunits, which were smaller than the center mechanism of the Y cell’s receptive field, extended across the entire receptive field.

Contrast gain control: Shapley and Victor (1978, 1979) pursued the matter further, and demonstrated that the non-linear subunits endowed the Y cells with a *contrast gain control*, a spatially extended mechanism that regulated the gain of the cell according to the ambient contrast. This gain control acts just like light adaptation: it reduces the cell’s response to a stimulus. However, here the adapting influence is due not to the ambient light but to the ambient contrast. Like light adaptation, the contrast gain control affects not only the *gain* of the cell, but also its *dynamics*: responses to low temporal frequencies are attenuated more than the responses to high temporal frequencies. The result is that the cell is now more transient, and can follow flickering light up to higher frequencies (see De Lange, 1958, and Dodge *et al.*, 1968, for similar effects due to light adaptation). The contrast gain control mechanism has one additional interesting effect on the response. As contrast increases, the response *phase* is advanced. This is seen clearly in M cells, but not in P cells (Smith *et al.*, 1992; Benardete and Kaplan, 1999b)

Models of Receptive Field dynamics: The dynamics of the receptive fields of X and Y cells was further investigated by Victor (1987, 1988). He has developed a comprehensive mathematical model, which accounts rather well for the temporal properties measured experimentally. Victor has shown (1987) that the nonlinear behavior observed in the ganglion cell response is not due to the nonlinear nature of the biophysical process of converting the (analog) membrane potential into a spike train. It must, therefore, represent a network property.

Homology: Initially, it had appeared that there was a natural parallel or homology between the two pairs of functional streams, the M/P of the primate and the Y/X of the cat. The similarities were appealing: the M/Y streams are both transient, fast conducting, with large receptive fields, axons and dendritic trees. The P/X streams

are both tonic, with slower conduction velocities, and smaller axons, dendritic trees and receptive fields. However, the usefulness of this homology in understanding the function or the circuitry of the two species is not established. Note that the diurnal old world primates, with their trichromatic, high resolution retina, must have optimized the circuitries of their retinas and subsequent visual stages for tasks that the nocturnal cat faces only rarely outside the laboratory.

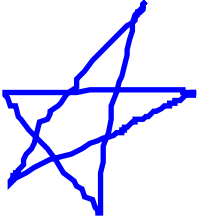
A more appealing alternative is the view that the old world primate has added the P stream, or at least part of it, to address the needs for high spatial resolution, which produced, as a bonus, the gift of well developed color vision (Boycott and Wässle, 1999).

The “multiplex” hypothesis

The phase lag between center and surround and its dependence on temporal frequency had been used to explain the loss of chromatic opponency seen in parvocellular neurons at high temporal frequencies (Gouras and Zrenner, 1979). Another approach was taken by Ingling and Martinez-Uriegas (1983), who pointed out that r-g parvocellular LGN cells will report the difference between their center and surround responses at *low* spatial frequencies, to which both center and surround are responsive, and the sum of the activation of center and surround at *high* spatial frequencies, to which only the (smaller) center can respond (see also Mullen and Kingdom, 1991). They thus viewed the r-g parvocellular cells as multiplexing luminance information (at high spatial frequencies) and chromatic information (at low spatial frequencies) information. This view requires a strict linearity of the receptive field dynamics of these cells, and, as we have shown above, this hypothesis needs to be re-examined in view of the various non-linear interactions reported by Benardete and Kaplan (1997b). Nevertheless, at low contrast, below 10%, the parvocellular cells are reasonably linear (Derrington *et al.*, 1984; Smith *et al.*, 1992; Lee *et al.*, 1994), and the multiplex hypothesis appears reasonable for those cells under these conditions.

Cone input to the surround of P cells: The analysis of Ingling and Martinez-Uriegas (1983) also relies on the separation of cone signals to the center and surround of the parvocellular r-g cells, following the early description of Type I LGN cells (Wiesel and Hubel, 1966). The issue of the selectivity of cone input to the surround of these cells is still a controversial one. Anatomical evidence does not support a surround mechanism with selective cone input of the type required by the results of Wiesel and Hubel (1966) or Reid and Shapley (1992), because both horizontal cells and amacrine cells make promiscuous connections with the various cones they happen to find within the reach of their dendritic trees (Boycott *et al.*, 1987; Calkins and Sterling, 1999). We note, however, that a mixed cone input to the surround probably makes little difference to the response of the cells, or to color vision as a whole (see Paulus and Kröger-Paulus, 1983; Lennie *et al.*, 1991).

Effects of light adaptation



As we mentioned above, light adaptation has a profound effect on the dynamics of the visual system, and that effect starts with the photoreceptors: the response to a brief flash (the ‘impulse response’) is monophasic in the dark adapted state, and biphasic in the light adapted state. In the frequency domain, that change translates to a temporal transfer function that is *low pass* when the eye is dark adapted, and *band pass* when the eye is light adapted (Dodge *et al.*, 1968; De Lange, 1958). The effect of light adaptation is propagated to the ganglion cells. Enroth-Cugell and Shapley (1973) have shown that in the cat retina there is a simple relationship between the summing area of a receptive field center of a ganglion cell and its state of adaptation: at any given light level, cells with larger receptive fields are more light adapted than cells with smaller receptive fields, simply because they capture more photons. The receptive fields of M cells are significantly larger than those of P cells at any retinal eccentricity (Croner and Kaplan, 1995), and therefore they should be more light adapted – and more transient – than P cells.

The effect of retinal illumination on the dynamics of monkey RGCs was investigated by Purpura *et al.*, (1990). They found that increasing the retinal illumination affected the dynamics in much the same way that it affects photoreceptors (Dodge *et al.*, 1968), turtle horizontal cells (Tranchina *et al.*, 1984) and the human observer when studied psychophysically (De Lange, 1958). Light adapted transfer functions were band pass and dark-adapted ones were low pass. A linear model with a negative feedback, similar to the one that accounted for the response of turtle horizontal cells (Tranchina and Peskin, 1988), accounted well for the changes in the RGCs dynamics. It thus seems that the psychophysical effects of light adaptation on the temporal performance of the visual system can all be accounted for by retinal processing.

How important are the non-linearities?

In this review we have summarized recent data that show that, under appropriate conditions, significant non-linearities can be detected in the responses of P cells (Figures 8, 9). These cells have been traditionally described as linear, and their linearity has been used (for instance, Ingling and Martinez-Uriegas, 1983) as a guide to their possible function in vision, as discussed above. Smith *et al* (1992) have used an elegant experimental approach to dissect the various components that contribute to the response of primate RGCs. They varied the temporal phase between red and green light emitting diodes that were modulated sinusoidally, and measured the effect of this phase relationship on the cells’ responses at several temporal frequencies. They were able to account for the results from most cells with a model that included only linear interactions among the cone contributions. Similarly, Lee *et al.*, (1989a,b,c; 1994) concluded that significant non-linearities could be found only in M cells, and only when a spatially extended stimulus (or a high contrast one) was used.

This raises the possibility that there are subpopulations of RGCs with varying degree of temporal nonlinearity, or that the stimuli used in some studies failed to elicit significant nonlinear interactions. It should be pointed out that the nonlinearities observed in the responses of P cells are not trivial: although the linear

component of the response is larger than the second order response shown in Figure 8, it is still substantial, and, as Figure 9 shows, the nonlinear interaction between center and surround is capable of reducing the center response by a factor of ~ 3 . Such non-linearities point to significant interactions in the dynamical retinal circuit, and these interactions should prompt a search for their underlying physiological, biophysical and anatomical substrates.

The underlying retinal circuitry

Functionally, the receptive field of most ganglion cells (except, perhaps, for the blue ON, yellow OFF ganglion cell; see Dacey, 1999b, and below) appears to include (at least) 3 distinct components:

1. A narrow (linear) center, which could be excited by either increments or decrements of light (ON or OFF)
2. A broader (linear) antagonistic surround, which produces a response whose phase is opposite (at low temporal frequencies) to that of the center's response
3. A nonlinear (rectifying) mechanism, which extends far beyond the boundaries of the receptive field surround or the dendritic tree of the cell.

The first two mechanisms are simply the ones described half a century ago by Kuffler (1953). The third, non linear mechanism, is associated with the non linear subunits of Hochstein and Shapley (1976a), and with the contrast gain control of Shapley and Victor (1979), and is probably the same mechanism that is responsible for the 'McIlwain effect' and the 'shift effect', as well as other spatially extended nonlinear effects (McIlwain, 1966; Krüger and Fischer, 1973; Enroth-Cugell and Jakiela, 1980).

Currently, it is thought that the center mechanism is produced (primarily) by the responses of bipolar cells. The surround antagonism is thought to be due to a negative feedback from horizontal cells onto cones, and the nonlinear responses are often attributed to the activity of amacrine cells, which contribute a significant synaptic input to the ganglion cells (Werblin and Dowling, 1969; Hochstein and Shapley, 1976b; Wässle and Boycott, 1991; Sterling, 1998; Calkins and Sterling, 1999; Demb *et al.*, 1999). Note that this suggested correspondence between anatomical cell types and functional components of the receptive field is not the only possible one. It is possible, for instance, that the H1 and H2 types of horizontal cells, each of which tiles the retina (Wässle *et al.*, 2000), contribute differently to the linear and nonlinear components of the receptive field. However, the overall wiring scheme of the retina suggests that the two layers that are arranged for lateral transmission of information, the outer and inner plexiform layers, will *both* contribute to the spatially extended computation that involves the surround mechanism.

The precise combination of cone inputs to the center, surround and the nonlinear mechanisms is still controversial, and it is likely that with time, additional mechanisms will be added to this hypothetical scheme. The great diversity of cell types and neurotransmitters in the inner plexiform layer (see, for example, McNeil and Masland, 1998) makes such an expansion highly probable.

Our current understanding of the structure of the receptive field can thus be summarized by the scheme shown in Figure 10.

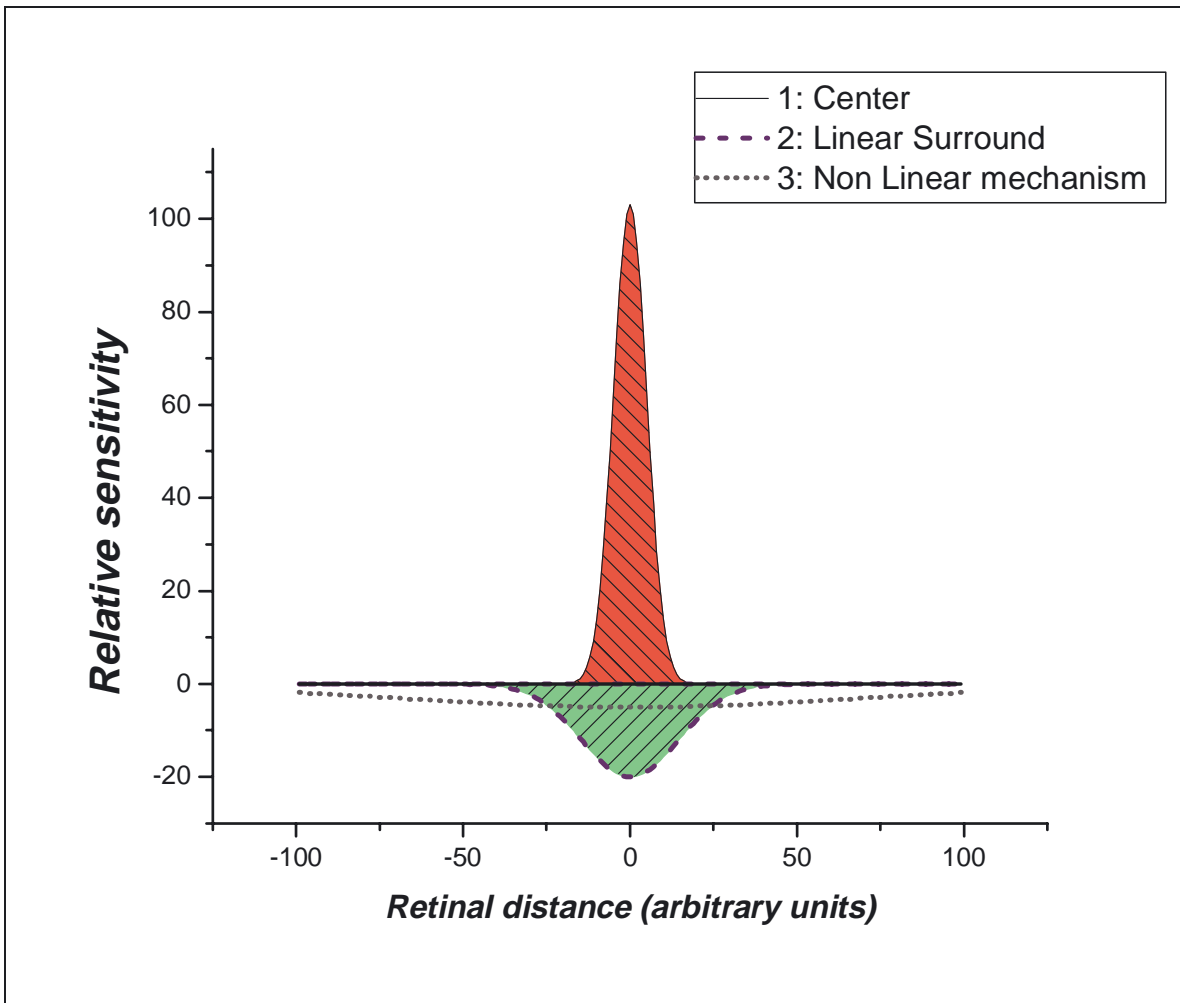


Figure 10 The sensitivity profile of the three components that make up the receptive field of ganglion cells. The abscissa is drawn intentionally with arbitrary units, to allow cells of various sizes, including both M and P cells. The numbers in the legend correspond to the numbered list above.

The blue ON, yellow OFF ganglion cell appears to differ from this general scheme, since its antagonistic center and surround regions appear to be coextensive (Dacey, 1999b). However, the notion that both plexiform layers contribute their individual part to the surround mechanism probably holds for these cells as well.

This general scheme of a surround with (at least) two components is consistent with several recent reports. Thus, for instance, Smith *et al.*, (1992) reported evidence for an additional chromatically opponent mechanism in the surround of M cells. In addition, Calkins and Sterling (1999) reported anatomical evidence of synaptic input

from amacrine cells to both M and P RGCs. These could provide the non-linear elements of the surround mechanism.

Functional implications

The distinct dynamical properties of the M and P populations, taken together with the ensemble of their other differences, suggest strongly that each is dedicated to a different set of visual tasks. The high temporal resolution, high contrast sensitivity, and coarse mosaic of the M cells (Kaplan and Shapley, 1986; Kaplan *et al.*, 1990; Croner and Kaplan, 1995) point to their role in motion analysis. The small receptive field, dense mosaic, chromatic organization, and tonic responses of the P cells suggest that they are used for spatial tasks, such as the analysis of shape, texture and color. A deeper understanding of their roles in perception must await more information about the fate of their signals once they reach the visual cortex.

Conclusions

We conclude with a brief summary of the facts as we currently know them, and a list of the things that are yet to be determined.

What is known

1. The center and surround of P cells are approximately linear at low contrasts.
2. Significant nonlinearities emerge in the P cell responses as contrast increases.
3. The interaction between the center and surround of P cells includes a nonlinear component.
4. The center and surround of P cells are chromatically opponent.
5. The phase lag between center and surround of P cells depends on temporal frequency, so that at high frequencies the center and surround are no longer antagonistic.
6. The M cell responses are nonlinear.
7. With increasing contrast, M cells show the effects of a contrast gain control, similar to the one found in cat Y ganglion cells.
8. Most M cells show linear spatial summation (X like), with a minority showing nonlinear spatial summation (Y like).

What is still missing

1. Are there different dynamical sub-types within the major 3 streams (M, P, K)?
2. If so, are they related to other aspects (morphology, connectivity, neurochemistry, biophysics)?
3. To what extent are the dynamical properties of the various types due to the *network* in which the neurons are embedded?
4. What are the dynamical properties of the Koniocellular neurons?
5. What are the contributions of the various anatomical cell types in the retina to the various functional components of the receptive field of the ganglion cell?

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