

# Response Properties of Cells in the Dorsal Lateral Geniculate Nucleus of the Albino Rat

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The response patterns of cells in the dorsal lateral geniculate nucleus of the albino rat were studied in order to examine the functional organization of the lateral geniculate nucleus. Both photic stimulation and electrical stimulation of the optic tract were used to activate single units in the lateral geniculate nuclei. Three different types of response patterns were found for principal cells, while interneurons all had similar response patterns. The first class of principal cells, E-S cells, responded to stimulation with a period of excitation, followed by a period when activity was suppressed. A second class of cells, S cells, responded to photic stimulation with an initial period when activity was suppressed. The final class of cells, E cells, responded with a period of excitation followed by a return to spontaneous rates of firing. The response patterns of E cells suggest that this type of principal neuron does not receive feedback inhibition of the type proposed in previous models of the lateral geniculate nuclei. Based on these and other observations, a new model of the functional organization of the lateral geniculate nuclei is proposed.

**Key words:** lateral geniculate, visual anatomical model, neurophysiology, visual response types, vision, central nervous system

## INTRODUCTION

The response of single cells in the lateral geniculate nucleus (LGN) of the albino rat to electrical stimulation of the optic nerve and the visual cortex has been described by Burke and Sefton (1966a, 1966b, 1966c). Based on the first 2 of these studies, Burke and Sefton (1966b) proposed a model for the functional organization of neurons in the LGN. In their model, principal cells (P cells) projected to the visual cortex and, in addition, gave off axon collaterals that excited interneurons (I cells). In turn, the I cells inhibited P cells. Most P cells responded to electrical stimulation of the optic nerve with a single spike. This was usually followed, 100-300 msec later, by repeating bursts of 2-5 spikes. I cells fired in an initial burst of 7-13 spikes followed by rhythmic bursts of activity. The receptive fields of LGN cells were studied by Sefton and Bruce (1971) in an attempt to further refine the model. While they found that most LGN cells had response properties that could be predicted by their model, a significant number of P cells showed firing properties that could not be predicted by their model. In general, these latter cells gave "on-off" responses throughout their receptive fields.

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In view of the failure of previous models to thoroughly define the properties of LGN cells, it would seem that a further examination of the LGN would be appropriate. The present investigation was designed to systematically study the response characteristics of single neurons in the dorsal lateral geniculate nuclei (dLGN) of the rat to both photic and electrical stimuli. It was felt that a detailed, computer analysis of the firing patterns of LGN neurons to photic stimuli and electrical stimuli applied to the optic tract would help to further define the functional organization of the LGN.

## METHODS

Adult, Sprague-Dawley, albino rats weighing 180–380 g were maintained in an environment of cyclic light (14 hr of light followed by 10 hr of dark in each 24-hr period). All rats were anesthetized with pentobarbital sodium (35 mg/kg body weight, intraperitoneally) prior to surgery, and the trachea was then cannulated. The rats were restrained in a Kopf, small-animal stereotaxic apparatus. The EKG was monitored on a Tektronix model 561A oscilloscope and an audio sound system. Body temperature was maintained by placing the animal on a Gorman-Rupp constant-temperature heating pad. Prior to recording, the cranial skin was incised and the calvarium and dura overlying the optic tracts and lateral geniculate nuclei were removed. Mineral oil was placed on the cortical surface to prevent drying, and the pupils were dilated with 1% atropine sulfate. Each animal was continuously monitored during the surgery and throughout the recording session by examining several physiological parameters, including: heart rate, respiration, and the condition of the cortex and associated vasculature.

Microelectrodes used in the experiments were glass capillary tubes pulled to a tip diameter of 1.5 to 3.0  $\mu\text{m}$  and filled with a saturated solution of fast green in 2 M NaCl (Thomas and Wilson, 1967). Coordinates for unit recordings in the LGN were derived from the Pellegrino and Cushman stereotaxic atlas (1967). Electrode tracts within the LGN were 3.0–4.0 mm anterior to the interaural line and 3.5–4.2 mm lateral to the midline. The LGN was normally encountered 4.0 mm below the cortical surface.

The photic stimulation in this experiment consisted of a brief, intense flash of light generated by a Grass model PS-2 photic stimulator (intensity switch set at "16"). Stimuli were presented at the rate of 1 every 5 or 10 sec. The strobe was 30 cm from the eye that was contralateral to the LGN being studied. Background light was carefully controlled so as to minimize extraneous visual stimulation. Electrical stimuli to the optic tract consisted of unidirectional, rectangular pulses generated by a Grass model S-4 stimulator and delivered to the animal through a Grass model SIU-5 stimulus isolation unit connected to a metal, concentric, bipolar macroelectrode. Electrical pulses had durations of 0.1–0.5 msec and intensities of 1–50 V.

All neuronal responses were recorded through a Grass high impedance probe, model HIP511C, and fed through a Grass model P511 preamplifier to a Tektronix model 549 storage oscilloscope for direct visualization. In addition, an audio monitor was used to aid in the detection of single neural units. When a unit responded to a visual stimulus presented to the contralateral eye, responses were relayed to a PDP-8L digital computer for on-line analysis. All neuronal units were initially tested for a response to a flash of light. Following the appearance of a visually evoked response, units were analyzed by con-

structing post-stimulus time histograms (PSTH's). Each histogram represented the sum of all activity following the consecutive presentation of 50 or 100 flash or electrical stimuli. The histograms were displayed on the storage oscilloscope. Unit responses and PSTH's were photographed with a Polaroid camera directly from the face of the storage oscilloscope.

At the conclusion of each recording session, the animal was sacrificed and perfused with saline followed by a 10% buffered formal-saline. The brain was removed and placed in a 10% buffered formal-saline solution for 2–3 weeks. A block of the posterior two-thirds of the brain was then sectioned at 30  $\mu\text{m}$  and stained with cresyl violet. The sections were then examined for confirmation of electrode placement.

## RESULTS

### Photic Stimulation

A total of 185 LGN cells was studied in 23 rats. One hundred and thirty of these cells were classified according to the response patterns they exhibited to flashes of light. One hundred and nineteen cells were classified as P cells, and 11 cells were judged to be I cells. P cells were distinguished from I cells on the basis of the number of spikes in the initial discharge following the flash. P cells had 1–4 spikes in their initial discharge, while I cells had 8–14 spikes in the first burst following the flash. The sensitivity of LGN neurons to the visual stimulus was determined by comparing control time histograms of spontaneous activity with the PSTH's generated with photic stimulation. The presence or absence of periods of stimulus bound excitation or suppression characterized different response patterns. Differences in response patterns were used to separate P cells into 3 classes, while there was no significant difference between the response patterns of I cells. Eighteen percent of the P cells responded only with a period of excitation following the flash. These cells are referred to as "E" cells. Sixty-six percent of the P cells responded to a flash with a short-latency period of excitation followed by a period of suppression. This class of cells is referred to as "E-S" cells. The remaining 15% of the P cells responded to a flash with an initial period of suppression and are called "S" cells.

The single period of excitation exhibited by E cells occurred with a latency of 20–55 msec following the flash and had a duration of 20–40 msec. An example of an E cell is seen in Figure 1A. This cell exhibited a stimulus bound period of excitation 20 msec in duration, beginning 30 msec following each stimulus. After the period of excitation there was a return to a spontaneous level of firing comparable to that seen in the control time histogram in Figure 1B. The spontaneous rates of E cells varied between 0.1 and 6.0 discharges per sec.

The largest group of P cells, E-S cells, responded to photic stimulation with an initial short duration (20–30 msec), short latency (20–40 msec) period of excitation, followed by a period of suppressed activity that lasted 100–500 msec. Figure 1C shows an example of an E-S cell. In this cell the periods of initial excitation and suppression were followed by 2 stimulus bound late discharges. Approximately 2 sec after each stimulus, the cell returned to a spontaneous rate of firing comparable to that seen in the control time histogram in Figure 1D. Depending on the cell, the number of stimulus

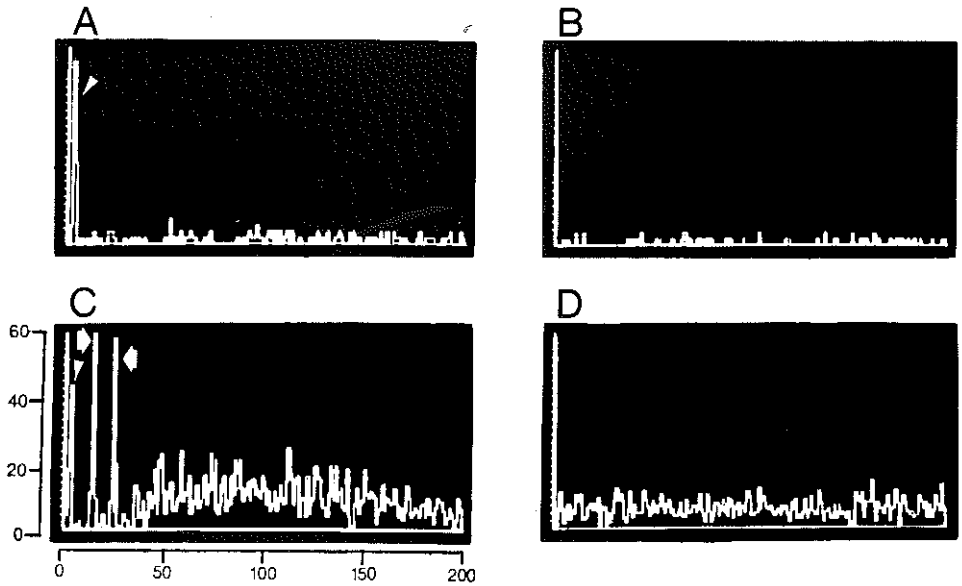


Fig. 1. Examples of an F cell (A and B) and an E-S cell (C and D). Frame A is PSTH showing the response characteristics of an F cell. Following the flash there was a stimulus bound period of excitation (indicated by arrowhead) that was followed by a return to a spontaneous rate of firing. Frame B is a control time histogram from the cell whose PSTH is seen in A. Frame C is a PSTH of an E-S cell. Following the flash there was an initial period of excitation (indicated by arrowhead). This was followed by a brief period of suppression of activity which was followed by 2 stimulus bound late discharges (indicated by large arrows). The rate of firing of the cell then slowly returned to the spontaneous rate of firing. Frame D is the control time histogram for the cell whose PSTH is seen in Fig. C. The time histograms show the number of spikes per bin on the Y axis and the number of 10 msec bins on the X axis. The total duration of the histograms corresponds to 2 sec. One hundred stimuli were presented to generate the PSTH's in this and the following figures.

bound late discharges that a cell had varied between 0 and 5. Some cells exhibited rhythmic bursting that lasted for up to 4 sec following stimulation. The spontaneous rates of E-S cells varied between and 0.1 and 6.0 discharges per sec.

S cells could be divided into 2 subclasses based on differences in response patterns. The first subclass displayed a single period of decreased activity, which occurred with a latency of 30–100 msec and had a duration of up to 400 msec. These cells had rates of spontaneous activity in the range of 10–20 discharges per sec. An example of this type of neuronal behavior is seen in Figure 2A, B. The second type of S cell also showed the initial period of decreased activity, but, in addition, exhibited a stimulus bound period of excitation following the suppression. The period of increased activity had a latency between 200–400 msec and a duration between 30–80 msec. In some cells, this rebound activity was followed by additional periods of suppression and excitation. The response patterns of a cell from this second subclass of S cells is shown in Figure 2C, D. It can be seen that there is an initial suppression, followed by a stimulus bound period of excitation, which precedes a second period of suppression. The second type of S cell exhibited spontaneous levels of activity ranging from 1.0–6.0 discharges per sec.

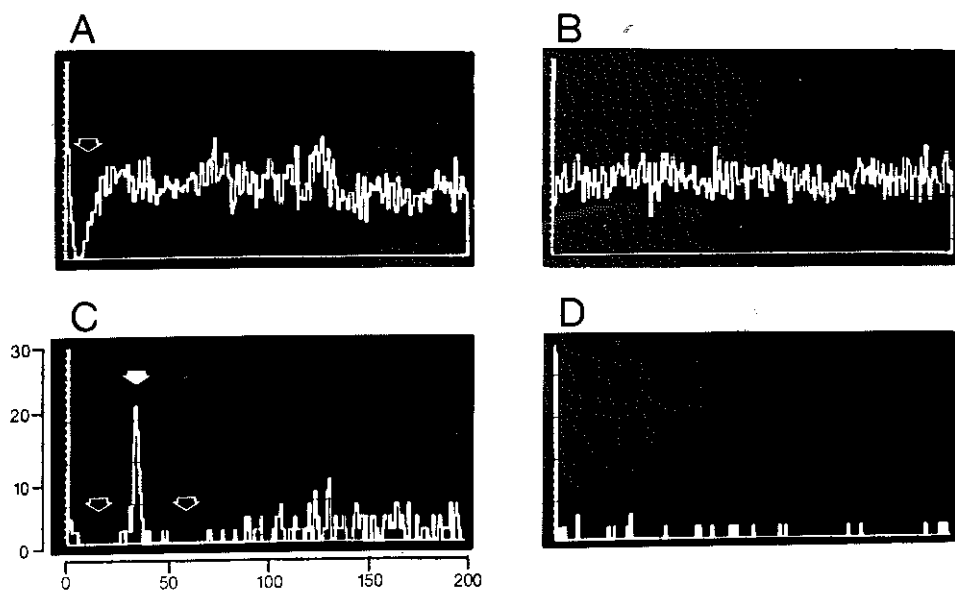


Fig. 2. Examples of the response characteristics of the 2 subclasses of S cells. Frame A is the PSTH of a cell representative of the first subclass of S cells. Following the flash stimulus the spontaneous activity of the cell was suppressed (indicated by open arrow). This was followed by a return to the spontaneous rate of firing. Frame B is the control time histogram of the cell whose PSTH is seen in A. Frame C is the PSTH of a second type of S cell. Following the flash stimulus there was a period of suppression (open arrow) followed by a stimulus bound period of excitation (filled arrow). Following a second period of suppressed activity (second open arrow) there was an increased rate of firing that lasted for at least 1 sec. Frame D is the control time histogram of the cell whose PSTH is shown in C. The duration of the time histograms was 2 sec.

Eleven I cells were tested for their response to photic stimuli. It was found that their response patterns consisted of an early discharge that was followed by a period of no activity. The latency to the initial discharge was 20–30 msec following stimulation. The duration of the early discharge was 20–30 msec, while the period of no activity lasted 250–500 msec. All of the I cells had 1 or more periods of excitation following the period of no activity. An example of the response patterns of an I cell is seen in Figure 3A, B. It can be seen that, while the initial discharge has a fixed latency, the latency of the late discharge was highly variable. All I cells had low levels of spontaneous activity, typically 0.1–1.0 discharges per sec.

### Photic and Electrical Stimulation

In 3 of the animals unit recordings were made in response to both electrical stimulation of the optic tract and photic stimulation. Full stimulation and computer analyses were performed on 8 units. These procedures included compilation of PSTH's to electrical and photic stimulation as well as control time histograms. In 7 of the 8 units the response pattern to electrical stimulation was similar to the response pattern to photic

stimulation. As an example, the E-S cell in Figure 4 showed 2 stimulus bound late discharges following both photic (A) and electrical (B) stimulation. One S cell was studied with both electrical and photic stimuli. When electrical stimuli were delivered to the optic tract, the S cell responded with a single spike. This was followed by a period of suppression and excitation similar to the suppression and excitation produced by photic stimulation.

In 4 of the cells, following electrical stimulation, the threshold of the initial discharge was the same as the threshold of the later discharges. The remaining 4 units had a

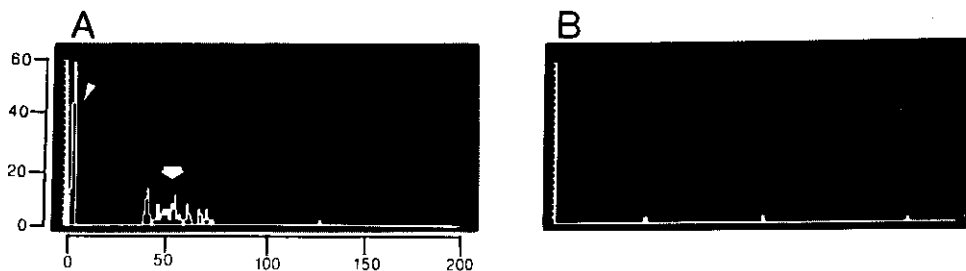


Fig. 3. The typical response pattern of an I cell is shown in Frame A. Following the flash there was a period of excitation (indicated by arrowhead) followed by a period of no activity. This was followed by a second period of excitation (indicated by large arrow). Frame B is the control time histogram of this cell. The duration of the time histograms was 2 sec.

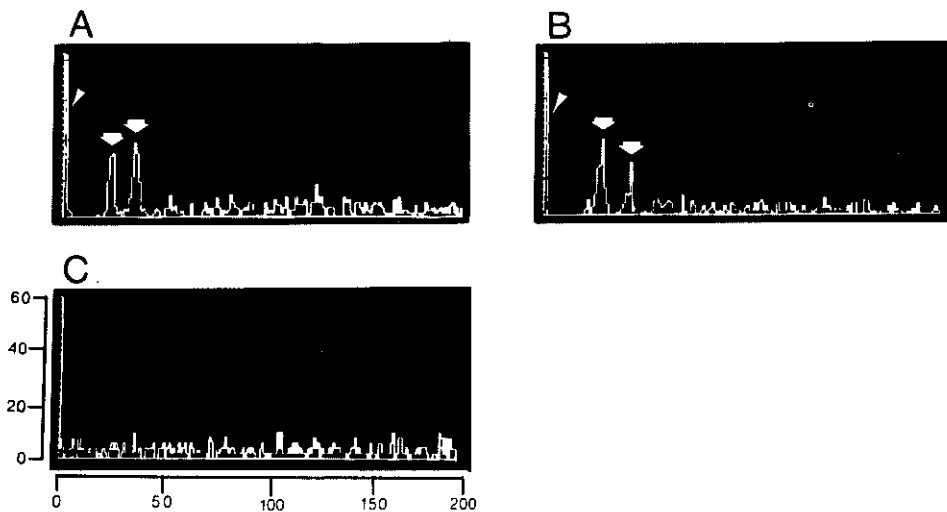


Fig. 4. The response patterns of an E-S cell to photic (A) and electrical (B) stimulation are included to demonstrate the similarities of the responses. Following either type of stimulation there was an initial period of excitation (indicated by arrowhead and seen immediately adjacent to the ordinate, because of the large, 25 msec bin width necessary to show all components of the response), followed by a period of profound suppression of activity. Following the suppression there were 2 stimulus bound late discharges (indicated by large arrows). Frame C is the control time histogram of this cell. The total duration of the time histograms was 5 sec.

lower threshold for the late discharges than for the initial discharge. As a result, it was possible to study the response patterns of cells to electrical stimuli that were subthreshold for the initial discharge but suprathreshold for the late discharges. In these cells the presence of an early discharge was not necessary to generate a period of suppression followed by a period of excitation. Also, the duration of the period of suppression was not significantly altered by the presence or absence of an early discharge.

## DISCUSSION

In 1966, Burke and Sefton (1966b) proposed a model for the functional organization of the LGN. It consisted of P cells that received their input from the retina, primarily via one optic tract axon. The P cells projected to the visual cortex and, in addition, gave off axon collaterals that synapsed on I cells. Each I cell projected back upon the P cell that excited it and onto several neighboring P cells as well. The I cells exerted an inhibitory influence upon the P cells. The model specifically stated that I cells were not directly innervated by optic tract axons. In subsequent work, Sefton and Bruce (1971) found 2 major classes of receptive fields among P cells and noted that the classes were of equal proportions. The first class of cells had a dominant center with an antagonistic surround. The second class had a dominant center without a demonstrable surround. They also reported that the number of cells that gave "on" responses as their dominant response was equal to the number of cells that gave "off" responses. I cells gave "on-off" responses throughout their receptive fields. The authors concluded that one I cell received an input from both on-center and off-center P cells and, in turn, inhibited both on-center and off-center P cells. In addition, it appeared that some of the P cells studied had "on-off" responses throughout their receptive fields and that one of the cells was directionally selective (as a point of interest, Montero and Brugge (1969) had previously reported finding numerous cells in the rat LGN that were directionally selective). It is of special importance that none of the responses of these latter cell types could be predicted by the Burke and Sefton (1966b) model. Thus, while numerous LGN cells that have been studied responded to photic or electrical stimulation in a manner that was predicted by the model, there was a sizable aggregate of cells whose responses were not consistent with the model.

Based upon our data and the data from previous experiments, there seem to be 2 primary deficiencies in the Burke and Sefton (1966b) model. The first relates to the assumption of the model that each P cell must inhibit itself, via an I cell, each time it responds. The second relates to the failure of the model to specify the existence of at least some P cells that receive no inhibitory connections by way of I cells. With regard to the latter deficiency, the identification of E cells in our study, which showed no suppression following the period of excitation, indicates that some P cells do not participate in inhibitory feedback loops. The E-S cells we observed, whose late discharges had lower thresholds to optic tract stimulation than did their initial discharges, bear on the first deficiency. Since an early excitatory discharge was not necessary to generate a period of suppression and since the presence or absence of the early discharge had no significant effect on the duration of the suppression, it would appear that the observed suppression was not the result of self-inhibition via I cells. Rather, it would seem that the observed suppression in these P cells came about through the activation of I cells via neighboring P cells. Our conclusion regarding the lack of either direct or indirect inhibition in some LGN cells is also supported by the findings of Baker et al. (1969), who noted that some

geniculate neurons showed suppression and rebound following the initial discharge, while certain other geniculate neurons had extended excitatory responses that did not include a period of suppression.

To account for our data, as well as the observations made in a number of other laboratories (Baker et al., 1969; Montero and Brugge, 1969), we have proposed a new functional model of the LGN. As can be seen in Figure 5, all P cells in our model receive an input from the retina and project to the visual cortex. Many P cells also give off collaterals that synapse on I cells. In some cases, as in P cell number 2, there is no feedback inhibition, although activation of this particular P cell activates an I cell, which in turn influences neighboring P cells by way of lateral inhibition. By contrast, P cell number 3 is exposed to both feedback and lateral inhibition. Thus, in our model, a P cell may inhibit itself and/or its neighbors, while other P cells receive no inhibitory connections at all. Not shown in the model is the possibility that some P cells may neither send connections to nor receive connections from I cells. While this latter notion is an intriguing possibility, we have no substantial evidence at this time for the existence of such a "straight through" type of P cell.

The model we have proposed can account for all of the response patterns we have observed in our experiment, as well as the directionally sensitive cells reported by other investigators. For example, the E cells we have described would receive an excitatory input from the optic tract, but would not receive an inhibitory input from I cells. It is most likely that these cells would have a receptive field without an antagonistic surround. On

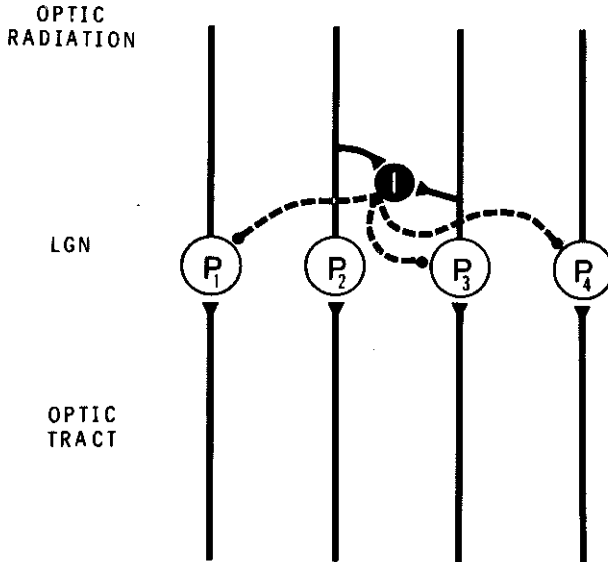


Fig. 5. Functional model of the lateral geniculate nucleus. P cells receive an input from retinal ganglion cells via the optic tract. The P cells project to the visual cortex and give off axon collaterals that synapse upon I cells. I cells, in turn, have inhibitory synapses upon P cells. Some P cells, such as P<sub>3</sub>, receive feedback inhibition from the I cells that they excite. Other P cells, e.g., P<sub>2</sub>, synapse upon I cells, but do not receive an inhibitory input from them. A final group of P cells (P<sub>1</sub> and P<sub>4</sub>) receives an inhibitory input from I cells, but this input serves the function of lateral inhibition and not feedback inhibition.

the other hand, S cells could receive a primary retinal input from optic tract axons that give an "off" response, or they could simply have their spontaneous rate of firing suppressed via lateral inhibitory influences. To illustrate the flexibility of our model, consider how it can handle the complex firing characteristics of an S cell to either electrical stimulation of the optic tract or photic stimulation of the retina. In one such cell we studied, optic tract stimulation produced a short latency (2–4 msec) spike, which was followed by a period of suppression, presumably reflecting an inhibitory process mediated via I cells. By contrast with the results of electrical stimulation, a flash of light to the retina produced only a period of suppression, probably because the S cell would not receive a direct input from the optic tract "off" axons, in this case, while it would when the optic tract is electrically stimulated. E-S cells, according to our model, would receive an excitatory input from the optic tract and an inhibitory input from the I cells, thereby producing a response pattern consisting of an initial period of excitation followed by a period of suppression.

With a model such as ours, where lateral inhibition is thought to be more common than feedback inhibition, it is possible to describe simple circuits that account for the response characteristics of directionally selective cells. Since directionally selective cells give "on-off" responses throughout their receptive fields it is possible that these cells receive an excitatory input from both "on" and "off" optic tract axons. If a cell with this type of retinal input, say  $P_1$ , received lateral inhibition from a second cell,  $P_2$ , and  $P_2$ 's receptive field was adjacent to  $P_1$ 's receptive field,  $P_1$  would be directionally selective. For example, if a target first moved through the receptive field of  $P_2$ , thereby producing inhibition in  $P_1$ , then  $P_1$  would give no response when the target entered its receptive field. On the other hand, if the target moved in the opposite direction, entering the receptive field of  $P_1$  prior to  $P_2$ ,  $P_1$  would respond.

In closing, it would seem pertinent to make some remarks about the relative infrequency with which I cells were observed in our experiment and in other investigations. One possible explanation relates to the fact that I cells are thought to be small cells, with soma diameters in the range of 10 to 20  $\mu\text{m}$  (Grossman et al., 1973; Kriebel, 1975), and this might be expected to decrease the likelihood of recording from these cells. On the basis of recent experiments in the rat (Sumitomo et al., 1976) and cat (Dubin and Cleland, 1977), it would appear that the density of I cells in the geniculate is very low. In fact, some of the I cells studied in these investigations were found to reside outside the classical boundaries of the LGN. Thus, it is conceivable that few I cells have been observed because there are relatively few of them compared to the number of P cells.

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