The Neuronal Basis of Direction Selectivity in Lobula Plate Tangential Cells

Timothy Melano and Charles M. Higgins

Biomedical Engineering Program / ARL Division of Neurobiology

The University of Arizona, Tucson

Abstract

Using a neuronally-based computational model of the fly's visual elementary motion detection (EMD) system, the effects of picrotoxin, a GABA receptor antagonist, were modeled to investigate the role of various GABAergic cells in direction selectivity. By comparing the results of our simulation of an anatomically correct model to previously published electrophysiological results, this study supports the hypothesis that EMD outputs integrated into tangential cells are weakly directional, although the tangential cells themselves respond to moving stimuli in a strongly directional manner.

Key words: Diptera, visual motion, elementary motion detection, tangential cells

1 Introduction

The Hassenstein-Reichardt (HR) correlation model, published in 1956 [1], has contributed greatly to the understanding of the optomotor response in insects. Many years after the development of the HR model, cells were discovered in the lobula plate of the fly that were sensitive to wide-field motion stimuli

Corresponding author: Timothy Melano, *tmelano@email.arizona.edu*.

and the electrical activity of which was well described by the HR model [2]. Although the HR model mathematically describes the responses of these so-called *tangential cells*, which are believed to integrate the outputs of many small-field elementary motion detectors (EMDs), it leaves the neural basis of this system open for investigation.

An important question that arises in motion detection is the method by which output from EMDs is integrated into lobula plate tangential cells (LPTCs) and whether direction selectivity arises presynaptically or within the dendrites of LPTCs. In 1996, a study conducted by Single *et al.* addressed this question by injecting picrotoxin (PTX) into the hemolymph after puncturing the lobula plate [3]. Picrotoxin has been shown to block inhibitory input to LPTCs and is an antagonist to GABA receptors [4]. The investigators conducted electrophysiological experiments and computer modeling studies and the results of the two were compared.

In Single *et al.*'s electrophysiological experiments, the activity of several tangential cells was recorded before and 10 minutes after the application of PTX (see Figure 2). Prior to the application of PTX, the LPTC depolarized when the visual stimulus moved in the preferred direction and hyperpolarized in the null direction. The change in cellular input resistance was negative and equal for both directions. After the application of PTX the LPTCs lost their directionality: the cells depolarized for both preferred and null directions. Also, the change in cellular input resistance was greater in the preferred direction than in the null direction.

Directional selectivity can take two forms: weak and strong. Weakly directional EMDs exhibit an excitatory response to visual motion in the preferred direction and little response in the null, while strongly directional EMDs exhibit an excitatory response in the preferred direction and an inhibitory response in the null. In Single *et al.*'s computer modeling, weakly and strongly directional EMDs were tested. These two types of EMDs were altered in systematic ways to simulate the different possible effects of PTX on the motion response and membrane resistance of LPTCs. When the inhibitory synapses of weakly directional EMDs were blocked, the motion response and the change in membrane resistance were similar to the electrophysiological results after PTX was applied. Based on this the authors concluded that physiological EMDs are weakly directional and that directional selectivity is calculated largely in lobula plate tangential cells.

In 1995, Douglass and Strausfeld recorded from T5 bushy T-cells, which are presynaptic to LPTCs, and described their activity as strongly directional [5]. This observation is in contradiction with one of the conclusions of Single *et al.* which states that strong direction selectivity first arises at the level of LPTCs and that the inputs to LPTCs are weakly directional. These recordings, along with other anatomical and electrophysiological evidence, led to the development of a neuronally-based model of dipteran elementary motion detection (see Figure 1a) [6]. In the present study, we simulated the possible effects of PTX on a tangential cell using the neuronally based EMD model in order to determine how the output of T5 cells are integrated at the level of LPTCs and propose interpretations that reconcile the above-mentioned studies. The present study also considers the possibility that, in the experiment by Single *et al.*, PTX also affected inhibition in the lobula, since the dipteran lobula plate is very thin and T5 dendrites are located nearby in the outermost stratum of the lobula [7].

2 Methods

Simulations of the computational model were conducted using the *Matlab* package (The Mathworks, Natick, MA). The image input was 40 x 40 pixels and the visual system was composed of 20 x 20 photoreceptors with a similar number of optic cartridges. In our model, an optic cartridge consisted of a set of retinotopic cells from the photoreceptors through the T5 cells (see Figure 1a). The filters used in modeling cellular activity were first order with time constants of 50 ms for the first high pass and low pass filters and 100 ms for the last low pass filter. A two-dimensional sinusoidal grating was used as visual input to the model. The possible effects of PTX were modeled by manipulating the equations that dictate the activity of cells that may be sensitive to this chemical (below).

The response of the simulated LPTC is represented by the spatial sum:

$$R_{LPTC} = \sum_{\text{All EMDs i}} (pos(T5_{L,i}) - f \cdot pos(T5_{R,i}))$$

where $T5_{L,i}$ and $T5_{R,i}$ are the membrane potentials of the two T5 cells in optic cartridge i with the same preferred-null direction axis but with opposite preferred directions (see Figure 1b). The *pos* operator has a rectifying effect, i.e. it only passes the positive values. In control simulations f was set to 1. Inhibition to LPTCs was blocked by setting f to zero.

3 Results

T5 endings are almost certainly presynaptic to lobula plate tangential cells [8]. Each optic cartridge contains four T5 cells at the level of LPTC dendrites. T5 cells have been shown to be strongly directional and to project only to the lobula plate [5]. Further, it has been proposed that there are two pairs of T5 cells with opposite preferred-null directions along each of the two axes of the compound eye [6]. It seems likely that both T5 cells with the same orientation are integrated into an LPTC to make maximum use of the redundancy inherent in this pair of opposing motion detectors. If so, one must be excitatory and the other effectively inhibitory since otherwise their activity would cancel. Single *et al.* demonstrated that strong directionality in LPTCs is lost when inhibitory inputs to LPTCs are blocked (see Figure 2b). The only way to produce this effect in our model is if the synapses of T5 cells onto LPTCs are rectifying (see Figure 1b). Anatomically, we suggest that one T5 neuron directly excites the LPTC, and the other inhibits the LPTC through the action of an inhibitory interneuron. Both synapses onto the LPTC are presumed to be rectifying chemical synapses.

In the study by Single *et al.*, it is possible that the application of PTX affected inhibitory synapses in the outer lobula as well as the nearby lobula plate. To investigate this possibility, we blocked Tm9 and IIN inhibition in the computational model, all of which occurs at the same level in the outer lobula. If this inhibition is removed, the model responds equally to stimuli moving in any direction, which is inconsistent with the results of Single *et al.*, and thus we conclude that only inhibition in the model at the level of the lobula plate could be affected by the simulated application of PTX.

Using the model shown in Figure 1b, we simulated the integration of T5 cells into an LPTC. In Figure 3a, we show the response to preferred and null direction stimuli of an LPTC before simulated application of PTX, comparable to the electrophysiological results in Figure 2a. After inhibition in the model at the level of the lobula plate is removed, simulating the effect of PTX, the response shown in Figure 3b is obtained, in qualitative agreement with the electrophysiological results.

In addition, since changes in cellular input resistance are proportional to changes in channel conductivity, it is likely that the input resistance data of Single *et al.* are also qualitatively supported by the model. After removal of simulated inhibition, the only conductance change in the simulated LPTC is due to excitatory input from T5 cells which respond more strongly in the preferred direction than in the null. Thus input resistance changes are larger in the preferred direction.

4 Discussion

In this study, the neuronal basis of signal integration into LPTCs was investigated. A model of T5 cell integration into LPTCs was proposed, and the effects of PTX on inhibition in the model were simulated. In the control case, where all synapses were unmodified, the mean response of the LPTC (Figure 3a) was qualitatively similar to the electrophysiological data in the study by Single *et al.* (Figure 2a). The cases where inhibition from T5 cells was blocked (Figure 3b) provided results similar to the electrophysiological results of Single *et al.* after PTX was introduced into the lobula plate (Figure 2b).

Electrophysiological data collected by Douglass and Strausfeld [5] shows that direction selectivity is computed presynaptic to LPTCs. Although the activity of T5 cells is strongly directional (i.e. depolarized in the preferred direction and hyperpolarized in the null) the rectification of the output of T5 cells in the model (Figure 1b) transforms the signal into a weakly directional one, in agreement with Single *et al.* The results of our study thus support both that strong directionality arises at the level of T5 cells, and that weakly directional activity (the rectified output of $T5$ cells) is integrated at the level of the lobula plate.

Acknowledgements

This work was supported by the Biomedical Engineering Program at the University of Arizona, and the University of Arizona Program in Applied Mathematics NSF IGERT for Biology, Mathematics and Physics Initiative. The authors gratefully acknowledge the comments of Dr. John K. Douglass of the University of Arizona Division of Neurobiology.

References

[1] B. Hassenstein, W. Reichardt, Systemtheorische analyse der Zeit-, Reihenfolgen- und Vorzeichenauswertung bei der Bewegungsperzeption des Rüsselkäfers Chlorophanus, Zeitschrift für Naturforschung 11b (1956) 513–524.

[2] K. Hausen, The lobula-complex of the fly: structure, function, and significance in visual behaviour, in: M. Ali (Ed.), Photoreception and vision in invertebrates, Plenum Press, 1984, pp. 523–599.

[3] S. Single, J. Haag, A. Borst, Dendritic computation of direction selectivity and gain control in visual interneurons, J. Neurosci. 17 (16) (1997) 6023–6030.

[4] T. Brotz, A. Borst, Cholinergic and GABAergic receptors on fly tangential cells and their role in visual motion detection, J. Neurophysiology 76 (16) (1996) 1786–1799.

[5] J. K. Douglass, N. J. Strausfeld, Visual motion detection circuits in flies: Peripheral motion computation by identified small field retinotopic neurons, J. Neurosci. 15 (1995) 5596–5611.

[6] C. M. Higgins, J. K. Douglass, N. J. Strausfeld, The computational basis of an identified neuronal circuit for elementary motion detection in dipterous insects, In Press, Visual Neuroscience (2004).

[7] J. K. Douglass, N. J. Strausfeld, Anatomical organization of retinotopic motion-sensitive pathways in the optic lobes of flies, Microscopy Research and Technique 62 (2003) 132–150.

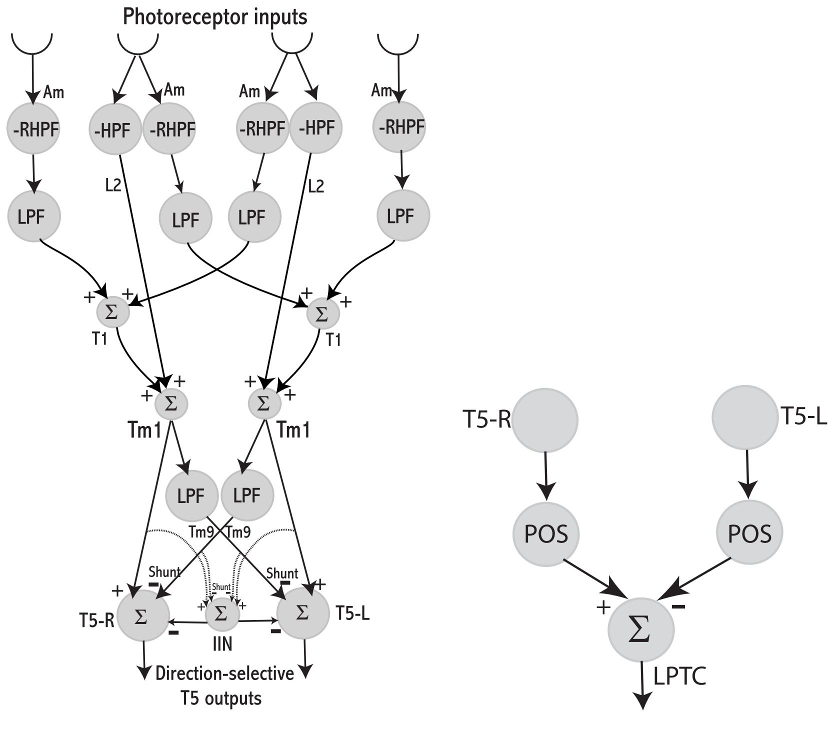
[8] N. J. Strausfeld, J. K. Lee, Neuronal basis for parallel visual processing in the fly, Vis. Neurosci. 7 (1991) 13–33.

Figure captions

Figure 1: (a) Neuronally based model of EMDs in dipteran insects. This model is composed of photoreceptors, amacrine (Am) cells, lamina monopolar (L2) cells, basket T-cells (T1), Tm1 and Tm9 transmedullary cells, an inhibitory interneuron (IIN), and T5 bushy T-cells (T5-L and T5-R). RHPF denotes a relaxed high pass filter (allows a small component of a sustained output), HPF denotes a high pass filter, LPF a low pass filter, and $\sum$ a sum. (b) An illustration of the computational model of EMD integration into an LPTC. POS indicates a rectification (allows only the positive component of the signal to pass).

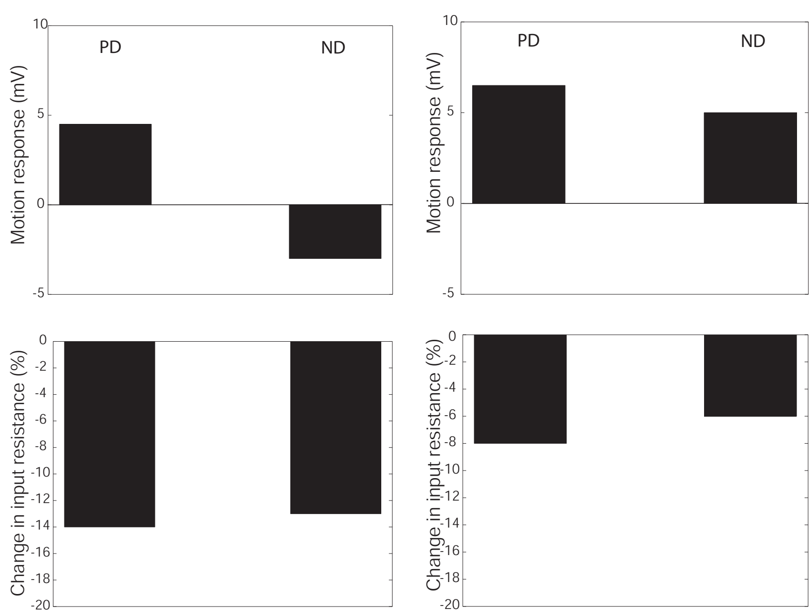
Figure 2: Experimental data from Single *et al.* The first row shows the mean response of LPTCs to moving visual stimuli. The second row shows the percentage change in LPTC input resistance. PD indicates motion in the preferred direction, ND in the null direction. (a) Data from LPTCs before application of PTX. (b) Data from LPTCs ten minutes after application of PTX.

Figure 3: Simulation results. The mean response of simulated LPTCs is shown to preferred (PD) and null (ND) direction stimuli. These results are qualitatively similar to the electrophysiological results of Single *et al.* (see Figure 2). (a) Control case: Inhibition to LPTCs is unblocked. (b) Inhibition to LPTCs is blocked.



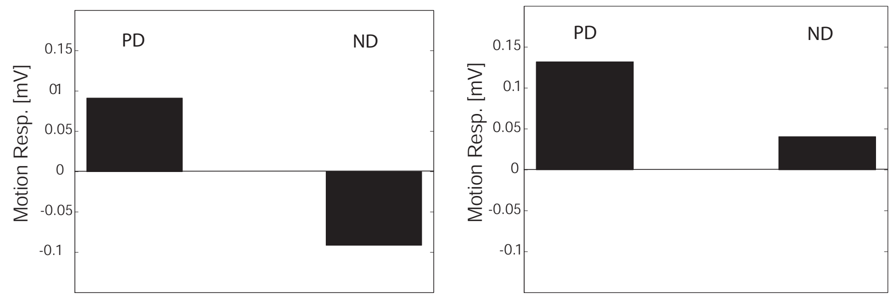
(a) (b)

Fig. 1.



(a) (b)

Fig. 2.



(a) (b)

Fig. 3.

Timothy Melano received his B.S. in Mechanical Engineering from the University of California at Berkeley in 2001. He is presently pursuing a Ph.D. in the Biomedical Engineering Program at the University of Arizona. His research interests are in computational neuroscience and neuroprosthetics.

Charles M. Higgins received the Ph.D. in Electrical Engineering from the California Institute of Technology in 1993. He holds joint appointments in Electrical/Computer Engineering and Neurobiology at the University of Arizona, where his research focuses on investigation of neurobiological computational and control architectures.